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Dynamic and High Temperature Quasi-static Examination of Tempered Glass

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Abstract

In everyday use glass materials cause a lot of damage or injuries when broken, as fracture mechanism and damage runoff cannot be predicted precisely. To gain knowledge on this issue, we studied the properties of tempered glass. The glass test samples were exposed to two types of destructive evaluations: normal and high temperature three-point bending and room temperature dynamic experiments with colliding small steel spheres. The evaluation showed that high temperature experiments are in correlation with sharp fracture edges, and dynamic impact creates shell featured circular crack propagation which prevents the spreading of the radial cracks, so the damage is concentrated to a small area.

Keywords: *tempered glass, quasi-static bending, fracture surface, dynamic.*

1. Introduction

Glasses are commonly used in the everyday life as building elements and objects. For safety reasons, it is worth examining the fracture mechanisms and the fracture surfaces of different glasses to reduce injury and the probability of accidents **[1, 2]**. In this research, the fracture properties of tempered glass were examined: which type of glass bears the highest mechanical loadings **[3]**.

Glass as raw material has high compressive strength, however it is notably brittle, as no plastic deformation appears before breaking. This means that the fracture occurs without any detectable signal **[4]**.

The solidification of amorphous, or non-crystalline materials are different from crystalline materials. While cooling, the glass becomes more and more viscous with decreasing temperature, but there is no definite temperature at which the liquid transforms to a solid **[5–7]**.

When a non-crystalline material cools down from a high temperature, internal stress builds up inside the material, which is called thermal stress. The cause of this behaviour is the difference in cooling rate and thermal contraction between the inner and outer regions. These stress values have the most influence on mechanical features. The glass tempering process implies deliberately generating internal stresses in the material. In soda-lime glasses residual stresses can be created by heating the glass up to 600°C, and then cooling down quickly to room temperature with an airstream. In this procedure the temperature of the surface cools more rapidly, and after dropping below the glass transition temperature it becomes rigid, while the interior remains warmer and cools down slower. In this case, the viscosity of the surface increases and is less susceptible to deformation, while the interior attempts to contract to a greater degree, so tension and compressive stress develops between the two surfaces (**Figure 1.**) **[7]**.

Failure of tempered safety glass is the least dangerous, and despite the much greater force required to break, the material will fall apart into small but obtuse pieces, which can be held together in most cases by the middle foil between the

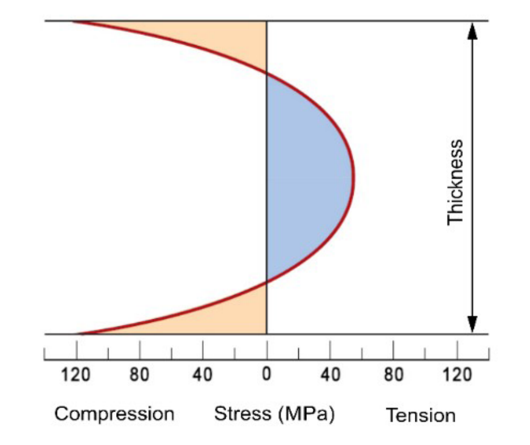

Figure 1. *Residual stress-distribution in the cross-section of tempered glass on room temperature based on [7]*

two layers [8]. This is significantly safer than untreated soda-lime glass, as the tempered glass can result much less physical injury [9, 10].

Quasi-static damage to brittle materials generally starts from a typically mirror-smooth small surface, and in the vicinity a veil surface is formed known as mist, followed by a hackle or needles spatially extending radially to the mirror-smooth surface [11–13].

There are typically two ways in which glass can be damaged by dynamic loads. Radial cracks may occur which, in the case of a cylindrical specimen, extend in the radial direction of the surface, splitting the surface into two or more parts [14]. These typically occur when any glass is damaged. Circular cracks, which usually stop radial cracks, result in a significantly smaller damage to the material. The latter is a characteristic failure mode of tempered glass [15, 16].

2. Materials and methods

The aim of this research was to estimate the damage and fracture processes caused by a certain mechanical load and heat by evaluating the fracture surface and breaking properties of the tempered glass.

For bending tests 5×15×100 mm bar shaped specimens were prepared from a soda-lime flat glass (Table 1.). The specimens were edge-polished, then tempered at 610 °C for 2 hours and cooled in an airstream.

The glass samples were heated to three different temperatures (23 °C, 300 °C, 600 °C) and a three-point bending test (3PB) was carried out with a quasi-static load on an Instron 5965 Universal Material Testing Equipment at the loading rate of 1 mm/min.

Table 1. *The composition of the glass material*

	SiO_2	Na_2O	CaO	MgO	Al_2O_3
Quantity (%)	74	16	5	4	1

Beside the quasi-static examination, a dynamic load test was performed with a pneumatic shooter from 700 mm with a Ø6 mm steel ball at a velocity of 100 m/s.

These tests were performed on a windscreen made of 5 mm thick safety glass, laminated with a two-layer polyvinyl butyral (PVB) film. The overall dimensions of the windscreen are: 1000×1600 mm, supported by the two shorter edges. The untreated flat glass specimens were also 5 mm thick with a frame size of 200×200 mm, also supported on two edges.

After performing the experiments, the fractured surfaces were tested with an Olympus SZX16 stereomicroscope and a Zeiss EVO MA10 scanning electron microscope (SEM), in addition the dynamic penetration was recorded with a FASTCAM SA5 model 775K-C3 high-speed camera.

3. Results

The quasi-static measurements show, that tempered glass typically breaks without a precisely defined crack start point. The fractured samples at room temperature are not sharp, but the cracks spread in several directions (Figure 2.). Sharpness is defined as the planes of the line joining the vertex of the edge to the lower point of the adjacent two valleys <90 °. It is important to notice, that the fracture appeared at 300°C testing temperature is starting from a small flat surface and spreading further in every direction (Figure 2. c, d). The specimen bent at 600°C no longer shows the characteristics like at lower temperatures and forms a sharp surface that is dangerous (Figure 2. e, f). The reason that the glasses were tempered at 610 °C, which is very close to the temperature of 600 °C, so the internal stresses during the elevated temperature measurement were reduced.

The three-point bending test results were processed to determine the flexural strength *(1)* and Young's modulus of the sample at different temperatures.

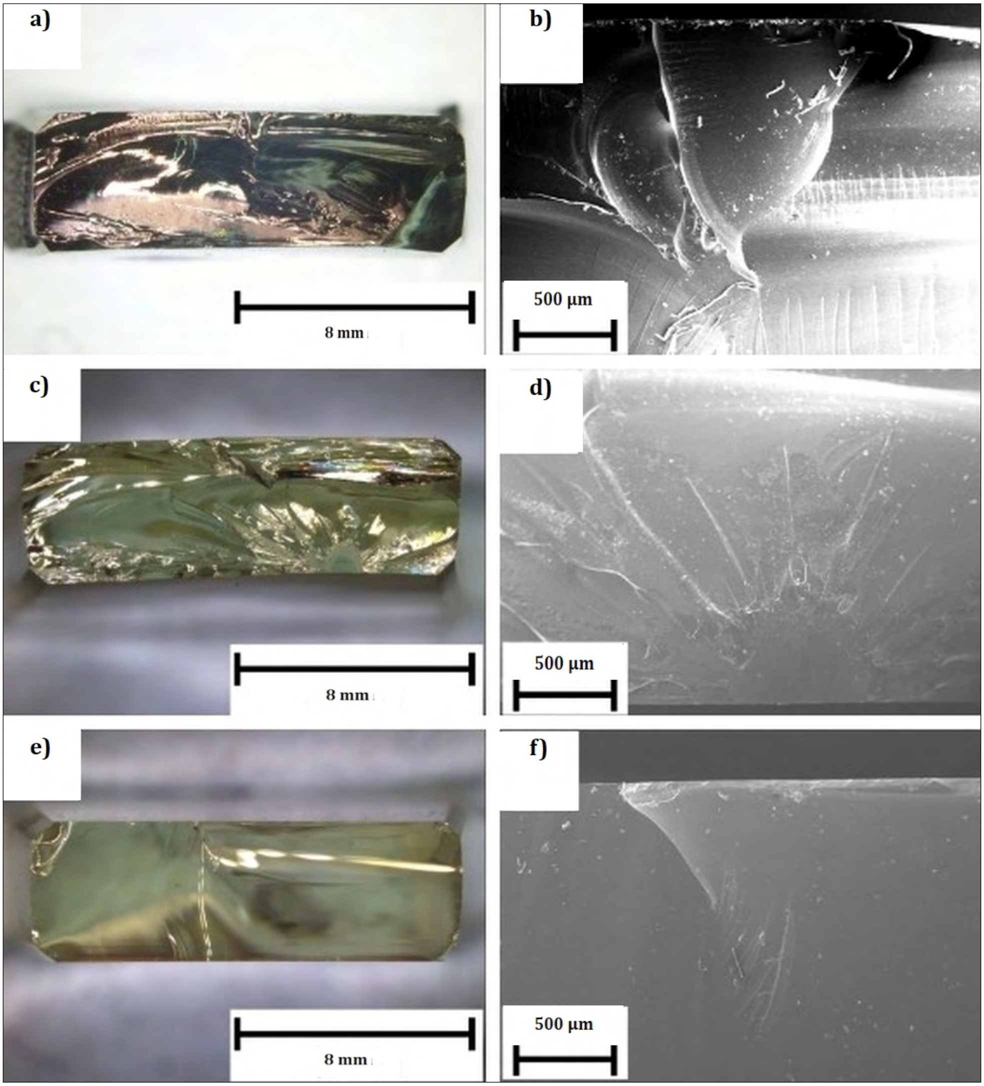

Figure 2. *Stereomicroscopic (left) and SEM (right) images of the fractured surfaces formed by three-point bending (23 °C a, b; 300 °C c, d; 600 °C e ,f)*

$$R_{mh} = \frac{M}{K} = \frac{\frac{F_m L}{4}}{\frac{ab^2}{6}} = \frac{3F_m L}{2ab^2} \quad (1)$$

where:

F_m – maximum force (N),
L – support distance (mm),
a – sample width (mm),
b – sample length (mm).

Figure 3. shows their characteristics. It can be observed that both attributes decrease with increasing temperature. On this basis, it can be stated that the mechanical properties of the test samples weaken, and their utility is limited in extreme conditions. This phenomenon can be explained by the fact that at 600°C it is already above the glass transition temperature of the test samples, namely its viscosity is significantly reduced.

During dynamic tests, the typical fracture pattern for safety glasses forms 0.100 ms after the impact occurs, and the cracks do not spread further (**Figure 4.**). Fine glass powder appears at the point of collision, as the material is most damaged there. It can be observed that in the vicinity of the impact has circular, spiderweb like cracks which stops the further radial crack propagation, thus

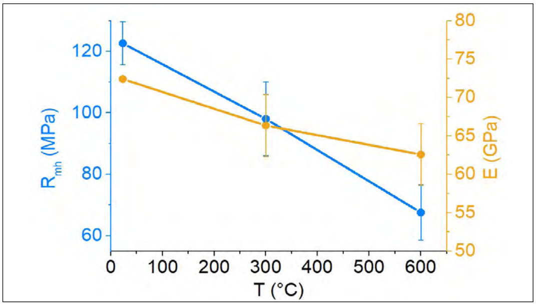

Figure 3. *Temperature dependence of the bending strength and Young's modulus*

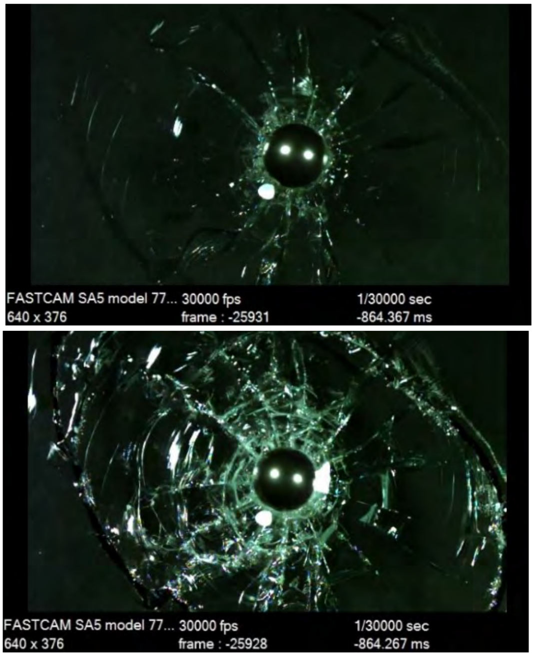

Figure 4. *High speed camera recording of bullet impact at impression and 0.100 ms later*

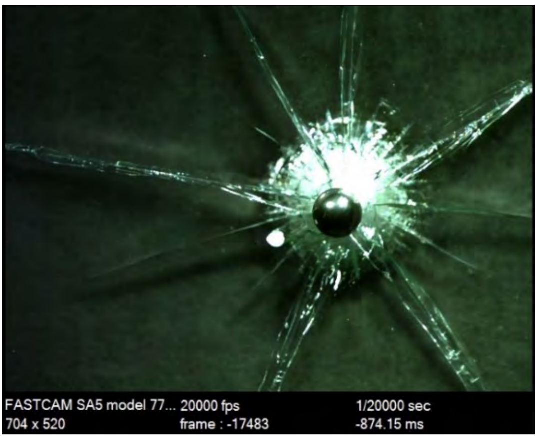

Figure 5. *Soda-lime glass fracture due to dynamic load*

the damage is limited to a small area. It is also important to note that only the outside of the windscreen was examined, since the dynamic impact is not expected on the inside. During the tests, the inner glass layer was not damaged.

Dynamic examinations were also performed on non-tempered soda-lime glass samples as a reference (**Figure 5.**). It can be observed that more cracks radially spread and run toward the edge of the sample, when the glass plate is divided into different sized sharp parts.

4. Conclusions

At room temperature the tempered glasses broke into small pieces with smooth edges and branched cracks after the quasi-static bending. The formation of these edges, which are less dangerous and can result lighter damages, is related to the multiple cracks and small detachments due to the internal stresses. These cracks create a more complex but smoother surface due to the small folds. At 300 °C, there is no significant difference between the fractures, however at 600 °C, the fracture surface is less distributed, but the edges are sharp and therefore dangerous.

Dynamic tests have been used to observe the responses of tempered glass to high-speed point-to-point impact. Windscreens are also resistant to low-speed and high-speed impacts (such as rocks), whereby the fracture is concentrated to a small area. The energy absorbing capacity of the outer glass and the PVB layer is high, so the damage to the inner glass layer has not been reached during the examination.

In conclusion, tempered soda-lime glasses cannot be used safely at high temperatures, although its failure mechanisms at low temperatures are much safer than the breakage of untreated soda-lime glasses.

Acknowledgements

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