Generation of Secondary Cracks in Tempered Soda-Lime-Silica Glass

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熱強化ガラスにおける 2 次クラックの生成

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Crack propagation and secondary crack generation in tempered soda-lime-silica glass were studied by high-speed photography. About 70% of the total secondary cracks observed developed within 1 ms after the initiation of main cracks.

Key-words : Tempered glass, Soda-lime-silica glass, High-speed photography, Secondary crack, Spline crack, Crack propagation

1. Introduction

Tempered glass is widely used for safety windows of automobiles, trains, buildings, etc. owing to two main characteristics, i.e. relatively high strength and unique cracking patterns. It usually has diced fracture surfaces at the time of fragmentation. Dicing phenomenon and generation of dangerous long slender fragments, called spline cracks, are very important for safety problems of tempered glass. Takatsu and Ikeda,¹⁾ and Akeyoshi et al.²⁾ studied the effect of the degree of temper on the total number of the diced fragments. Aratani et al.^{3),4)} studied the mechanism of spline generation. However, these studies were performed after the completion of specimen fracture. For example, counting the fragments was carried out after twenty minutes¹⁾ or one day²⁾ from breakage. On the other hand, many secondary cracks were generated in the tempered glass plates used, where delayed secondary cracking takes place bridging adjacent radial cracks and consequently forming an enormous number of small fragments. Since secondary crack generation functions in reducing the number of dangerous spline cracks, its time dependence is important from a viewpoint of safety problems. As far as the present authors are aware, very few studies have been done on the dynamic fracture process of tempered glass; the process closely related with the secondary crack development. Gardon⁵⁾ reported that the secondary cracks were marked by large elongated fragments and almost right angles to the primary fracture surfaces. However, little have been studied on delayed secondary cracking, especially the time dependence of

secondary crack generation.

In the present study, we investigated the dynamic fracture process of impacted tempered glass using high-speed photography to obtain basic knowledge regarding the development of spline cracks. Attention was focused in particular on the time dependence of secondary crack generation.

2. Experimental

The specimens tested were soda-lime-silica glass plates of 900 mm in length, 400 mm in width and 3.5 mm in thickness. Their chemical composition is shown in Table 1. Tempering was done by the air blowing method so that the whole surface could be uniformly quenched.

An in-laboratory constructed Cranz-Schardin type camera⁶⁾ was used for high-speed photography. The camera had 30 frames and its maximum framing rate was 10⁶ frames/s. Figure 1 shows our experimental setup. An air gun propelled a small bullet of cement

Table 1. Composition of the specimen glass.

SiO ₂	Al ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	others
72	2	8	3	13	1	1

(wt %)

Fig. 1. Experimental setup.

carbide with a conical head at a velocity of about 25 m/s, letting the bullet impact against the glass specimen. Since the mass of the bullet (0.2 g) was so small, the kinetic energy delivered to the specimen by impact was considered to be negligibly small. The role of the bullet impact should have been no more than a trigger for the fracture initiation, and the fracture once initiated should have been advanced by the release of internal residual stresses. The spark light unit for the Cranz-Schardin type camera was triggered at a time of laser light interception by the impacting bullet. A photo-diode and a storage type oscilloscope were used to monitor the time interval between light pulses for separate illumination.

3. Results and discussion

3.1 Generation of secondary cracks

An example of serial generation of secondary cracks is given in Figs. 2 a) and b), which indicate the same area of a fractured specimen: Figure 2 a) was taken when the propagating crack fronts were still in the object field, whereas Fig. 2 b) was taken 60 s after it passed through the field. The secondary cracks newly observed in Fig. 2 b) are marked by the open circles. We counted the number of such secondary cracks generated in an area of 10×10 [mm], 100–150 mm away from the fracture origin as a function of time at an interval of 100 ms. The numbers, after being averaged for different areas, are plotted in Fig. 3 where the number is assumed to be zero at 100 μ s. One can see in Fig. 3 that about

Fig. 2. Secondary cracks, a) fracture just behind the propagating crack fronts, b) secondary cracks can be observed within the open circles.

Fig. 3. Relation between the secondary crack density and time after impact.

70% of the secondary cracks were generated within 1 ms after the main crack initiation.

The secondary cracks so far described were between relatively long radial cracks and bridged them nearly perpendicularly. The principal stress in the direction normal to the radial cracks must practically have been relaxed by the primary cracking. Hence, it seems probable that the residual stress whose direction was almost perpendicular to that of the relaxed stress was occasionally high enough to initiate secondary cracking. This mechanism has been confirmed by a study of high speed photoelastic color photography.⁷⁾

4. Conclusions

Impact fracture occurring in the plates of tempered soda-lime-silica glass was studied by high-speed photography. Results are summarized as follows: Roughly 70% of the secondary cracks were generated within 1 ms after the main crack initiation.

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