Dependence of Glass Strength on the Surface Flaw Characteristics

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Abstract
Biaxial testing was used to get insight into the incidence of the surface flaw properties (size, shape) on the strength of float glass specimens. Grinding grooves and Vickers' indentations were introduced as defects at the surface of annealed float glass specimens. The machined and fractured surface was observed and studied using optical and confocal microscopes. The influence of the flaw characteristics on the strength of glass was evaluated and analysed in the light of the fracture mechanics.

Introduction
The flaws existing in the surface and in the bulk of materials have a degrading effect on the strength characteristics. The objective of this research work is to characterize the dependence of strength of soda lime silica float glass on the surface flaws size. The surface defects which usually originate during technological process or machining are more sensible to environmental influence and stress level in comparison to the bulk defects. The real defect geometries in glass specimen are random and complicated. That's why the model of surface flaws is used to describe natural defects. Two main approaches are used for characterization of surface flaws: machining approach (using grinding) and indentation approach. Grinding process leads to a system of grooves with longitudinal, later interconnected cracks, parallel to the groove and of subsequently formed transverse to groove cracks similar to the median crack of a static indent [1]. The Vickers approach assumes producing an idealized flaw system with two principal crack systems propagated from indentation site: radial/median (R/M) crack which causes strength degradation and lateral crack which leads to material removal [2]. Both types of cracks are

affected by residual stresses due to the plastic zone directly under indenter [3]. The strength was determined using the biaxial ring-on-ring (ROR) test where the effect of inaccurately prepared edges of samples is neglected. Due to the symmetry of the stress state, the weakest direction is expected to lead to failure. Inside the loading ring constant maximum biaxial stress state prevails on the surface. Radial and tangential stresses are uniform here and equal in magnitude [4].

Experimental methods

At least 10 square specimens 35x35x4 mm^3 cut from one sheet of glass were tested on the atmospheric side for each of the condition: a) samples were ground manually in one direction at 300 RPM speed for 120 s, using a new SiC paper with grit sizes 120, 320, 800 or 1200 for each specimen. The specimens were immediately broken in biaxial flexure test or exposed in air (~60% relative humidity and temperature 20°C) for 5 days and then annealed at 540°C for 30 min before testing; b) samples were loaded by Vickers indenter using 10g - 1000g load and dwelling time of 10 s. They were immediately broken or aged (24 hours and 14 days) in air before been broken.

ROR apparatus is set up on an universal compression Lloyd machine at the cross-head speed of 1 mm/min and is used to determine biaxial strength of studied material at room temperature. The diameters of the loading and supporting stainless steel rings (2 mm of curvature) are 11 and 26 mm, respectively. The specimens were covered by adhesive tape on the compressive side to preserve the fracture path and thin pieces of polymeric sheet were used on both sides of specimen to minimize the contact friction.

Strength was calculated for the maximum stress generated in ROR test according to:

$$\sigma_{\max}^{ROR} = \frac{3P}{4\pi h^2}\left[(1-\nu)\left(1-\frac{R_L^2}{R_S^2}\right)\frac{R_S^2}{R^2} + 2(1+\nu)\ln\left(\frac{R_S}{R_L}\right)\right],$$

where P is the load of failure, h - thickness of the sample, ν - Poisson's ratio, R - average of the half-diagonals, R_s and R_L are the radius of supporting and loading rings, respectively. The stress distribution was analysed using two-parametric Weibull distribution function. The broken samples were observed using optical and confocal microscopes.

Results and Discussion

The characteristic strengths obtained for the ground samples are shown in Fig.1.

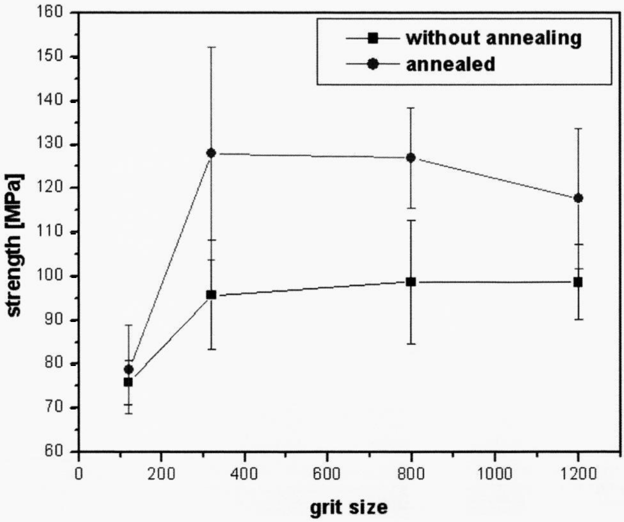
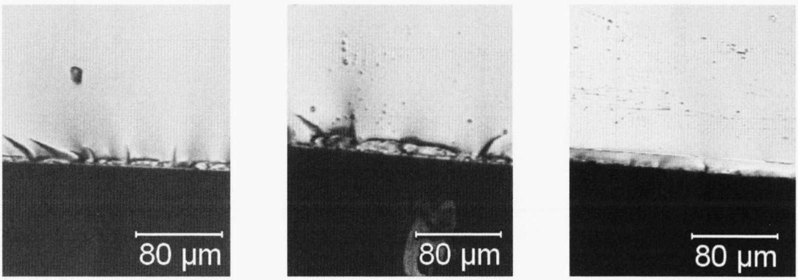


Figure 1. Dependence of the biaxial strength on the SiC grit size.

In comparison with strength of as-received glass which value is 177 MPa used grindings decreased the measured strength of material. Samples ground with 120 grit size paper have characteristic strength about 25 % lower as samples ground with grit size 320 for glass without annealing. In case of annealing the strength of ground samples with 320 grit size is about 50% higher than for samples grinding with 120 grit size SiC paper. No significant difference in the characteristic strength was found in the range of 320 - 1200 grit size for samples without annealing. Similarly it was with strength dependence for annealed samples in range 320 – 1200 only the shift of the dependence to higher value was observed due to healing of same flaws during heat treatment. The annealing increases the strength of ground specimen of about 25 %. The same dependence for heat treated and untreated samples means that the same processes control strength of the glass regardless of the treatment.

Fractography analysis was used to identify the fracture-initiating flaws of the broken samples and to locate the region of crack origins. In all cases, the fracture was initiated from surface defects which are the result of machining and the critical flaws are preferentially oriented along the grinding direction. Three different types of surface flaws were revealed as failure defects by fractography analysis and illustrated in Fig 2.: "zipper crack" which consists of several semi-elliptical crack segments [5], "V machining crack" are created by several surface machining cracks slightly staggered with respect to each other, and large "flat grooves parallel with the surface". Investigation of fracture surfaces gives explanation for the same strength in certain range of grit sizes: dimension of the fracture defects (depth) are similar from 320 to 1200.



Zipper crack V machining crack Flat parallel crack

Figure 2. Failure initiated flaws for grinding with grit size 320.

Although the additional roughness measurement of different samples showed corresponding differences between the mean values of roughness, R_a, on the samples ground with different grit size, the values of maximum peak to valley height, R_t, which represents the maximum flaw size were very similar regardless of the grit size. This suggests an explanation for the constant characteristic strength at grit size 320 - 1200.

Direct measurement of the critical flaw size is difficult because the fracture comes from the biggest defect which position is a priori unknown. Large distributions of the size of ground cracks suppress the effect of strength on flaws size in grinding material therefore Vickers indentation was investigated. Vickers approach assumes generation of flaws with predetermined location and size by a sharp indenter. The measured strength values of indented samples are summarized in Fig. 3. Strength increases exponentially by decreasing of the load. Fig. 3. also demonstrates a correlation between dependence of the measured strength on applied load and dependence of the strength gives by equation in [6] (load-size effect is not considered). The measured strength depends on load to the –0.276 power. Expression taken from [6] gives for the mentioned dependence power –0.334. Characteristic strength of indented samples for different aging times 24 hours and 14 days have the same values of strength like for samples tested immediately after indentation. In this case the aging of specimens do not influence the value of resulted strength. Observation of the R/M cracks after 24 hours and 14 days reveals a subcritical growth of cracks in comparison of crack lengths

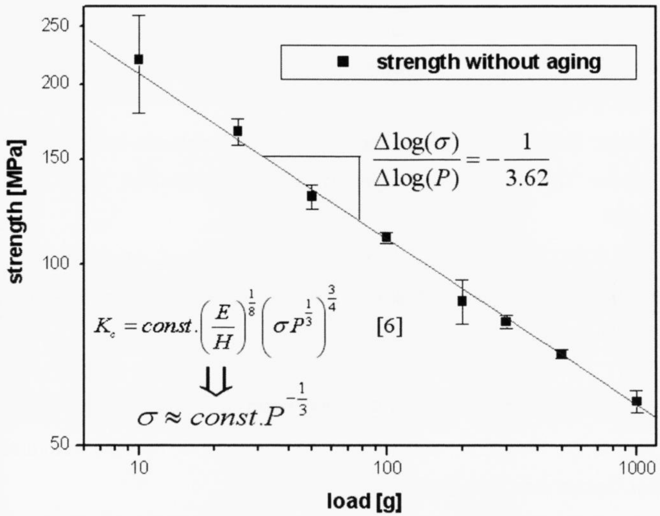


Figure 3. Strength of indented soda-lime silica glass as a function of load. Note: no cracks were observed for loads less than 100 g.

measured immediately after indentation. However, the same strength for aged and non-aged samples was obtained. This can be explained by the same depth of R/M cracks: during aging process, they propagate on the surface only whereas their depth remains approximately constant. The observation of fragments confirms that the fracture occurs along the R/M cracks.

Conclusions

The dependence of surface flaws on strength was investigated. The following results were found:

- Grinding process with grit size in the range of 320-1200 SiC papers give the same degradation effect and the same values of characteristic strength

- Heat treatment of ground specimens improves the strength properties by 25% in comparison with ground untreated material
- Increasing of load decreases the strength of indented specimens by power 3.62
- 24 hours and 14 days aging time do not change the strength of the indented specimens

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