Glass Breakage - Nickel Sulphide Inclusions

Inherent in the glass production process are microscopic imperfections in the glass, known as inclusions. Most of these are completely harmless, but nickel sulphide (NiS) inclusions have been shown to cause disastrous failure of tempered glass. When annealed (aka float) glass is heated in the tempering process, so are any NiS inclusions present in the glass. However, when the glass is rapidly cooled to achieve the properties of tempered glass, the NiS remains in a high-temperature form. Over several years, the NiS will return to its low-temperature state, and in the process will increase in volume. This can cause cracking and additional tensile stresses which, in tempered glass, have led to spectacular failures with no visible cause. This phenomenon has also been referred to as “glass cancer” and “spontaneous glass failure”.

The main risk this poses to the building industry comes from in-service failure of window panels containing tempered glass with NiS inclusions. When these windows break, they shatter into thousands of pieces which can fall from panes and cause injury to inhabitants of the building or pedestrians around it. The pieces can also cause damage to building finishes in addition to the cost of replacing the window, which can often be extremely costly. This article seeks to explain the history of NiS, how NiS is introduced into glass, how NiS effects tempered glass specifically, what measures are being taken to prevent NiS from ever entering glass, and finally how NiS can be detected in completed, installed glass. It concludes with several mini case studies indicating the typical magnitude and severity of NiS failure on a building.

Brief History of Nickel Sulphide Inclusions

The first acknowledgement of NiS as a problem was made by PPG Industries (a major US glass manufacturer) in the 1940’s. However, it was not until 1961 that any official documentation was published on the subject, when E.R. Ballantyne published a paper entitled “Fracture of toughened glass wall cladding” (Jacob 2001). M.V. Swain is also considered an authority on the subject for the research he published on the chemical composition of NiS in the Journal of Material Science in 1981. However, the first record that could be found by this author of a company publically acknowledging the problem was not given until 1990, by Luxguard S.A. (Bowler-Reed 2002). Since that time, the industry as a whole has made great strides in understanding and resolving the problem of nickel sulphide inclusions. As of yet, however, they have not succeeded in eliminating the concern entirely.

Glass Production Process

Glass production especially that of tempered glass is a multi-step process. Having a basic working knowledge of this process will facilitate the discussion of the properties of the resulting glass and how it is affected by nickel sulphide.

Annealed Glass

The most basic form of glass is known as annealed, or float, glass. This begins as five base ingredients: silica sand, soda ash, dolomite, limestone, and salt cake. These are heated in huge furnaces to 2700 degrees F (1480 C), and then floated out on a pool of molten tin (hence the name “float glass”). The large sheets are pulled onto a conveyor belt, and taken through an annealing layer, which is a furnace that prevents the glass from cooling too fast. If glass were left to simply cool without the use of the layer, it would be susceptible to thermal shock, and therefore immediate cracking or additional vulnerability to cracking while in service. It is this controlled cooling process that gives glass it’s more technical name, annealed glass. The cooled glass is cut into large sheets, and then sent to other processing locations for finishing, such as cutting to size, strengthening, or insulating (Meshulam 2009). A large glass furnace can easily produce up to 600 tons of glass each day (Glass on Web 2004).

Heat Strengthened and Tempered Glass

Heat Strengthened and tempered glass are created through the same process. At a processing plant, large sheets of annealed glass are cut to the appropriate size for the windows to be made, and any holes or shaping required in the panels are created. It is especially important to do this prior to strengthening or treating in any way, as any modifications after strengthening will shatter the glass, and coatings may be damaged by these processes.

After the glass is sized, it is heated again. However, this time the furnace is only heated to 1100-1500 degrees F (590-815 C). This temperature is held until the glass softens slightly, at which time it is rapidly cooled through the use of air jets, a process referred to as quenching (Meshulam 2009). Quenching reduces the temperature of the surfaces of the glass significantly, but due to the low thermal conductivity of glass, the core of the panel remains at a much higher temperature. As this core cools, it induces compression in the already-cooled outer layers, and a balancing tension force is formed in the core of the panel. The commonly accepted stress profile for this process is a parabola, as shown in Figure 1. This stress distribution results in a core tension that is half the magnitude of the surface compression.

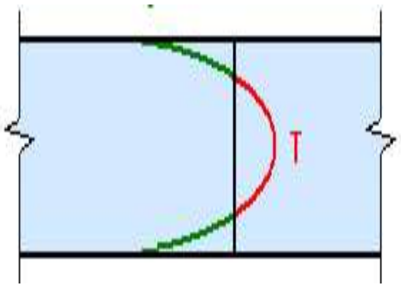

Figure 1: Tempered glass stress profile (Produced by author, based on image from Solinov 2007)

The difference between heat-strengthened and tempered glass is the speed at which they are cooled, which results in different surface compressions and therefore different overall glass strengths. Heat-strengthened glass is the weaker of the two materials, and is mostly used in applications where a higher tolerance to rapid or uneven temperature variations may be experienced, especially if these variations are cyclical in nature (such as back-painted glass subjected to a solar load). It has a surface compression of 3,500-7,500 psi (24-52 MPa), and is approximately twice as strong as annealed glass (Meshulam 2009). Due to the lower core tensions in heat-strengthened glass, this material very rarely suffers from spontaneous failure (in 1995, only one heat-strengthened panel had ever reported this failure) (Brungs and Sugeng 1995).

Fully tempered glass has all the benefits of heat-strengthened glass, but is additionally resistant to blunt impact (such as a pedestrian walking into a door). It is because of this characteristic that tempered glass is required for use in all glass doors and sidelights, and it is often used for large glazing panels on high-rise buildings as a precaution should something impact the building (Vigener and Brown 2009). Tempered glass is created by cooling the outer layers even faster than heat-strengthened glass, resulting in a minimum surface compression of 10,000 psi (69 MPa) and glass that is 4-5 times stronger than annealed glass (Meshulam 2009). A more typical industry surface compression standard is 14,500 psi (100 MPa) (Jacob 1997).

The additional strength of tempered glass is also called upon to resist high wind loads on high rise buildings. Lastly, the high stresses in the glass lead it to fracture into small, relatively smooth cube-like pieces (referred to as fracture dice) upon breaking, which can only be accomplished through mechanical means with a sharp point or edge damage to a pane (Barry 2006). From this property, tempered glass has also earned the name “safety glass.” However, it is because of this higher surface compression–and thus higher core tension–that tempered glass alone is susceptible to failure due to NiS.

NiS in the Glass Production Process

It is at the very beginning of the life of the glass that inclusions are introduced. Inclusions are microscopic particles that are incorporated into the structure of the glass in the initial heating process. According to the Glass Association of North America (GANA), there are approximately 50 different types of dirt or other inclusions recognized, but almost all of them are completely harmless (Johnson 2008). Nickel sulphide is the only exception, and even then it is only a problem in tempered glass.

The sulphur in the nickel sulphide is actually added to the glass as a fining agent in the form of sodium sulphate. Fining agents are chemicals added during the glass production process that encourage the formation of large bubbles from the smaller bubbles that rise to the surface of the hot glass during the initial heating period (Barry and Ford 2001). However, there is still debate in the industry as to how the nickel is introduced. There are three possible sources indicated:

- Raw material contamination
- Contamination of materials used in storage/handling of the raw materials
- Contamination in the furnace via fire bricks or burners

Major strides have been made in reducing the contamination of raw materials, and great care is taken to avoid the contact between the raw materials and any nickel-containing alloys (such as stainless steel). In addition, all glass furnaces now use natural gas instead of fuel oil, because it was found that fuel oil contains nickel oxide (NiO) in trace amounts up to 3 parts per million (ppm) (Kasper and Stadelmann 2002). This may seem insignificant, until it is considered that this quantity of nickel is sufficient to form a nickel sulphide inclusion of a potentially dangerous size every 2mm on a float line (Kasper and Stadelmann 2002). In fact, one gram of nickel, once made into NiS, has the potential to contaminate all glass produced on a typical float line for ten days (approximately 6000 tons of glass) with NiS stones (Kasper and Stadelmann 2002). It is obvious with such small concentrations being so incredibly problematic; any nickel that enters the float glass can become a serious concern.

There is a reasonable consensus in the industry as to how NiS forms from the compounds that are initially introduced into the glass. Assuming that the nickel enters in the form of a nickel-alloy metal, which is the most commonly accepted explanation for its origin, nickel sulphide forms in a three-step process. First, the nickel separates from the other materials in the alloy, then it bonds with sulphur in the high heat of the original furnace, and finally is trapped in the glass as the glass cools (Barry 2006). Further explanation of how this affects the glass is discussed in the next section.

Effect of NiS on Tempered Glass

It is important to explore exactly how NiS affects tempered glass. It is the distinctive behaviour of this compound that leads it to be such a threat. In order to understand how to address the problems it causes, the nature of these problems must be better understood.

Properties of NiS

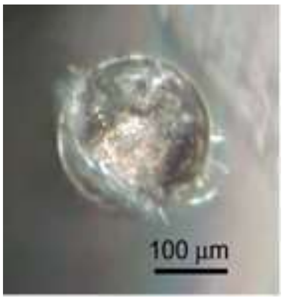

Figure 2: Microcracking around an NiS Inclusion, as seen under an electron microscope (Source: Barry 2006, permission requested)

Nickel sulphide is an interesting compound that, like many compounds, exists in different phases at different temperatures. Pertinent to this discussion are two specific phases of NiS, known as the alpha-phase and the beta-phase. At temperatures below 715 degrees F (379 C), nickel sulphide is stable in the beta-phase form (Jacob 1997). Above this temperature, it is stable in the alpha-phase. Therefore, when glass is produced in the furnace, it is overwhelmingly likely that any NiS inclusions will be in the alpha-phase. In typical annealed glass, the slow cooling process provided by the annealing layer allows the NiS ample time to transform to its beta-phase as the glass cools. However, in the fast cooling process used in both heat-strengthened and tempered glass, there is insufficient time to complete the phase transition (which is a relatively slow process). The inclusions therefore are “trapped” in the glass in their high-temperature alpha-phase.

However, once the glass cools past the phase change temperature, the NiS inclusion seeks to re-enter its lower energy beta-phase. For “trapped” inclusions, this process takes anywhere from months to years. This would have no effect on glass whatsoever were it not for the fact that when the NiS changes from alpha-phase to beta-phase, it increases in volume by 2-4% (Jacob 1997). This expansion creates localized tensile stresses that are estimated to be as much as 125,000 psi (860 MPa) at the glass-NiS Interaction surface (Jacob 1997). The magnitude of this stress drops off sharply away from the face of the inclusion, but is sufficient at the face to cause microcracking, as can be seen in Figure 2.

In compression zones, even this large of a stress is not a concern due to its extreme localization. However, in the core tension zone of the glass, these microcracks are propagated by stress concentrations at the tip of the crack until the structure of the glass is undermined completely and the tempered glass undergoes its characteristic shattering, which causes the seemingly spontaneous failure.

Stoichiometry of NiS

Nickel sulphide is a compound that comes in various forms as well. Extensive research has been done into the stoichiometry of NiS, and how this affects its behaviour with respect to tempered glass. Stoichiometry is the term in the chemistry field for the ratio of different elements in compounds. The most common forms of NiS encountered are Ni_7S_6, NiS, $NiS_{1.03}$, Ni_3S_2 and Ni_3S_2+Ni. When viewed under an electron microscope, Ni_7S_6, NiS, and $NiS_{1.03}$ are yellow-gold in colour and have a rugged surface similar to a golf ball. These three types are non-magnetic and have been found to cause failure in tempered glass. However, Ni_3S_2 and Ni_3S_2+Ni are metallic grey in colour and have a relatively smooth surface under an electron microscope. These are magnetic and have not been found to cause failure in tempered glass (Barry and Ford 2001).

Impurities in any of these compounds, such as other metals, significantly alter the behaviour of the basic compounds. Of particular concern is iron contamination, which slows the transition process from alpha-phase to beta-phase below the rate found in purer samples of NiS (Kasper; Jacob 2003).

Critical vs. Sub-Critical Inclusions

Research has created an equation that predicts the theoretical diameter of a NiS inclusion that would cause failure which depends on the internal stress of the glass panel. The smallest theoretical inclusion that could cause a fracture in tempered glass is 50 um in diameter (Gelder 2001). Inclusions larger than this are typically referred to as “critical” inclusions, whereas any inclusions smaller are “sub-critical” inclusions.

It is important to note that sub-critical inclusions are capable of causing failure if the glass is placed under additional tensile stress due to bending or thermal loading. It has been shown that when glass undergoes deflections that are in excess of 75% of the panel thickness, the stresses in the glass due to lateral loads change from a bending stress profile to a membrane stress profile. Under this condition, the tensile stresses at the centre of the glass may be increased by lateral loads. When the glass contracts due to a drop in temperature, additional tensile stress is introduced into the centre of the glass.

The relationship between stress and diameter of an inclusion can be used to prove that stress increases as small as 205 psi (1.4 MPa) are enough to cause failure in an inclusion that is slightly smaller than 50 um in the tensile zone of glass with a surface compression of 14,500 psi (100 MPa). This corresponds to a 2.8% increase in stress (Gelder 2001). Since glass is easily capable of developing up to 1,450 psi (10 MPa) of membrane tensile stress and 290-435 psi (2-3 MPa) of tensile stresses due to thermal changes, it is evident that this failure mode is can be a significant concern (Jacob 1997). It is, however, extremely difficult to anticipate the actual levels of additional stresses that will be incurred in service. Tempered glass that is not contaminated with NiS is more than capable of resisting stress increases of this magnitude, and so it is clear that even very small NiS inclusions can be a danger to tempered glass.

Breakage Frequency and Timeline

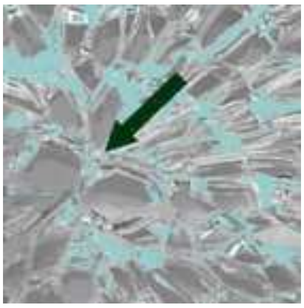

Figure 3: Fracture pattern due to NiS, with fracture origin indicated by the green arrow (Source: Barry 2006, permission requested)

Estimating how many nickel sulphide inclusions occur in a typical batch is extremely difficult. However, most estimates are within the same range of frequency. Napier & Blakely cites the rate of occurrence as 1 inclusion in 500 panes of average size, which is perhaps the easiest rate to conceptually comprehend (Napier & Blakely 2008). Another source uses weight to relate the frequency, citing approximately 5 ug of NiS in 1.1 tons of glass (Barry and Ford 2001). A final source mixes the two approaches by claiming the typical rate of occurrence is 1 inclusion in 880 tons of glass, even though it also relates the case of a toughening plant that monitored its production for five years and found they had 1 NiS-induced failure in every 500 tons of glass (Jacob 2001). Although the numbers do not match, it seems clear that failures due to NiS inclusions are incredibly rare. Buildings that have seen multiple instances of NiS failures often have huge expanses of glass, which automatically increases the odds of such a failure occurring. It is also possible for a particularly bad batch of tempered glass to be produced, which would have a higher failure rate if no preventative measures are taken to mediate the concern.

Another aspect of nickel sulphide failure is the fact that these failures rarely occur upon installation or even within the first few months following installation. Nickel sulphide failures produce a fracture pattern that is often referred to as a “double D” or a “butterfly” pattern, as shown in Figure 3 (Bowler-Reed 2002, Barry 2006). This is easily recognizable if the fractured glass is recovered more or less intact. However, if the glass is at all disturbed upon breaking or the fracture origin is not recovered, the breakage pattern can be mistaken for an edge damage failure, and an edge damage failure can be mistaken for a NiS failure. Therefore, the statistics on when these failures occur is not as reliable as they could be.

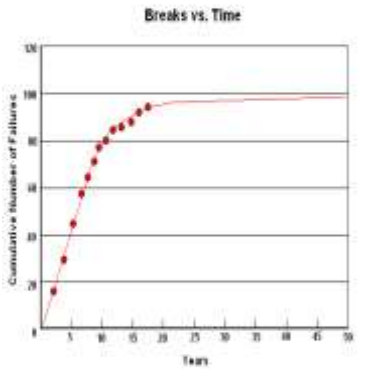

Figure 4: Number of NiS-induced failures on a project (Produced by author, based on data from Jacob 2003)

Even so, the overwhelming trend is that most panels break in the first 2 to 7 years, after which the number of breakages tapers off with what is commonly considered a logarithmic decay, which is illustrated in Figure 4 (Bowler-Reed 2002). No record was able to be found of any breakage occurring more than 30 years after installation (Bowler-Reed 2002). Factors which may influence the time from installation to fracture include the purity of the inclusion, the location of the inclusion within the glass, the magnitude of tempering stress, the size of the initial microcracking around the inclusion, the environmental conditions the glass is subjected to, and the size of the panel of glass in which the inclusion is located (Jacob 2001). Due to the high number of influencing factors and the lack of control which we are able to impose on any of the factors, we are unable to predict failures with any real level of accuracy.

Preventative Measures

The industry is pursuing several courses of action in order to reduce the risks and costs associated with nickel sulphide in tempered glass. For the purposes of comparing various preventative or corrective methods, three criterion were selected which seem to be a fair evaluation of the effectiveness of a solution. In order to be a successful solution, the method must be cost-effective to implement, eliminate the costs of replacement of panels upon breakage (which is often the highest cost associated with nickel sulphide), and prevent any injury to bystanders in a failure. So far, no solution has adequately fulfilled all three criteria, and thus the industry is still searching. However, a summary of preventative measures already in use or development in the industry is discussed here.

Decreasing the Use of Tempered Glass

This method is mostly common sense. If less tempered glass is used in a building, there are fewer opportunities for breakage to occur. A particular proponent of this method of limiting breakages is the Whole Building Design Guide, which recommends the use of tempered glass be limited to areas where it is required by code or for strength (Vigener and Brown 2009). It also recommends using laminated glass wherever possible, as this uses a film to keep the panel intact should it shatter. This prevents small pieces of glass from falling out of the pane in the event of breakage, largely eliminating any danger to building inhabitants. However, this may be prohibitively expensive to the owner, and does not offset the cost of replacing any panels should they break. Therefore, although this is good design practice, it is possibly the least effective solution.

Controlling NiS in Annealed Glass

As was discussed in the section titled “NiS in the Glass Production Process,” it is very difficult to prevent the tiny concentrations of nickel sulphide required to cause inclusions from infiltrating into the glass melt. The whole problem associated with NiS originates from the fact that NiS is insoluble in glass, which then results in it forming distinct inclusions. However, testing conducted by M.P. Brungs and X.Y. Sugeng in 1995 demonstrates that this is not entirely accurate. The truth is that NiS is soluble in glass, but it takes too long to dissolve in most glass to occur during the glass melting process. However, they also found that glass with high oxidation states (as determined by the ferrous/ferric ratio within the glass) actually allows NiS to dissolve into the glass melt at a rate that would be acceptable for most glass production processes. These researchers recommend the formation of a standard for the oxidation state of glass intended for tempering.

As of yet, no such standard exists. The reason for this seems to be largely cost-driven. In order to ensure such high oxidation states were maintained, extremely stringent quality control would have to be imposed on the production process, which may not even be practical for the industry, and would certainly be costly. There is also no definitive proof that implementing such a standard would entirely neutralize the threat of nickel sulphide. It is possible that it would reduce the failure rate even further than the present rate, but without a guarantee of complete elimination, it seems unlikely the industry will ever adopt such a severe control when the problem it is intended to reduce the frequency of is already so infrequent.

Heat Soak Testing

Heat soak testing (or HST) is a subject of great controversy in the industry. It was first introduced in 1982, and it is a destructive method via which panels of glass contaminated with NiS can be eliminated (Napier & Blakely 2008). At its essence, it consists of reheating tempered glass panels for a third time, maintaining it at an elevated temperature that is still below the phase transfer temperature of NiS for a set time, and then allowing it to cool. This was originally regulated by the German-based standard DIN 18516, but in the last decade the newer standard prEN 14179 has become the most common (Jacob 2003). This standard requires glass to be heated to 554±50 degrees F (290±10 C) and held for 2 hours, which is a shorter duration than DIN 18516 (Jacob 2003). The reduction in time was based on recommendations from research which indicated that less than 1 break in 10,000 panes of glass was expected to occur after 2 hours (Kasper). Maintaining an elevated temperature facilitates faster conversion of the alpha-phase NiS to beta-phase, and therefore the idea is that any panels which will fail from NiS fail in the HST oven rather than on the building.

This method suffers from several draw-backs. The first is that the secondary heating of tempered glass relaxes surface compression slightly without a corresponding decrease in core tension, which reduces the strength of the glass (Solinov 2007). This is much less of a problem now that the length of the HST has been reduced, but it is still of concern for designers.

The second issue the process encounters is the vagueness of the prEN 14179 standard. Although this standard mandates calibration of the HST oven to ensure the desired temperature is being reached, the calibration procedure outlined may not be effective enough. Also, the standard specifies no heating or cooling rates (Jacob 2003). These rates have been found to be important to the success of the HST, since approximately 80% of the breaks occur during the heating period, leaving only 20% to occur during the holding period (Kasper).

The final issues are related to the costs associated with the process. To heat glass a third time is a costly proposition that has to be justified by the gains, which some authors in the subject don’t seem to feel is the case (Jacob 2001). To reduce the energy demands for heating the glass, it has been suggested to further reduce the heating rate, which would enable the test to be performed at a lower temperature (Sakai and Kikuta 1999). It has also been suggested to begin the HST directly after quenching, before the glass fully cools (Sakai and Kikuta 1999). This second process is rejected by other designers, due to the importance of the heating period (Kasper).

A secondary cost of HST that is often not accounted for is the fact that, since all cutting must be done on a panel before it can be tempered, when a panel breaks in an HST oven, all the time (and subsequent money) that went into the production of the panel is essentially lost. In addition, glass is usually loaded into HST ovens very tightly, often with fractions of inches between adjacent panels. When one panel shatters, it can do damage to the neighbouring panels, potentially even causing them to break as well and propagating the problem (Barry 2006).

As a result of the drawbacks of the HST process, it is not used as commonly in the US as it is in Europe. Often, US glass manufacturers will either choose not to perform the HST, or they will perform it at lower temperatures for shorter durations (Johnson 2008). This reduces the effectiveness of the HST, further tarnishing its reputation.

In spite of all the issues with the process, it is still the only method the industry has to eliminate a large portion of nickel sulphide inclusions in batches that are compatible with large-volume production. The success rate of HST is hard to define because of the difficulty of accurate data collection on resulting nickel sulphide failures. However, most tempered glass manufacturers that perform the HST are capable of providing a certification indicating the HST was 95% effective. For specialized designs where breakages must be limited more severely, some manufacturers will even perform HST’s certified to 98.5%. As of yet, 100% success in eliminating nickel sulphide from tempered glass cannot be guaranteed by any method.

Other Methods

Those who feel the costs of heat soak testing are not justified by the results often recommend other methods to detect NiS inclusions, such as laser imaging, ultrasound, and using a controlled mechanical load to create an increased tension in the panel which will induce failure in any panels with inclusions. Laser imaging and ultrasound are especially promoted as they are non-destructive. However, the equipment required for each of these test methods is expensive, and although they can be largely automated, they still require individual testing of each panel. This would significantly decrease the production capacity of tempering facilities, and thus is unacceptable. What is more, none of these methods provides a guarantee of elimination of NiS inclusions. The results of ultrasound and laser imaging must be interpreted by a person, and the margin of user error might be prohibitively large when searching for such a small problem. Also, since a mechanical load must be specified for an induced tensile load test to be performed, any calibration errors in the loading could result in breaking more panels than strictly required or not breaking panels with NiS inclusions that should have been eliminated. None of these methods is at present practical for large-scale use.

Detection of NiS in Completed Structures

Another major problem facing the industry is remediation of buildings that experience nickel sulphide failures. When panels begin to break, the owners of the building obviously replace the shattered panels. However, proactive owners also look to minimize or eliminate future breakages. The most brute-force method to achieve this is to remove all tempered glass and heats soak it, if this process was not already performed. However, the costs of this are usually far in excess of using an available detection method to identify panels with problems, allowing the owner to replace only those panels. All of these detection methods are extremely labour intensive, require specialized equipment, and are prone to user error due to the incredibly small size of the object of their search. They are also difficult to complete because of the amount detail that is required to detect these images. Some detection methods are summarized in this section.

Ultrasound

Ultrasound is a technology that uses sound waves and their echoes to create an “image” of the interior of the glass. These readings must be performed and interpreted by skilled technicians, as they are often extremely difficult to interpret to the untrained eye. To use an ultrasound on large expanses of glass is a time-consuming, labour intensive process, and may not have a full success rate simply due to the minute size of the particle being located. Upon locating an inclusion, microscopes and the known properties of NiS inclusions which cause failure must be used to determine whether or not the inclusion is critical enough to merit replacement of the panel. Every inclusion located in the glass must be examined in this manner, which is what makes this such an incredibly time-consuming process.

Laser Imaging

Laser imaging uses the property of light which causes it to scatter upon striking an object. It involves aiming a laser at the panel of glass, and using a detector on the other side which is designed to deflect the primary (or direct) light from the laser while still receiving the secondary (or scattered) light that occurs when the laser strikes an inclusion. A laser is used because it is a concentrated, monochromatic light source for which the properties of scattered light are easy to predict. It is the predictability of the scattered light which allows the results collected on the detector to be used to determine the size of the inclusion. Once the inclusion is located and determined to be of a size that requires further study, users must use microscopes and the known properties of NiS inclusions which cause failure to determine whether or not the inclusion is critical enough to merit replacement of the panel. Every inclusion located in the glass of a significant size must be examined in this manner, which is what makes this such an incredibly time-consuming process. It is slightly more efficient than ultrasound because the preliminary data provides some criteria to eliminate some inclusions on the basis of being too small to be of concern. That being said, it also requires both sides of the glass to be accessible and transparent, which make this method impractical for use on most spandrel panels.

Photo glass Process

This process was developed by a partnership between the University of Queensland and Resolve Engineering. Detection is accomplished in three stages and was summarized by Barry in his 2006 article “The Achilles Heel of a Wonderful Material: Toughened Glass.” In the first stage, glass panels are photographed from an angle. In order to accomplish the detail required for detection, wide format (120 mm) film was used. The angle of the camera causes the inclusion to show up on the film as a characteristic dot pair. In the second stage, the film was systematically examined via microfiche. The dot pairs must be located, and then their spacing can be used to determine the depth of the inclusion within the glass. At this point, inclusions that are not in the tension region are entirely disregarded, as they cannot cause failure regardless of what type of inclusion they are. The final stage of the process is to inspect the glass using a 10x Lupe eyepiece or a microscope, which enabled the inspectors to view the colour and surface texture of the inclusions in the tensile region. The colour and surface texture of the forms of nickel sulphide which cause failure are not mimicked by any other type of glass inclusion, and therefore the harmless inclusions could easily be disregarded.

This method is limited by the extensive manpower required to complete it successfully, as well as the accuracy of the persons conducting the photography and review of the images. It also uses equipment and materials that are highly specialized, particularly the film for the original photographs. For these reasons, it is costly. However, it may be performed with excellent results on all glass on a building. In the initial trial, the team testing the system was able to examine 4,194 panels of glass (totalling nearly 159,000 ft2 (14,753m2)) and identify 53,594 inclusions, of which 291 were determined to be nickel sulphide in the critical tension region.

This test was performed in 1995, and the process may benefit from a modernized, digital system. However, it should be noted that to photograph even a 70 um inclusion, a pixel size of 35 um would be required. To analyse 32 ft2 (3 m2) of glass at this resolution would consume 3 GB of data (Barry 2006). Therefore, to analyse the square footage incorporated in the original test, nearly 5 TB of data would need to be collected, stored, and processed. This would be a strain on most typical company's technological infrastructures.

Detection via Light

In its purest form, this method as proposed by Xiang et al. in their paper is a mixture of laser imaging and the photo glass process. As was acknowledged in the section on laser imaging, inclusions cause light to scatter when it hits them. The drawback of laser imaging is that it requires access to and transparency of both sides of the panel to be inspected. This process uses the reflection properties of light to eliminate this concern. When light is introduced through the glass, it bends slightly. If it is introduced at such an angle as to cause it to bend exactly to its total internal reflection (TIR) angle, the light will become "trapped" within the glass, propagating over a length that depends on the thickness of the glass, but is most typically about a foot and a half before the light intensity becomes too weak to be useful for inclusion detection. Xiang et. al produced an apparatus that can be attached to the glass via suction and allows the light to enter at the correct angle to achieve TIR in the glass. Then, inclusions in the glass show up as bright dots due to the light they scatter in all directions.

So far, the process seems more effective than the others noted. However, once inclusions are located, the only way to determine their depth and nature is to inspect them with a microscope. This manual inspection of every inclusion makes this process equally as tedious as any of the other proposed detection methods.

Seemingly in recognition of the tedious nature of the labour intensive nature of their process, Xiang et. al also propose the use of a tilted camera to identify the depths of the inclusions before performing more significant analysis. Upon the incorporation of the tilted camera, the process becomes a variation on the photo glass process. The only major difference between the two systems is the method via which inclusions are located for further investigation after the photos are used to identify inclusions in the tensile region.

Case Studies

Since nickel sulphide failure is a universal problem in tempered glass, it is very difficult to successfully assign blame in the event of litigation following a breakage. Therefore, many of these cases are settled out of court, and many of these settlements are accompanied by a so-called "gag-order." Frequent or persistent nickel sulphide failures may also decrease the property value of a particular building, and so owners tend to be reluctant to release any details. For all these reasons, locating verifiable cases of nickel sulphide failure is extremely difficult. This section includes what information could be found on some case studies.

Figure 5: Image of the John Hancock Tower in Boston, MA, USA

Case Study 1: Hancock Tower

The most well-known failure of windows on the Hancock Tower, located in Boston, MA in the USA, is commonly attributed to the bond layer material. Some originally attributed to nickel sulphide inclusions, although this was later disproved. (Johnson 2008). The failure began in 1972, while the building was still under construction, but it became especially significant during a wind storm in January of 1973. The bond material created too strong of a connection, leading to pieces of the glass being pulled off the pane at the glass-bond layer interface. Glass is ill-equipped to cope with the stress increases associated with this edge damage, and therefore underwent spontaneous failure of the glass. Following the discovery of this issue, all 10,344 glass panels on the building were replaced with tempered glass at a very high cost (estimated to be $5-7 million at the time of the replacement). Much less known is that some of these replacement panels suffered from nickel sulphide failure (Schwartz 2001). An exact number of panels that failed as a result of NiS were unable to be determined.

Figure 6: Image of the Foster & Partner's City Hall in London, England

Case Study 2: Foster & Partners' City Hall

Foster & Partner's City Hall is located in London, England. It was likely affected by nickel sulphide failure in 2004, when several floor-to-ceiling panels of tempered glass on the interior of the building spontaneously shattered (Arnold 2004). The glass had not been heat soaked prior to installation. At the time of the publication of the Arnold article in which this information was found, an official investigation was in progress, and the preliminary findings pointed to nickel sulphide. This author was unable to find any record of the final cause determined.

Figure 7: Image of Waterloo International Rail Terminal in London, England

Case Study 3: Waterloo International Rail Terminal

This case was mentioned in passing in the article regarding the Western Morning News Building (discussed below). The two buildings were designed by the same architect, and the article therefore tries to connect the issues experienced on the buildings. The Waterloo International Rail Terminal is located in London, England. All that was said in the article was that it experienced glass failure due to nickel sulphide in 1999 (Booth 2002).

Conclusion

The problem of nickel sulphide inclusions continues to plague the tempered glass industry today. Although the failure rate is small (around 1% for a typical batch of glass), it can pose some injury risk to bystanders and create severe financial difficulty for owners of buildings which experience this unfortunate condition. Despite significant research into the behaviour of NiS and what causes these failures, the industry has yet to produce a method to eliminate the inclusions from the production process which can keep up with the high volume of glass production plants and still be reasonably economical. A reasonable method for detection of NiS in windows already in service has also eluded the industry, as most methods prove to be labour- and time-intensive with a high potential for human error. Therefore, it is an issue which designers should be aware of, and take into account when deciding how much tempered glass to use in their buildings.