Rev 3 9/13/2019

Chemical Strengthening Data Sheet

Why Choose Cat-i Glass?

Cat-i Glass' products are used in more than 40 different markets around the world. As we have for five decades, our company still fabricates products for sight glass, with the capabilities for hundreds of other products in markets such as aerospace, display, instrumentation, lighting, medical, military and scanners. As an engineer-driven glass fabrication company, Cat-i has the expertise and a company ethic to inform customers when they are adding to some heavy costs on their part and tell them how they can reduce them. Cat-i's engineers can even go to a customer's facility to observe operators work with the glass and to give suggestions and tips in terms of cleaning, inspecting, handling and assembly. They are also able to apply their knowledge and expertise towards making product that is commonly difficult to produce a possibility. And as previously stated, Cat-i is well equipped to target certain strength properties by taking advantage of PLC controlled machines to control the temperatures and duration of the process that achieve the desired result of the customer. Cat-i's customers range from small businesses to Fortune 100 companies. All opportunities are welcomed from prototypes to mass production. Cat-i's glass fabrication capabilities and systems allow for all projects, all while being positioned to expand capabilities to match customer needs, as it benefits the customer as much as it benefits Cat-i to be more capable across the board. This level of expert consultation and the commitment to train and teach its customers is a huge advantage of choosing Cat-i Glass over the next competitor.

Definitions:

Compressive Stress (CS) - Induced by chemical strengthening process. Located in and around all surfaces of the glass sample where ion exchange occurs.
Central Tension (CT) - Byproduct of compressive stress that is formed on the outer shell of the glass sample. Also a derivation of Compressive Stress, making this property only useful in specific applications.
Depth of Layer (DOL) - The depth from the surface of the glass at which the ion exchange process occurs.
Modulus of Rupture (MOR) - Or flexural strength, refers to the maximum stress within a material just before it yields in a flexural test (MOR Break Test).
Stress Singularity - A point at which induced stress is infinite.
Microfracture - A very fine, minute, high aspect ratio crack.
- **High Aspect Ratio** - One dimension is greatly larger than the other. In this context, microfractures have virtually zero width and, therefore, far greater length in comparison.

Edge Quality - This refers to the state of the edge of the glass part. Cut edge quality mainly only refers to the squareness of the edgewall once cut. Ground edge quality mainly depends on how fine the grit of the grinding operation was.
Edge Work - This refers to post process(es) done to the edge wall after the initial cut/grind. This includes edge seaming, profile grinding, and beveling.
Glass Fines - Glass fines are very small shards of glass that are not quite yet powder, but still sharp. Usually resemble very small slivers.

Glass Types

- **Soda Lime (SL)** - Most common substrate of glass. It’s a float glass with a slight green tint that is attributed to its name.
- **Low Iron (LI)** - A float substrate with a colorless tint, that has similar properties to Soda Lime.
- **Borosilicate (Boro)** - A popular float substrate with a slight yellow tint, favored its hardness and low thermal expansion.
- **High Ion Exchange (HIE) Types** - HIE glass substrates are designed to be more susceptible to the ion exchange process, causing them to achieve higher compressive stress and deeper compression layers.
  - **Dragontrail™ (DT)** - Created and only manufactured by Asahi Glass Corporation (AGC), Dragontrail™ is a float substrate that is most common among HIE glass.
  - **Gorilla® Glass (GG)** - Created and only manufactured by Corning, Gorilla® Glass yields relatively higher strength properties than Dragontrail™. It’s created via the fusion-draw process, which is a gravity driven process that yields no “tin side” because there is none.
  - **Dinorex™** - Created and only manufactured by Nippon Electric Glass (NEG), Dinorex™ is the most recent addition to the HIE glass family. Cat-i already has experience manufacturing product with this substrate and extensive knowledge on its strength properties from various experimentation and analyses.

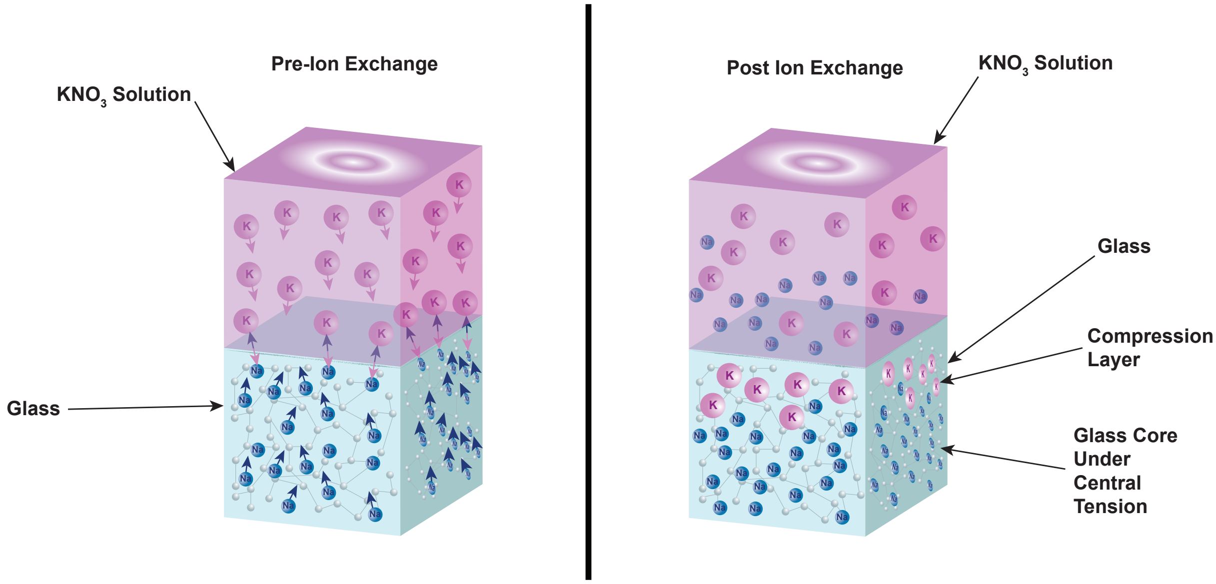
Price Comparisons - Material costs only; processing costs will vary depending on customer specification.
** - Price varies with thickness of glass.

GlassSubstrate	Price Multiplier
Soda Lime	1x Base Cost
Low Iron	4x
Borosilicate	20x
Gorilla® Glass	5 - 10x**
Dragontrail ™	8 - 15x**
Dinorex ™	5 - 10x**

Overview:

Chemical strengthening is a process that uses a molten salt bath at high temperature to induce an ion exchange process between smaller ions in the substrate, and larger ions in the salt bath. This ion exchange process occurs on all surfaces of the substrate, as they are the planes of first contact. Once the substrate is submerged and soaked at elevated temperature, the smaller sodium (lithium) ions that were originally in the glass are replaced with the larger potassium ions in the salt bath. Once the preset soak duration is completed, the strengthened glass will exhibit higher strength characteristics deriving from the induced Compressive Stress and Depth of Layer (CS/DOL) of the ion exchange.

Illustrations are of Glass Cross Section



Chemical Strengthening Characteristics

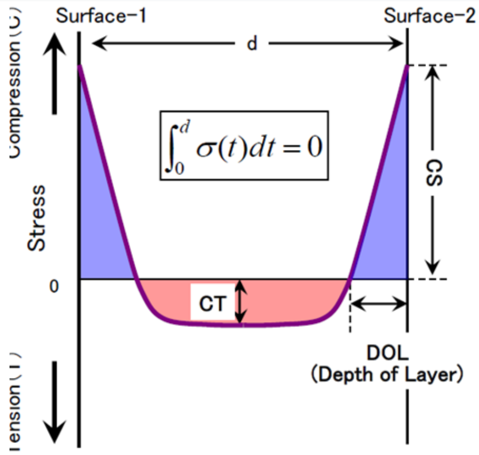
•Impact Resistance - The substrate's ability to resist an impact without cracking, shattering, or producing digs or chips.
- As CS increases, impact resistance also increases.

•Scratch Resistance – The ability of the substrate's shell to resist scratches from the frictional forces of outside sources.
- As DOL increases, scratch resistance also increases.

NOTE: As duration of the chemical strengthening process increases, DOL increases.

•Flexural/Bending – The substrate's ability to bend without breaking. This is measured via MOR (Modulus of Rupture).
- MOR is the amount of pressure, measured in pounds per square inch (PSI), and it represents amount of PSI it would take to rupture the substrate via bending load.
- As MOR increases, the flexural bending range also increases.

During the chemical strengthening process, CS and DOL have an inverse relationship with one another. This means that glass that has obtained a relatively high measurement of CS will most likely have a relatively lower DOL than another glass sample that is said to have obtained "typical" measurements. This is not to say that obtaining a relatively higher measurement, CS or DOL, will leave the other measurement at a lower, undesirable point. However, one cannot custom tailor a chemical strengthening process to obtain higher relative measurements of CS and DOL.



d – Glass Thickness
DOL – Depth of Layer
CS – Compressive Stress
CT – Central Tension
CT = (CS*DOL)/(d-2*DOL)

$$\int_0^d \sigma(t)dt = 0$$

The figure to the right is illustrating the physical properties of a chemically strengthened substrate from a side, cross-sectional view. The variable, d, is the thickness of the substrate between Surface-1 and Surface-2. The parabolic representation of stress illustrated is showing you the relation between DOL, CS, and CT. The net stress of the substrate will always equal 0. Simply put, when a tempered or strengthened substrate does not spontaneously shatter, it means that the sum of all of the stresses within it equal 0. With a certain amount of CS, comes a counteracting, corresponding CT to keep the glass at equilibrium. The illustration above is showing that by representing CT as a "negative" stress value on the graph. By summing the areas together, the stress cancels out. The illustration is also showing that the DOL is essentially the "boundary" where which CS ends and CT begins.

Below are Cat-i's suggested minimum values for glass that undergoes a common chemical strengthening process:

Substrate	Compresive Stress (CS) (MPa)	Depth of Layer (DOL) (μm)
Gorilla Glass	700	40
Dragon Trail	650	35
Soda Lime	425	7

Making the Right Choices for Chemical Strengthening

When deciding to move forward with a product using chemically strengthened glass, there are a few items that must be considered to help optimize the performance of the product, with respect to the cost it takes to produce it. These items include the glass substrate, thickness, and the edge work.

Substrate (HIE vs Non-HIE)

A common concern in substrate choice among customers is the price. SL will be the most economical choice, being offered in virtually any thickness and yielding reliable mechanical advantages offered from chemical strengthening. However, chemically strengthened HIE glass will yield deeper compression layers and higher compressive stresses, offering better mechanical advantages than chemically strengthened non-HIE glass. Generally speaking, Dragontrail™ is better suited for scratch resistance applications due to yielding deeper compression layers than Gorilla® Glass, but Gorilla® Glass will usually yield higher compressive stresses making it better suited for impact applications.

Thickness (Flexural Bending vs Maximum Strength)

When choosing a thickness, the first question that must be answered is, "how exactly is my product supposed to perform in the field?" Or more importantly, "what may my product undergo, while in the field?" These initial questions are important because both substrate types will yield similar, but unique, physical properties once chemically strengthened. HIE glass will be far better suited for applications where flexural bending may occur often, as well as for times where the bending is of high magnitude. SL is able to bend, but not as much as HIE glasses will. HIE glass also yields higher compressive stress and depth of compression layer than non-HIE glasses will, meaning higher impact and scratch resistance. Where non-HIE glasses prevail are in high loading applications where thicker glass is needed to support said loading. HIE glass will commonly not be manufactured above 2.0mm thickness, where SL can achieve much higher thicknesses.

If thickness is ever a constraint and a certain application requires that the glass yields the highest CS or DOL possible, Cat-i is well equipped to target certain strength properties by taking advantage of PLC controlled machines to control the temperatures and duration of the process that achieve the desired result of the customer.

Edge Work (Failure Reduction)

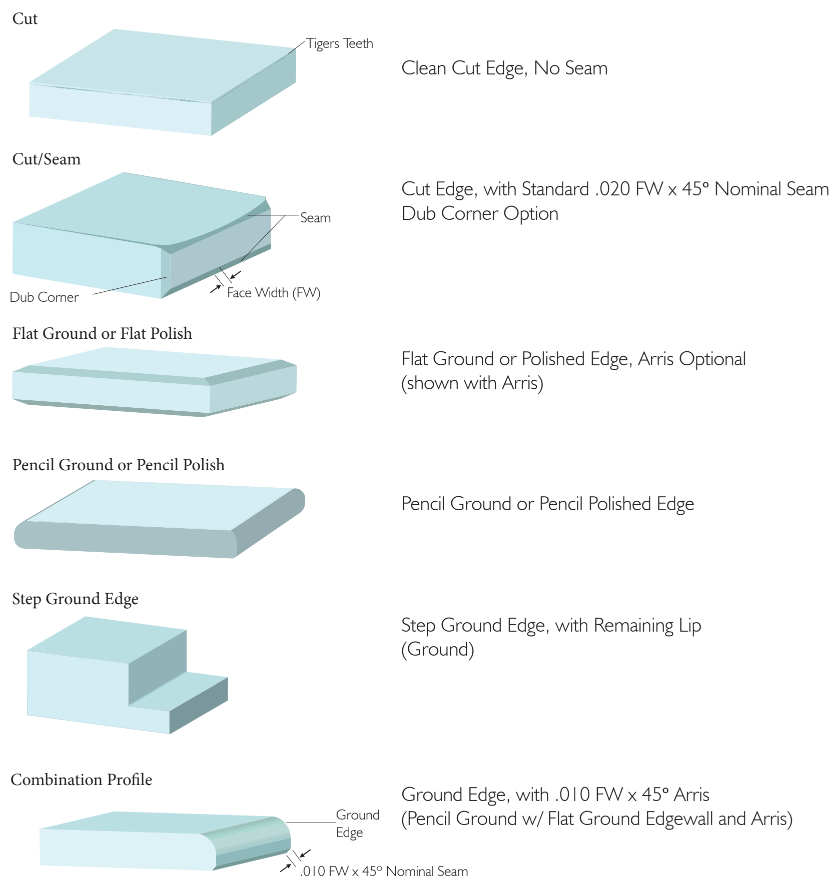
To ensure the mechanical integrity of the glass during and after the chemical strengthening process, Cat-i recommends that some form of edge work be performed on the glass prior to beginning the process. While it's true that chemical strengthening decreases the introduction of defects into the glass post-process, defects in the glass (especially around the edges) during the process can cause the glass to fracture while it's being strengthened in the molten salt. This is due to stress singularities located all around the edges of a purely cut or ground glass part. Adding edge work to the glass part will effectively remove all of those stress singularities, giving the glass a much higher chance of surviving through the chemical strengthening process.

As far as choosing exactly which edge work to have performed on a glass part goes, one simple question to answer first would be, "is the edge of my finished glass part going to be exposed?" If the intended end goal of the glass part edge is to not be exposed, then a simple cut/seam edge would be the most economical, while still reliably removing all sharp edge corners from the perimeter of the glass part. For exposed edges, the suggested edge profile would be one of the ground profiles. Grinding operations are going to add cost to the glass part, but in general will yield increased mechanical reliability than offered from general cut/seam operations. As opposed to only addressing the edge corners by performing a seam operation, grinding operations address the entirety of the glass edge by finely grinding the edge corners and edge wall, further decreasing the defect count of the glass part.

Some common applications that best fit certain edge profiles are listed as follows:

- **Cut/Seam**
  - Reliable defect removal of edge corners only. Most economical option. Best suited for 2-sided housings that completely cover glass edge.
  - Best suited for housings with more allowance for dimensional variance of the glass.
- **Flat Ground w/ Arris**
  - Common, aesthetic finished look for exposed edge.
  - Well suited for adhesives in 2-sided housings. The angled ground edge corners provided by the Arris grind allow more adhesive to fit within the space that the glass is set into.
  - Well suited for clamp-style brackets, for pure flat groundedge. The clamps of the bracket can be designed to go as close to the edge to maximize viewable glass surface area.
- **Pencil Ground**
  - Very common, aesthetic finished look for exposed edge. Round profile offers high resistance to edge chipping.
  - Well suited for adhesives in 2-sided housings. The round ground edge allows more adhesive to fit within the corners of the space that the glass is set into.
- **Step Ground Edge**
  - Used when it is desired for the glass surface to be flush with a bezel or housing.
  - Designer must be conscience of remaining lip thickness for proper strength.
- **Combination Profile**
  - Custom engineered profile by Cat-i to improve glass aesthetics when screen printing all the way to the glass edge.
  - Combines aspects of other profiles.
  - Can be used in exposed edge applications

Standard Glass Edge Profiles



Designing With Chemically Strengthened Glass: Part Creation Scenario

In this scenario, Engineer A works for a company that wishes to sell screen protectors made from chemically strengthened glass for their new line of tablets.

Being a new model of tablet, Engineer A already understands that this tablet does not have any pre-designed chemically strengthened screen protectors to buy and use for the tablets. Engineer A is now tasked with designing and purchasing screen protectors from a glass fabricator for the new line of tablets.

Assuming that Engineer A has already designed the shape of the glass screen protector and created the blueprint, the next action he takes is assembling all of the required criteria that the chemically strengthened screen protector will need to met.

Boundary Condition	Required Criteria
Depending on the application of use for the user, hands may or may not be clean and could cause scratches or digs on the surface of the glass. Solid debris will increase chances of scratches with swiping operations.	**Criteria #1 -** Each screen protector must aim for high scratch resistance.
10" tablets will weigh relatively more than the small formatted tablets that are available. Minimal weight addition is desired.	**Criteria #2 -** Each screen protector must be light weight (very low thickness). Weight difference desired to feel negligible to the user once picked up.
A drop could prove fatal to the screen protector, if hitting the floor at a failure-inducing position. It will be highly recommended that a case be fitted to the tablet to lower the chances that the screen protector will be damaged directly from a fall.	**Criteria #3 -** Each screen protector must be able to withstand possible impacts and flex easily to best fit the slight flex of the tablet during an impact.
Edges desired to have a fine ground finish to look aesthetically clean (for tablets without a case).	**Criteria #4 -** Each screen protector must have a fine ground finish.

Now that Engineer A has listed all of the required criteria that the screen protector must satisfy, he uses his datasheet supplied by Cat-i to help choose design parameters for the screen protector. Starting with the first criteria...

Required Criteria	Criteria Parameter
Criteria #1	Engineer A decides to use an HIE substrate since the desired part thickness will likely be in the range of HIE glasses. •Engineer A chooses Gorilla® Glass as the substrate to help achieve optimum DOL measurements once chemically strengthened. •Cat-i to custom tailor chemical strengthening tanks to aim for high DOL to achieve optimum scratch resistance
Criteria #2	•Engineer A chooses 0.70mm as the thickness of the substrate. Thin enough to have negligible weight difference when fitted to tablet.
Criteria #3	•Impact resistance will be lower due to indirect correlation between impact and scratch resistance, however it should still be able withstand impacts of lower magnitude. •Thin glass will allow for slight freedom in bending if impact causes flexing of the tablet.
Criteria #4	•Engineer A chooses to add a pencil ground edge to the screen protectors to optimize chip resistance, as well as give the screen protectors an aesthetic finished look.

Assuming that all other part processing details have already been planned out (glass cutting, film/adhesive application, etc), Engineer A is ready to contact the Sales department at Cat-i to put in a purchase order! Cat-i prides itself on being able to produce parts exactly to the customer's specification. Some details of an order may change depending on the conversation that is held between designer and salesman, but it is a significant help to the salesmen when the customer also has a good idea of what they have in mind for their chemically strengthened product.

Benefits of Chemical Strengthening

In general, all industries considering the use of glass in their product want the glass to be as strong as possible to reduce breakage. In specific industries, such as lighting, thermal tempering is an acceptable glass hardening process because the end goal is for the glass to be able to handle high heat for long periods of time. However for other industries, such as display, chemical strengthening would be more preferable due to the ability to process very thin glass parts, without inducing any optical distortion. This is one of the many key benefits of chemical strengthening that thermal tempering will not be able to replicate.

Chemical Strengthening vs Thermal Tempering

	Chemical Strengthening	Thermal Tempering

General Facts	• **Finished State:** Chemically Strengthened
	• **Minimum Thickness:** 0.30mm
	• **Maximum Thickness (HIE):** 2.0mm
	• **Maximum Thickness (SL/LI/Boro):** 19.0mm
	• Uses potassium nitrate bath
	• Can process HIE glass
	  • Corning® Gorilla® Glass
	  • AGC Dragontrail™
	  • NEG Dinorex™
		• **Finished State:**
		  • Ink Cure - SL/LI/Boro
		  • Heat Strengthened - SL/LI/Boro
		  • Fully Tempered - SL/LI Only
		• **Minimum Thickness:** 2.0mm
		  • Difficult to fully temper under 3.0mm
		• **Maximum Thickness:** Greater than 19.0mm
		  • Uses controlled combination of heating and rapid cooling
		  • Uses oscillating conveyor/batch system

Pros	• Can process glass thinner than 3mm
	  • Virtually no thickness constraints
	• Increases strength of HIE upwards of 6x-8x
	• Increases strength of Soda Lime upwards of 5x
	• Zero optical distortion
	• Improved thermal shock resistance
	• Improved scratch resistance
	• Improved impact strength
	• Improved flexural strength
	• Virtually zero warp
		• Cycle times are relatively fast
		• Cycle time decreases with thickness of glass
		• Strength of Heat Strengthened parts increased by 2x-3x
		• Strength of Fully Tempered parts increased by 4x-6x
		  • Safety tempering available for safety hazard applications
		• Improved thermal shock resistance
		• Improved impact strength

Cons	• Long cycle times (8hr, 12hr, 16hr) • CS/DOL properties highly dependent on state of potassium nitrate bath • Aggressive post-processing relieves CS within the glass, decreasing strength of glass • Coated material experiences lower, irregular ion-exchange, or none at all, depending on the metal coating on the surface of the glass • Tin side of float glass can hinder the ion exchange, causing warp on very thin glass	• Cannot process glass thinner than 3mm • Cannot process HIE glass (too thin) • Warp increases as thickness decreases • Optical distortion • Increases with warp • Full Temper specification not possible for glasses with low thermal expansion (Ex: Borosilicate) • Strength properties dependent on ambient temperatures • Aggressive post-processing causes glass to completely fracture due to internal stresses being relieved

Measurement, Analysis, and Validation of Chemical Strengthening

Cat-i prides itself on being a company that takes very technical, engineering approaches to the experimentation and analysis of our product. This holds especially true for chemically strengthened glass, as it is a delicate process that can yield vastly different results if parameters aren't held to a strict constant. Even then, like results still have a degree of variation among themselves due to minute differences latent in the glass, as well as the salt bath the glass was in during the ion exchange process. Cat-i has performed extensive testing and analyses on chemically strengthened glass using in-house metrology equipment to gather correlating knowledge on how all of the main facets of chemical strengthening (state of salt baths, thickness of glass vs strength properties, different glass substrates, etc) tie together. These tests and analyses include taking CS/DOL measurements from our surface stress meter and MOR break tests, or 4-point bend tests, which places chemically strengthened glass strips and places them under an increasing, controlled load until the glass yields (breaks). The 4-point bend test isn't perfect, however. It is required to run several sample strips within the same salt bath to acquire the mean of the summed MOR measurements. This is necessary because small defects in the sample strip, especially edge defects, can cause the strip to yield early, giving much smaller MOR measurement than its "potential" measurement.

Effects of Edge Quality on MOR Break Testing

To be able to understand the importance of the effect that edge quality has on an MOR test, one must first understand how microfractures under pressure turn into stress singularities. A stress singularity, in this context, is where the stress at a given cross-section of the glass is infinite. The edge corners of the score-side of the glass have several microfractures throughout the perimeter of the glass due to the pressure of the cutting wheel. The cross-section of a piece of glass at the location of a microfracture will show that the fracture ends at a point. The point acts as the singularity due to having essentially zero cross-sectional area, causing the infinite stress at that location to cause a propagation and therefore breaking the glass. The back-side edge corners of the cut glass may have microfractures as well, but the geometry of the almost-perfect, 90° edge corner makes the corner itself a stress singularity. These corners become the target area for microfractures (whether it's establishing and/or propagating them) once under the pressure load of the MOR anvil.

A glass sample with a ground edge, as opposed to a cut edge, will yield similar results. A quality of the ground edge will have a large effect on whether or not the MOR strip will break early due to the fact that grinding glass causes many, many microfractures on the ground surface. The quality of the grind will dictate the size and frequency of microfractures; i.e. the finer the grit of the grinding operation, the better results will be yielded through an MOR break test. Ground edge corners will never have as sharp of edge corners as cut glass, but the increase in microfracture count will play a role in causing premature breaks.

Effects of Edge Work on MOR Break Testing

Through extensive trial and error, Cat-i has found that additional edge work performed on sample strips prior to being chemically strengthened has shown sample strips to yield at higher stress points than solely cut/ground edged sample strips. The edge corners are sources of stress singularities. Therefore, by removing them with a fine grit seam, the sample strips are now more prone to yield uniformly within the volume stress area under the anvil of a 4-point bend test. The biggest tell-tale sign that an MOR strip has broken early will be the fact that it has broken along a single fracture line. A successful MOR break test will show the glass strip shattering into small pieces, meaning that the entire volume area of glass uniformly failed under the load of the MOR anvil. When it only breaks into two separate pieces, it means that a microfracture propagated and caused the strip to break only along the line of the propagation. While there are other edge profiles that are also effective in removing bare edge corners, seaming them off is a simple, yet very effective way of achieving that goal without putting too much processing into a sample strip that will be broken anyway.

High Ion Exchange (HIE) Glass

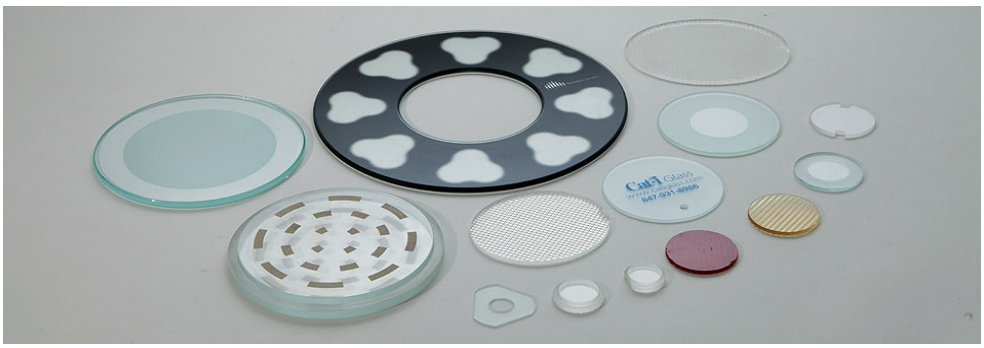
HIE glass opened the doors wide open for thin glass applications. In just about any industry, glass acts as an "invisible" barrier, allowing people to see while driving their car without wind blowing in their face or allowing sunlight into household windows without the outside elements coming inside. Often times, glass is thermally tempered to increase it's strength properties to reduce the chance of breakage. For thin glass, thermal tempering is very difficult due to the physical limitations of the thickness of the glass with respect to the vigorous quench process required to induce stress into the glass. HIE glass has become a #1 choice for manufacturers to use as the substrate for thin products to be made, due to the major advantages of chemically strengthening the glass. HIE glass is typically used for protective electronic display screens such as smartphones, laptop and tablet computers, mobile devices, touchscreens, sensor windows, etc. HIE glass provides exceptional resistance to flexural breakage, scratches, digs, and temperature fluctuations. Soda Lime is also made in thicknesses comparable to most HIE glasses, however HIE glasses, once chemically strengthened, exhibit far better strength properties. As as example, Cat-i testing has found that 1.1mm DT is capable of sustaining upwards of 35lbf in a 4-point bend test, while 1.1mm SL is only capable of sustaining about 20lbf in the same test.

Strength Differences of Chemically Strengthened 1.1mm SL vs. 3.0mm SL

A common topic among display applications - Each thickness has its unique strengths, but mainly those strengths are only going to apply best to the application that it's chosen for. The reason for discussing the differences between 1.1mm and 3.0mm specifically is because they are the most common "thin" and "thick" thicknesses used in chemical tempering.

The main strengths you'll see in 1.1mm SL are it's internal strength properties. 1.1mm SL will yield higher CS/DOL measurements than 3.0mm SL. This means that it will have higher impact and scratch resistance, which is preferable for applications such as screen protection where scratching and impacting could occur highly. 1.1mm SL will also have a higher bending point than 3.0mm SL. 1.1mm SL would be more desirable in applications where flexing occurs often, but HIE glass would be the recommended glass substrate group to choose from for flexing-specific applications. 1.1mm SL also has the advantage of being a candidate for "thin" applications. Using the example of screen protection again, it is more desirable to have a 1.1mm SL screen protector on a cell phone than it would be to have a 3.0mm SL protector. It would add significant weight and size relative to the cell phone, making the cell phone less desirable of a product as a whole.

The main strengths you'll see in 3.0mm SL are it's physical strength properties. Although 1.1mm SL yields higher CS/DOL measurements, it is not by a large margin. It will have lower impact/scratch resistance relative to 1.1mm SL, but it can sustain much higher loads before yielding. Extensive testing by Cat-i has shown that a 3.0mm SL sample strip is capable of sustaining over 200 lbf in a 4-point bend test, while 1.1mm SL is only capable of sustaining over 20 lbf in the same test. 3.0mm SL is highly recommended in display applications where impact/scratch resistance is desired, but having the glass capable of handling high loads is more important.



Chemical Strengthening of Coated Glass

Cat-i recommends that glass to be chemical strengthened should be uncoated, so that the glass gets the full effect of the ion exchange process. Coatings are composed of various metals and other materials that act as a protective layer on the glass, in regard to the ion exchange process. Naked glass will undergo the ion exchange process as normal, but coatings would either alter or completely hinder the process from taking place. This means that for 1-sided coated glass, one side may undergo a reduced, irregular strengthening. For 2-sided glass, the same goes for both sides, causing a reduced, irregular ion exchange on both faces.

A coating will also serve another negative purpose of distorting, or possibly completely blocking, light transmission, which completely eliminates the possibility of determining CS/DOL values. A surface stress meter uses light transmission through the glass to gather the data for it's measurements. Even if measurements can be obtained with a coating on the glass, the measurements will be wrong due to a distorted "image" of what the machine uses to calculate CS/DOL.

If chemically strengthened coated glass is necessary to have for a customer's application, Cat-i highly recommends that the application is suitable for the glass to have general increased strength properties. Any application where the glass exhibits high loads or high possibility of impact/scratch damage should have the glass used reconsidered to be without a coating. Another recommendation for customers who absolutely need both a coating and the full benefit of chemical strengthening is to have their uncoated glass chemically strengthened prior to having it coated. This will ensure that you have the full benefit from the ion exchange process, as well as the added feature given by the coating.

Chemical Strengthening of Etched Glass

Etchings are not coatings, but abrasions on the surface of the glass. This means that the surface is still purely glass and will undergo the ion exchange process without any hinderances. However, one important aspect to note is that etchings cause distortion of light. With regards to analyzing the compressive stress and depth of layer, there can be no light distortion from the surface of the glass when analyzing using a surface stress meter. The surface stress meter may not even be able to gather results from glass analyzed from the etched side. If it can, then the measurements will be incorrect due to the distorted light pattern that the machine receives.

The only way to analyze etched glass is if one side is uncoated and unectched. This will enable non-destructive analysis of the glass sample, as opposed to resorting to the destructive MOR, 4-point bend test.

Proper Metrology Techniques

Surface Stress Meter

Cat-i uses a surface stress meter to determine the CS/DOL of a glass sample. When using the surface stress meter to gather CS/DOL measurements, there are best practices to keep in mind.

1.Optical properties matter! The surface stress meter is very useful in giving accurate strength measurements. However, if the optical properties, photo-elastic constant and refractive index, are not set as the parameters for the current glass substrate when taking measurements, all measurements will be incorrect. So before measuring the CS/DOL of the sample, make sure that the optical property parameters are set correctly to avoid misinformation.

2.Be aware of glass position on sight window of surface stress meter. When placing a glass sample on the sight window, one should be able to see perfectly vertical striations on the display. This means that the glass is perfect flat against the window, causing the light used for measurements to "flow" properly. If the glass is tilting laterally, the position of the striations on the display will shift left or right. If the glass is tilting longitudinally, then the striations will tilt at an angle, causing the stress meter to error out. Once the glass sample is correctly placed on the sight window, the stress meter will be able to take measurements again.

3.Light intensity is important when taking measurements. This is especially important for operators that experience taking measurements of different glass substrates, often. Depending on the substrate being examined and the state at which the glass sample was chemically strengthened, the striations may not be the most visible in one light intensity as they will be in another. Light intensity will also affect the accuracy of automatic measurements, due to the fact that the striations need to be "visible" to the stress meter itself.

4.Ensure that the surface stress meter is calibrated! It is critical to the credibility of taken measurements that the machine being used is calibrated to date by the manufacturer, or an external calibration party. Also contact the manufacturer of the machine about possible, periodical self-calibration to ensure that the stress meter is operating correctly.

4-Point Bend Test (MOR Break Test)

Cat-i utilizes the 4-point bend test for measuring the MOR of glass sample strips. As stated above, there are best practices to keep in mind when performing these tests.

1.Firstly, why use 4-point instead of 3-point? For starters, a 3-point bend test focuses the amount of stress in the middle of the sample strip, leaving reduced stressed as distance from the center increases. A 4-point bend test bends from two equally offset positions that puts more volume of glass under stress than the 3-point. Putting more volume of a sample strip under stress will increase the likelihood that a defect, or microfracture, will cause the sample to fail. It can be said that the generalized flexural strength given by a 4-point bend test, as opposed to a 3-point, will be less due to the wider range of defects that will be under stress. Using a 4-point bend test pushes Cat-i further to produce defect-less product so that customer standards are met or exceeded by using a more strenuous test.

For HIE glass - When Cat-i needs to perform a bend test on HIE glass, it is far easier to cause the glass to fail under a 4-point bend test, rather than a 3-point. Geometrically speaking, the highest bend point for a 3-point bend test requires much more travel of the anvil, because it's distance below the level point of the sample strip is exactly its highest bend point. While for a 4-point test, the anvil's travel below the level point of the sample strip will scale the bending point of the glass higher as the anvil descends. Simply put, the center point of the sample strip will be at the bottom of the parabolic curve that the anvil and the glass creates, and the parabola will increase in depth as the anvil descends. This is important for HIE glass, because they were made more or less not to break when bent. Being able to bend the glass much further than possible with a 3-point bend test has allowed Cat-i to successfully break and obtain accurate MOR measurements from HIE glass.

2.Keep all points clean of glass fines/shards. After many sample strips have broken in succession, small glass shards and fines are going to be noticeably accumulating. If they end up on the surface of a point where a sample strip will lay, it may alter the results of a bend test by causing extraneous stress around the shards large enough to cause digs. There's no simple way of telling if a sample strip broke early due to this specific issue, but it is in best interests to keep all points clean of glass shards/fines.

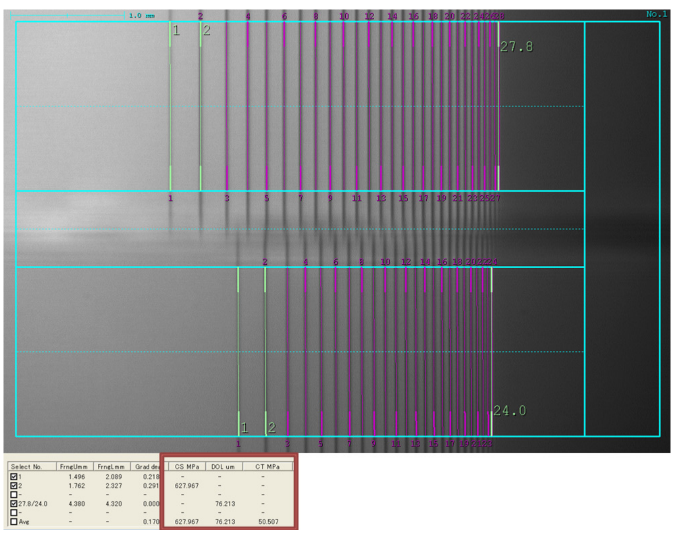
3.Align glass in bend test fixture as evenly as possible. If glass is offset to one side or another, stress induced by the anvil will also be offset, possibly giving different results than what an evenly spaced sample strip would yield. Also make sure that the glass is perpendicular to the points. If the sample strip is at an angle, then the anvil will not be applying pressure in a perfectly lateral direction, giving the glass additional, opposing torsional stresses in the longitudinal direction. This will most likely cause the sample strip to break early.

4.Orient score side up (facing the anvil). Per ASTM C158-02, the glass is to be oriented with the side of the cutting wheel under compression. Meaning that if the sample strip is facing upwards, the top face of the sample strip will be bend concavely and put that plane of glass under compression. This also serves to set another variable as a constant throughout multiple break tests

Moving Over to Non-Destructive Format Analysis

While Cat-i has the capabilities to perform a Modulus of Rupture (MOR) Break Test analysis on our chemically strengthened glass, we have recognized the benefit to verifying the increased strength of our Chemically Strengthened products via non-destructive methods.

- The MOR Break Test is a destructive analysis following ASTM C158-02. Due to its destructive nature, customer's parts cannot be processed directly.
- The ASTM specification calls out for specific dimensions of sample strips to be processed in the salt bath. Due to the dimensional requirements of the sample strips, customer's products cannot be processed in this test.
- Using our specialized metrology equipment, we are able to non-destructively analyze the actual customer glass sample's compressive stress and depth of layer. By relating CS/DOL measurements with results from MOR break testing, Cat-i has developed standard minimums that a certain glass substrate must meet in order to be considered properly chemically strengthened. (i.e. the CS/DOL values infer that the glass substrate would pass a certain PSI requirement of a 4-point MOR break test).
- The repeatability of obtaining accurate CS/DOL measurements trumps that of an MOR break test, because many minute, physical factors of an MOR break test cause seemingly exact samples of glass to yield different results. MOR test results have shown to be highly dependent on the sample strip's edge work and quality.



Surface Stress Meter Screenshot

Because of the aforementioned reasons, Cat-i strives to look for more consistent, reliable means of producing quality product that is acceptable for customers.

1. Cat-i has performed hundreds of CS/DOL measurements of sample strips prior to subjecting them to a 4-point bend test. The purpose is to derive a relationship between average MOR results with CS/DOL measurements of the same sample strip, at weekly or monthly intervals over the duration of many months. The results of these numerous tests are Cat-i's standards of minimum CS/DOL measurements that were set in place to represent sample pieces that would yield results similar to that of the sample piece undergoing a MOR break test.

2. Analyzing CS/DOL data, instead of MOR data, offers more insight into the states of the salt baths that we used to chemically strengthen glass. Each time glass is dunked into the baths to be strengthened, the ion exchange process is giving the glass more potassium ions and receiving more sodium ions. Over time the alternating ratios of potassium and sodium negatively affect CS/DOL measurements. To supplement this finding, Cat-i has also sent in monthly salt bath samples to have the potassium and sodium levels analyzed to link increasing sodium and decreasing potassium content to decreased CS/DOL measurements, as well as MOR.