SELF HEALING STRATEGIES IN GLASS STRUCTURES

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Glass structures are known for their frangibility. They are also comparatively costly and widely used in modern architecture. The comparatively high cost of material and construction makes it a logical choice to introduce pre-emptive and self healing properties. Cutting down on the cost of replacement of for instance glass bus shelters will give significant cost and safety benefits. This paper analyses the problems in fracture of glass based on earlier work by the author. From this several strategies for pre-emptive and self healing are outlined. The feasibility of these strategies are discussed and a research programme to develop a combined arsenal of self healing and pre-emptive healing is outlined.

Keywords: self healing, glass, reinforcement

1 The structure and processing of glass

Glass is an amorphous material. That implies there is no structure in glass, which is a wrong assumption. Looking at the nano-level structure of soda lime glass, a series of primitive shapes can be identified. These shapes are rings containing between three and seven Silicium atoms with bridging oxygen atoms in between. These rings are locked into a three dimensional structure by primary chemical (covalent) bonds. Some of these rings are broken by OH- groups and Na+ ions. These are the result of the soda additive which decreases the melting point by breaking up the 3-D network. This structure is schematically given in figure 1. Thus although there are some discernible structural elements, there is no systematic repetition of this structure and thus no crystallinity by the standard definition. Glasses outside of the soda lime family can have different nano-structures as described by Rouxel (1). The lack of a crystal lattice prevents dislocations being formed and thus eliminates any possibility of plasticity. In any case the covalent bonding between the majority of the atoms cannot reform easily if broken. Any local stresses around a defect that exceed the chemical bond strength will thus cause bond failure, and in the process increase the local stresses further as the defect will have grown. The material can thus only deform elastically or fracture.

Float glass is made by pouring molten glass onto a bed of liquid tin (Sn) in a nitrogen (N2) atmosphere. The liquid glass forms a continuous ribbon moving from the hot glass oven side to the colder annealing side, solidifying in the process. Glass thickness is controlled by the rate at which the molten glass is poured onto the tin. The liquid glass is pushed using paddles into a ribbon about 3.5 m wide. In this phase sometimes coatings can be applied to the hot glass on the nitrogen side. After leaving the tin bad the glass ribbon is cooled slowly (annealed) to avoid freezing in residual stresses. The ribbon is then cut down to a length of 6 m and later cut to a standard width of 3.21 meter.
These standard Jumbo plates are then distributed to be cut to size, have the edges ground down and polished, tempered or laminated as the needs of the consumer dictate. The quality control of the process is such that there are usually no significant impurities or inclusions in the glass. The controlled cooling leads to a homogeneous structure without internal defects. A problem that is often ignored is improper annealing. In any firm that processes glass regularly there are instances known where the glass cracked spontaneously on the cutting table due to residual stresses. In practice this probably affects less than 0.1% of glass production in western European plants. There are reports that eastern European factories operating in winter have much higher levels of annealing problems due to the severity of their winters and poor thermal isolation of factories.

In almost all cases the float glass panels need to be cut. This is done by scratching a line on the glass using a scoring wheel of very high hardness. The glass is then subjected to bending or heated locally to put the scratch into tension which leads to unstable crack growth from the scratch through the thickness of the plate, cutting the plate. Simple as this sounds it is quite complicated, especially for thicker glass where the crack growth has a more three dimensional character. Important in all cutting is using the right type of wheel (hardness and cutting angle), the right lubricant and the right pressure. Too much pressure can cause damage on the back side of the glass. Some aspects of this are explained by Whittle et al. (2002) and Hand et al. (2006). Important to realise is that cut glass by definition is not flat and that the two sides have different geometries.

To give a more even surface and thus better strength the edges of the glass can be ground. This uses a rotary action to remove material. The process on a micro level involves locally cracking the glass into micro fragments which are washed away. The rough surface of the cut glass is thus transformed into a smooth surface with no visible defects and an assumed higher strength.

Grinding can be done to give a flat edge but usually the right angles are also ground down to 45 degrees in the belief that this improves the strength. On a given industrial grinder there are several ways to finish the glass. It is known that this affects the strength of the glass produced, see Corti et. al. (4). More important than the settings of the machine is the degree of maintenance of the machines. Both for cutting and grinding old and worn down cutting heads or grinding rolls can produce damage which can significantly affect the strength, even if the differences can not be seen by the naked eye.

Figure 1: Nano-structure of soda-lime glass
2 Failure of glass

Glass can mechanically fail for a number of reasons. The most important of these are:

- mechanical overloading
- impact of a soft, heavy and slow object
- failure due to thermal stresses
- impact of a small hard fast object

In practice the first one should not occur in correctly designed structures unless there is a serious problem such as subsidence. In many cases safety can be build into a glass structure by using reinforcement (5,6). The second one, mainly dealing with human impact is not very important in practice as this can only lead to failure if the glass is supported to stiffly too dissipate the shock energy. Failure due to thermal stresses is unavoidable unless a special glass composition such as borosilicate is used which has an almost zero thermal expansion coefficient. Impact of a small, hard and fast moving object is a big problem as it causes failure of car and aeroplane windscreenes while vandalism is a main cause of failure in architectural glass.

In essence this comes down to that glass can fail by overloading or by high stresses caused by local impacts. The failure due to overloading is caused by unstable crack growth from a defect. A good treatment of this is given by Veer, (7). Summarized unstable cracks grow from microscopic areas on the edges which are “damaged” in processing. There is some evidence that there is some stable crack growth before the cracks become unstable but the stable crack extension is only several \( m \), see (2,3).

The failure due to impact damage is caused by high local stresses which are caused by high local pressure. This is complex phenomenon varying from impact of liquid drops to impact of metallic spheres. An interesting treatment of the liquid impact is given by van der Zwaag and Field. (8). One category of these high velocity impacts can be described by the Hertzian cone failure equations as given by Tsai and Chen, (9). The most important of these is:

\[
\sigma_r = \frac{1}{2} \times (1 - 2\nu) \times P_0 \times \left(\frac{a}{r}\right)^2
\]

Important in this is the role of the Poisson ratio. As this decreases the local stresses increase. A Poisson ratio of 0.15 causing under the same conditions local stresses cause more than double the local stresses than a Poisson ratio of 0.35. As soda lime glass has a Poisson ratio about 0.15 increasing this decrease the local stresses at impact and thus the susceptibility of the material to damage. This can be considered as pre-emptive healing as this prevents the impact from initiating damage.
3 Ways to healing behaviour

The previous analysis suggests the following necessary steps to healing behaviour:

1. changing the glass chemistry to decrease the thermal expansion coefficient
2. changing the glass chemistry to increase the Poisson ratio
3. changing the glass chemistry to lower the Youngs modulus
4. finding a way to heal microscopic surface damage and small crack extension before the crack destabilises
5. finding a way to keep large cracks from causing structural failure.
6. finding a way to heal large cracks

The first step is easy as this has already been done by the development of borosilicate glass, see also Shelby, (10). Thus we do not need to discuss this in depth.

3.1 Increasing the Poisson ratio

The second step has never been consciously tried but all the necessary knowledge exists. Rouxel, (1), gives in his seminal paper on the elastic properties of glasses, the necessary information. Figure 2 shows the relation between the atomic packing density and the Poisson ratio of amorphous materials.

![Figure 2: Relationship between atomic packing density and Poisson ratio, form Rouxel (1)](image)

Although the value of \( \nu \) is determined by more than the atomic packing density it shows that the value for window glass is quite low and can be raised. This implies changing the chemistry to introduce nano-physical changes. Rouxel also gives some other indications how this can work. This is shown in figure 3 where the Poisson ratio is plotted against the glass network dimensionality. The conclusion from this is that high chemical disorder, weak bond directionality and low cross linking are necessary to achieve a high Poisson ratio.
3.2 Decreasing the young’s modulus

Decreasing the Young’s modulus seems to be an illogical step. In practice most transparent materials have similar fracture toughness values, about 1 MPa√m for PMMA, 0.65 MPa√m for window glass. PMMA is considered tough, mainly because it flexes due to its low Young’s modulus preventing it from breaking. The strength values for the two materials are comparable. PMMA is used in modern cars for rear lights due to its lowered susceptibility to impact failure compared to the glass rear lights of two decades ago. The low Young’s modulus and poor scratch resistance of PMMA preventing it being used for the windshield, where glass is necessary. Decreasing the Youngs’s modulus of glass from 70 GPa to 40 GPa will not mean any significant change in engineering, but will decrease susceptibility to impact fracture.

3.3 Healing microscopic damage and small cracks

Hand describes two processes to do this, (3). One of them based is based on the hot application of a silica sol-gel coating. The other on the low temperature application of an epoxy based coating. These have both been found to be able to heal the processing damage in glass in the sense that they increase the strength. There is a lot of discussion about the mechanisms involved. For the epoxy method Hand concludes that some form of crack filling and crack closure effect based on thermal expansion mismatch is the operative mechanism.

3.4 Preventing large cracks from causing structural failure

The author has previously developed a concept for reinforcement of glass, which keeps components stable even if large cracks have developed. An extreme case is shown in figure 4. This is described by the author and others in references 5 and 6.
3.5 Healing large cracks

If we assume that any glass structural component by its nature is transparent and will be reinforced, we can also assume that the cracks will form in the tensile zone, where the reinforcement will be. This allows us to create a reservoir for a healing agent in the reinforcement. Cracks can draw a liquid healing agent into the crack by capillary action, where the sunlight can be the catalyst for the healing action to start. The concept is schematically shown in figures 5 and 6.
4 Discussion

The analysis of the failure behaviour shows that a number of steps are needed to create the technology to produce healing treatments in glass. The first of this is changing the glass chemistry to introduce pre-emptive healing. The composition of glass has changed almost nothing in 3000 years. In an era where engineered materials are the norm, it is sensible to engineer glass also. This essentially involves decreasing the thermal expansion coefficient and Young’s modulus while increasing the Poisson ratio. The steps necessary for this can be found in existing work, such as that by Rouxel, (1).

The second step is to heal the small damage points introduced by processing and handling. Hand, (3), has shown that this is possible. By developing a polymeric coating that maybe has some self healing behaviour by containing micro-capsules of liquid healing agent, such as used by Brown et al., it might be possible to introduce self healing to the glass surface. The technology for this would probably have a much higher applicability, for instance in the use of self healing paint coatings.

The third step is to heal large cracks that might occur. The metallic reinforcement which is required in structural glass components could serve as a source of an healing agent, while the sunlight which shines through the glass might serve as a catalyst.

Combining these three steps would allow the production of highly reliable glass products that due to their significantly decreased replacement needs would also justify the increased cost.

In addition the increased human safety by introducing these technologies into windscreens alone would be very valuable.

5 Conclusions

The analysis shows that theoretically glass can be made self healing. The necessary steps in the research have been identified and described. As considerable cost and human safety benefits exist there is a clear motivation to start this research.
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