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Spontaneous Shattering of Tempered Glass

Wong CW, HC Tan and Chew SC
Setsco Services Pte Ltd

Introduction

Spontaneous shattering of tempered glass has of late attracted lots of public attention in Singapore. It follows the widespread media reports on the sudden shattering of glass shower screens installed in a number of Housing and Development Board's flats. Many explanations and recommendations were offered by industry players to address the phenomenon. Possible causes and claims put forth include amongst others, rough usage, improper installation and impurities. According to the recent newspaper reports, the industry players are now lobbying the Government to pass laws to check the import of such glass, in particular to make it compulsory for heat test to be carried out on the glass. This heat test, also known as heat soak test (HST) is able to identify a glass with impurities, namely nickel sulphide impurities. The authors have involved in carrying out inspection of tempered glass used as glazing and curtain walling over the past seven (7) years. Though there have been cases where the glass panels were mistreated and poorly installed, a great number of the spontaneous shattering which the authors had investigated were attributed to NiS impurities. In some cases, NiS was found to be the single major contributing factor to such failure. This brief article revisits the problems of spontaneous fracture and the experience the authors gathered while conducting inspection and investigation works of such nature.

Historical Background

The spontaneous fracture of tempered glass used in façade glazing was first thoroughly investigated in Australia by CSIRO on the ICI House Building in Melbourne. This was one of the first buildings that used tempered glass. The glazing was completed in September 1958 and in 1960, failures were noted. The cause of the failures have been identified to be NiS inclusion. In another case, the Waterfront Place, some 140 well-documented spontaneous failures have occurred between 1990 and 1997. On 68 occasions, the NiS inclusion at the initiation point was recovered, analysed, photographed and measured. Since the first discovery of NiS, many other researchers have further investigated the phenomenon and analysed the kinetic of the NiS phase transformation. The authors themselves have investigated more than 10 cases involving failures of glass in the last few years alone. In more than 90% of the cases, NiS was detected at the fracture initiation point.

Fracture of Tempered Glass

Tempered glass is about 4 times stronger than annealed glass due to the level of compression at the surfaces and edges. When tempered glass breaks, all the stored energy is released at once and the glass breaks into small fragments, also called dices. When a flaw occurs in the central tensile zone of a tempered glass lite, the glass may shatter spontaneously without any apparent cause or warning. If the glass fragments remain intact in the opening, the origin of fracture is apparent from its sunburst crack pattern (Figure 1).

Whether the breakage is due to NiS impurities, surface damages such as scratches and edge damages, the failure characteristics are always similar.

The Case About Nickel Sulphide (NiS)

The sudden fracture of tempered glass is known to be brought about by an expansion of the nickel sulphide (NiS) stones as the result of a slow crystalline transformation from alpha-NiS to beta-NiS. During tempering, the NiS stones are completely transformed to the high temperature state under the heating process but afterwards, the glass is cooled too quickly while going through tempering and heat strengthening to allow the reverse transformation to the low temperature beta-NiS. This reverse transformation occurs later over periods of time ranging from few minutes after thermal treatments to more than 10 years after the glazing installation. In fact, the authors' first encounter with spontaneous fracture involved a building of more than 10 years old. The transformation is accompanied with about 2-4% in volumetric expansion of the said impurity. Consequently, small cracks may develop from the inclusion and if these cracks penetrate the central tensile zone of the glass, the resulting release of energy will cause the glass to break spontaneously. This transformation can be accelerated by heat and hence, external glazing exposed to solar heat tends to break earlier in service than internal glazing.

The mechanism for the formation of nickel sulphide is not known. However, the potential for its formation exists, where nickel-rich contaminants such as stainless steel are present in the glass melt materials, or if the nickel is added in the manufacture of tinted glass. It may combine with sulphur in the glass batch or furnace fuels to form NiS impurities. Sulphur bearing compounds are known as the basic ingredients in the manufacture of glass.

These impurities or stones are minute in size generally ranging from 50 to 150 microns and usually spherical or slightly spheroidal. (Figure 2). From the authors' experience, size of inclusions more than 500 microns have also been identified. They are impossible to totally eliminate, not easily visible in the glass substrate and not considered a product defect in annealed (raw) glass.

Heat Soak Test (HST)

To reduce the possibility of breakage from NiS inclusion in the field, accelerated exposures at high temperatures are sometimes conducted. This has been referred to as the heat soak test (HST) or now famously coined as the S$200 heat test in the press.

The HST is a destructive process, which heats the glass in oven for several hours at about 290 deg C to speed up the alpha to beta NiS transformation and consequently eliminates the contaminated glasses. Standard heat soak test requires more than 10 hours thermal treatment including 1 - 6 hours to heat large quantities of glass up to 260 - 300 deg C followed by several hours of temperature plateau before cooling down slowly. The duration of dwelling time within the oven is determined by the volume, glass thickness and the air gaps in-between the glasses.

Procedure of HST is described in DIN 18516: Part 4: 1990. According to this German standard, the panels are to be heated to an oven temperature of 290 deg C for a duration of eight (8) hours and thus undergoes a heat storing test. By extending the heat soaking period, the number of spontaneous breakage can be increased. However, soda lime glass held for too long a storing time will lose much of its tempering property or become re-annealed.

When glass is heated, the nickel sulphide inclusions expand as a function of time and temperature. If located near the central thickness of the glass, these inclusions when expanding may provide sufficient stresses to produce spontaneous breakage. An inclusion that expands at a rate greater than the glass, will cause the glass to break from within. The inclusions that transform at a rapid rate may thus fail in the test. The accelerated exposure or "HST" may then reduce the likelihood of field breakage in some cases.

However, because there is a critical relationship of the nickel to sulfur ratio, some of these inclusions, when exposed to the same combination of time and temperature, will cause tempered glass to break more rapidly than others. Those inclusions that transform at a slow rate may be transformed to the point of causing imminent failure. This glass would likely to fail soon after installation. In the latter case the incidence of breakage in the field may be increased from the effects of the "HST". While the process may help cull glass with large nickel sulphide stones, it may also make small stones grow larger. What may normally have been a stable stone can change into an unstable stone, which can grow from exposure to sunlight. Other factors that affect the time of breakage include: the size of the inclusion; tempering stress and the location of the inclusion within the glass thickness.

One of the prime objectives of the HST is to have the glass that contain NiS to break in the heat soak oven thus reduces the risk of potential field breakage. From the experience of some glass manufacturers, nickel sulphide inclusions tend to occur in some batches of glass The use of statistical heat soaking process by some manufacturers is useful in identifying potential problematic glass lots that may have a high incidence of inclusions. Though heat soaked process does not completely eliminate the potential of spontaneous breakage in-situ, but when used in a consistent and effective manner, the test can help to identify highly contaminated batches of float glass.

Inspection of Glass for NiS Impurities

Researches have been carried out to develop non destructive techniques of detecting NiS in glass, especially, those that have been installed. Many methods have been explored including stress identification with polarised light, laser light scattering, photographic method, infra red and visual inspection. Due to the smallness of the inclusion, which was quoted "no bigger than the full-stop on this page", it is very difficult to detect such particles (often in the range of 0.1mm diameter). In addition, there are a number of factors contributing to the poor success rate including visual and physical fatigue of inspectors after several hours of inspection and uncomfortable working environment on external façade.

In one project in Australia, photographic method was used. The basic steps in the process are simple and a photograph of the glass is first taken. Then the developed negatives are magnified many times so that an inclusion can be easily spotted. This is followed by examination of the glass to identify the inclusions and assess the likelihood of future failure. The main disadvantage in this case is the cost, the need for specialised film and availability of the film processing facilities.

The authors meanwhile have been relying on a combination of the polarised light and visual inspection. Though, such inspection is very tedious and time consuming, it has proven reliable to detect the presence of NiS inclusion (Figure 3) and thereby assess the risk of potential failure. During the course of the inspection, other telltale sign that indicate potential failure will also be identified. From the large numbers of glass inspected over the years, experience tells us that there are many other factors, which may cause the glass to shatter suddenly. These include deep scratches, weld splatter, edge spall and shells (Figure 4 to 8).

The visual inspection method can be very tedious and straining to the eye of the inspector. It also requires trained and skilled personnel and may not guarantee that all dangerous NiS can be identified. Notwithstanding these shortcomings, it has the advantage of being able to provide a more holistic survey on the glass to check for other defects due for instance to poor handling, installation, abuse, rough use and poor design.

When NiS inclusion is detected in a glass panel, it is often important to assess the risk or likelihood of failure of that particular piece of glass. Not all inclusions will cause failure. The assessment will have to take into considerations such as location of impurities, size and presence of vents around the inclusion and aspect ratio as well as exposure condition of the glass.

The Need for Failure Analysis

In the event that a tempered glass shatters suddenly, it can be extremely difficult to identify the cause. This is primarily because the origin of fracture or initiation point could not be preserved as when the glass fails, it breaks into small pieces which fall to the ground. However, at times, the fragments are held in place by the frames or structural sealant due to the interlocking dices. In other cases, the glasses used were laminated and hence the fracture origins were well maintained. Under such circumstances, the fracture origin could be preserved and examined. Through the field of fractography the authors have managed to investigate a number of such cases and a majority of them were attributed to NiS or at least NiS has contributed to the failure.

It is impossible to predict the exact time of the NiS phase transformation and the subsequent fracture since the transformation time is a function of the total heat absorbed by the particle and its chemistry. Some lites break from NiS impurities before they have cooled from the tempering process but others may break years after manufacture. Nevertheless, once spontaneous breakage is reported, detailed investigation is necessary to determine the cause of the breakage and potential for future failure. This includes analysis of the fracture pattern and origin, where possible, examination of the source of glass, history of past breakage, design consideration, installation and manufacturing records that include raw materials, heat soak process, percentage of breakage during HST, etc. Following the sequence, the authors had in some cases successfully identified different sources of glass supplied to a particular building project and invariably isolated the source of the problematic glass.

Figure 1: Sun-burst crack pattern of spontaneous breakage caused by expansion of Nickel Sulphide inclusion

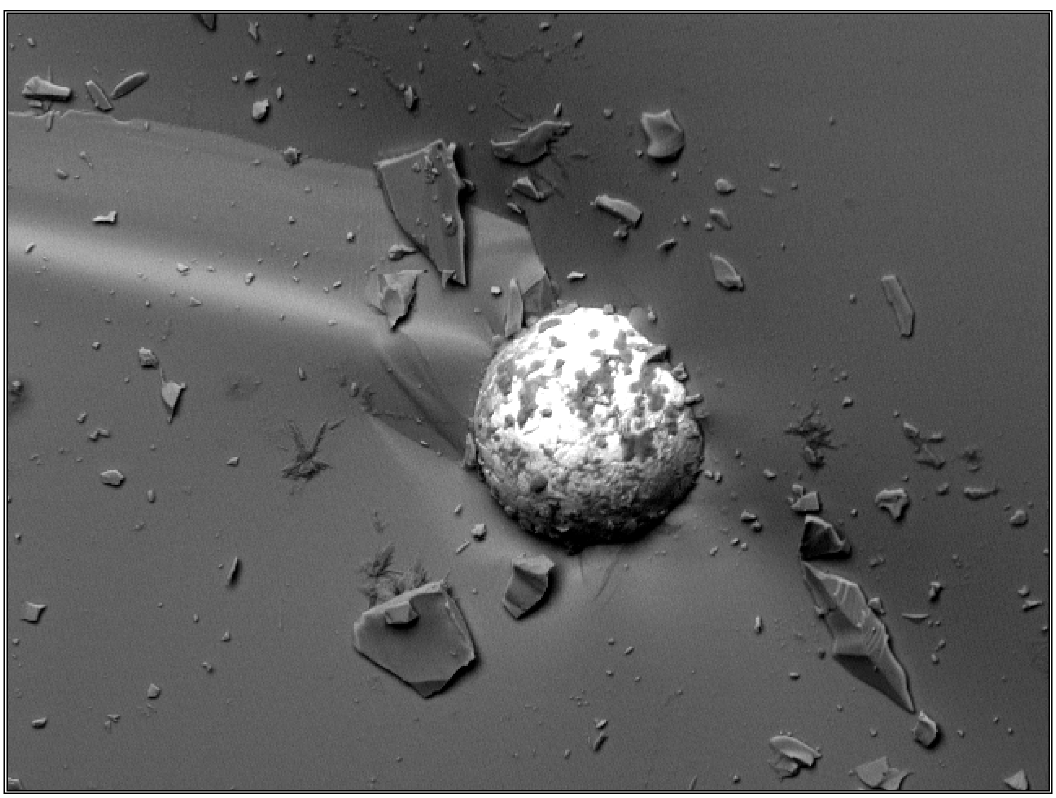

Figure 2: Backscattered image of Nickel Sulphide embedded in the glass (image magnified at 450 times)

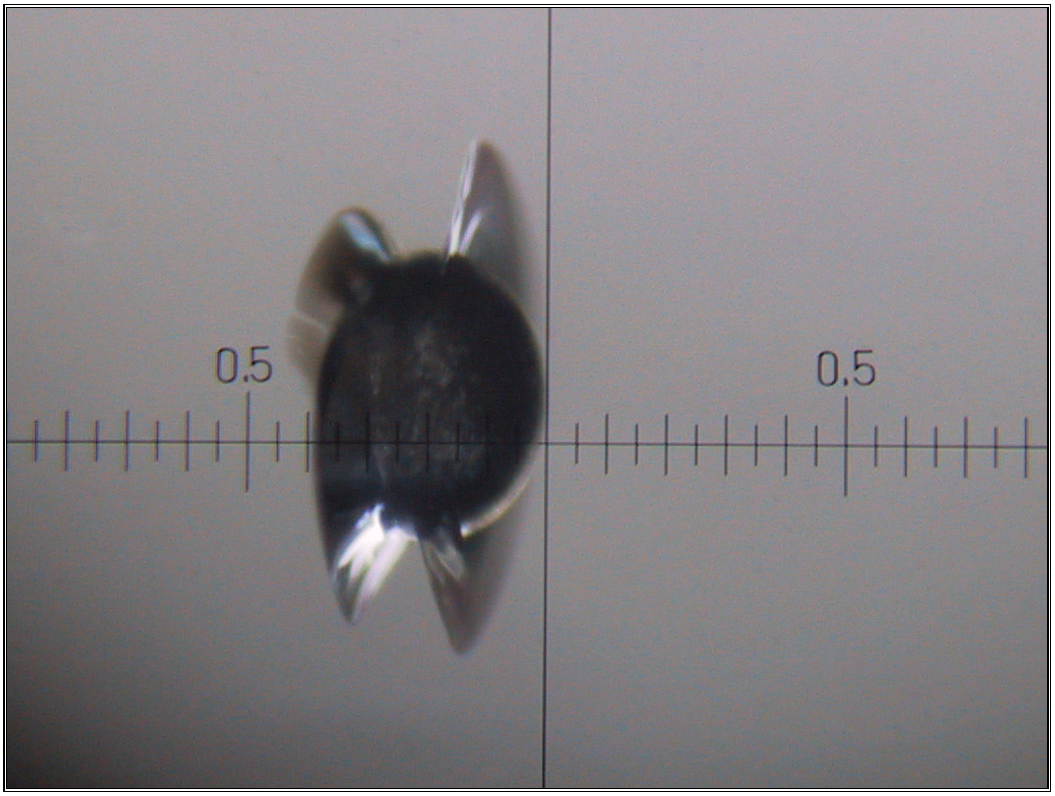

Figure 3: Inclusion in glass with possible fracture planes

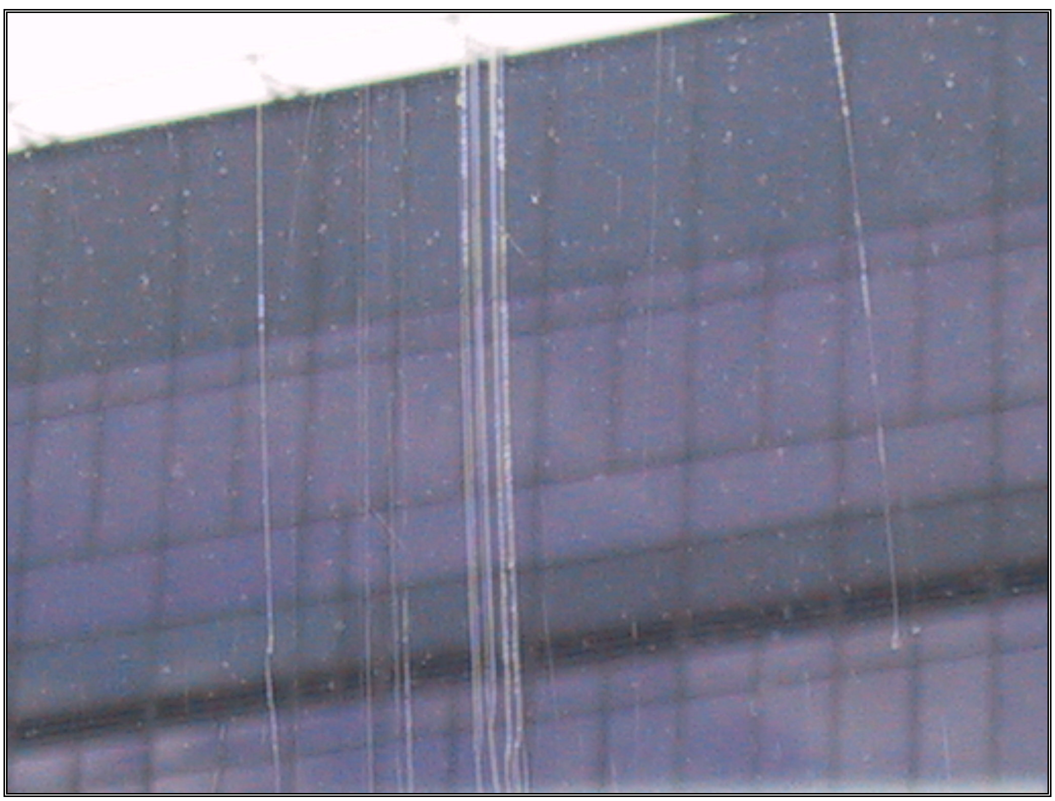

Figure 4: Deep scratches

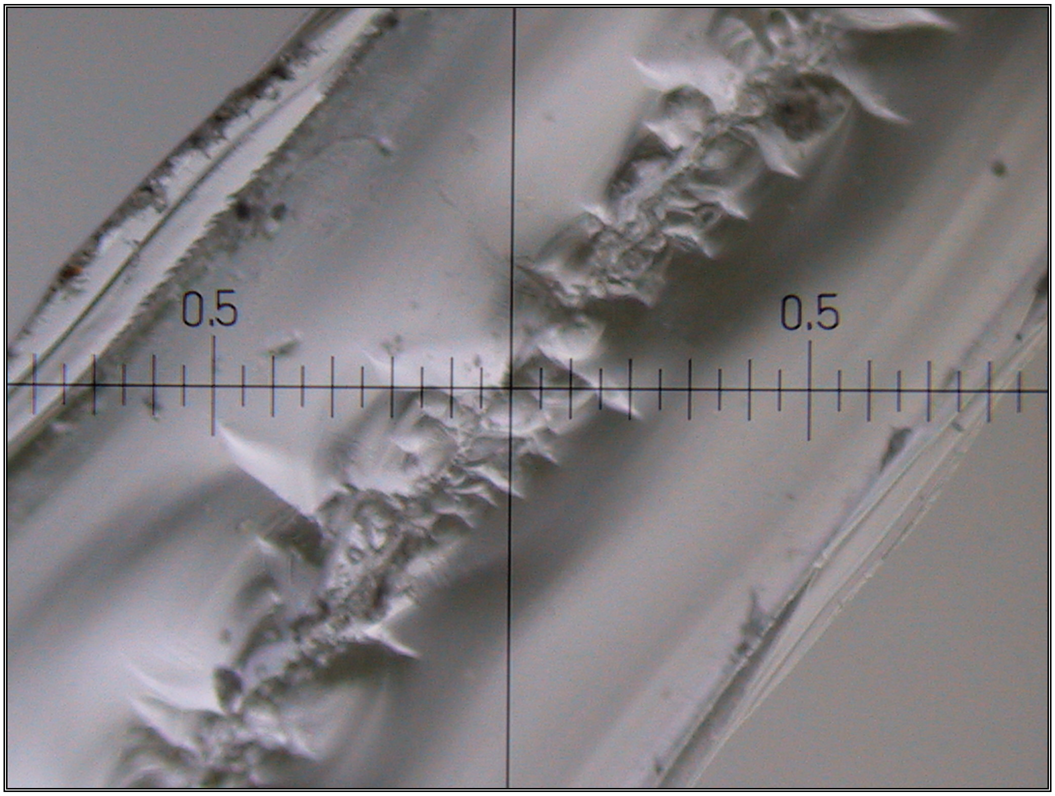

Figure 5: Deep scratches under microscopic view

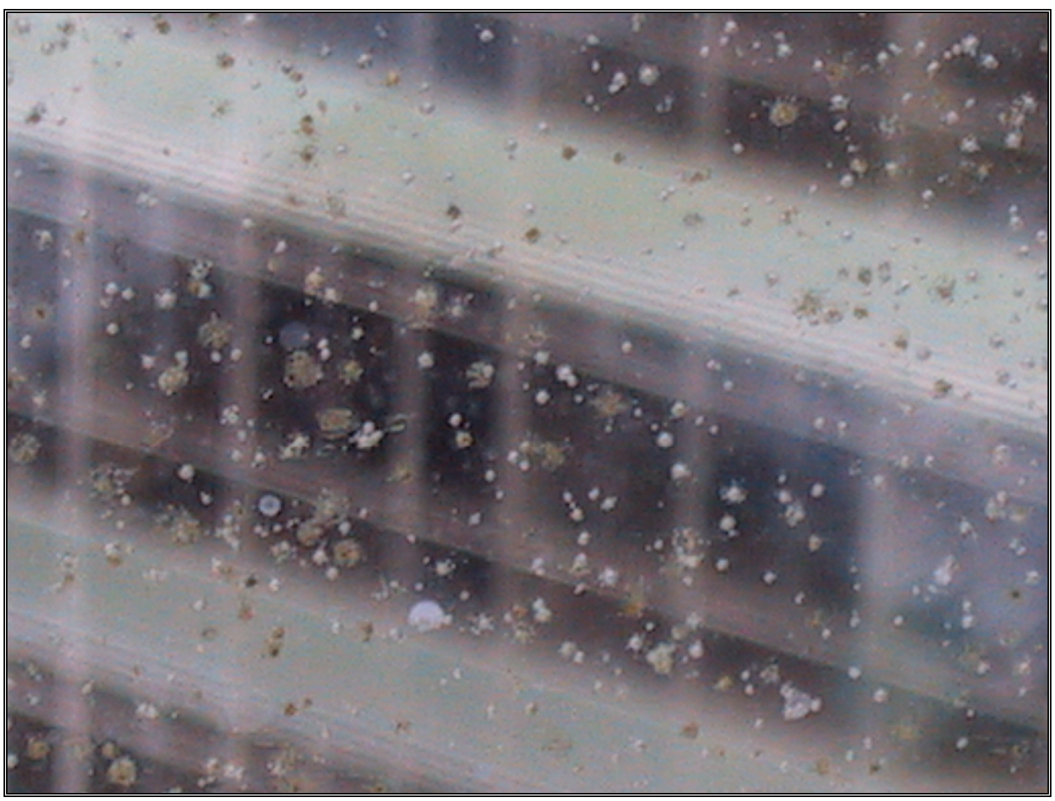

Figure 6: Typical weld splatter on glass

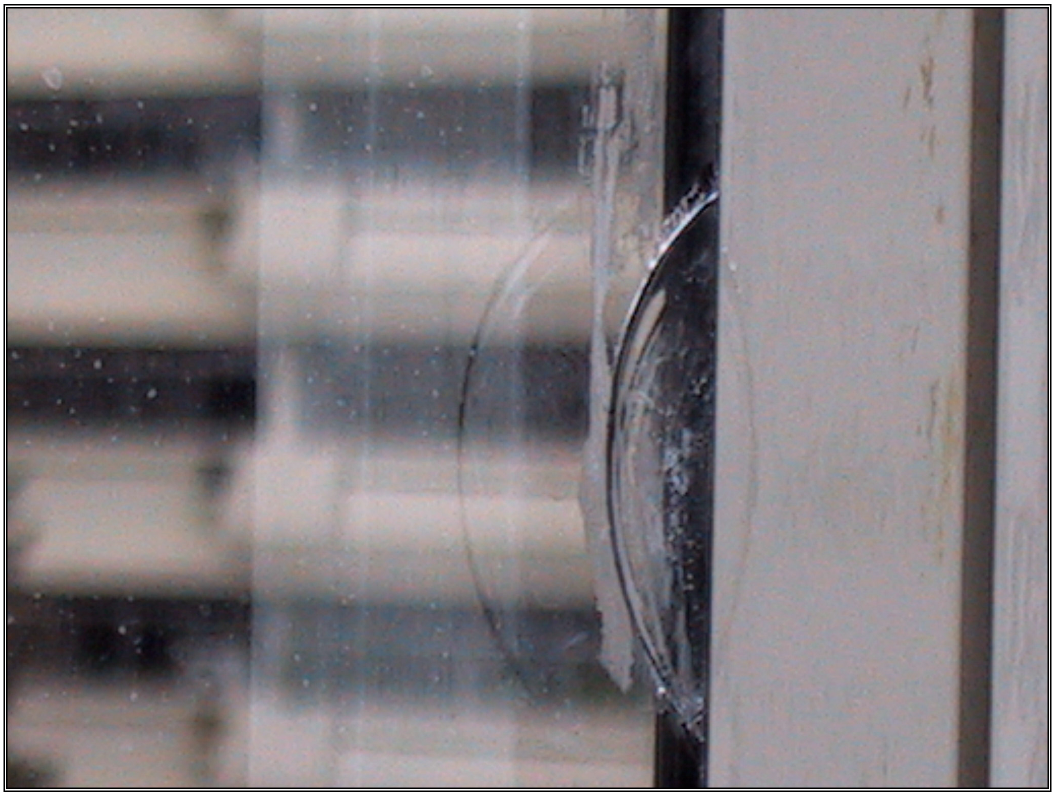

Figure 7: Edge spall