

E-1 PHOTOGRAPHIC STUDY OF CRACK PROPAGATION
IN GLASS PLATES IN CONTROLLED ENVIRONMENTS

Shin-ichi Hyodo and Haruo Nakatsuka*

ABSTRACT

Fracture velocities of soda-lime glass plates in different environments such as air, vacuum, helium, nitrogen, carbon-dioxide and water were measured by means of high-speed photography. No environmental effects were observed on the terminal fracture velocity. However, when elastic strain energy stored in the specimens was not enough to keep cracks running at the constant maximum speed, some effects appeared to be present. These results may be interpreted in terms of the generally accepted theory.

Three kinds of theory have been published regarding the velocity of cracks propagating in a brittle isotropic material. These theories reach different conclusions as to which characteristic elastic wave velocity the maximum fracture velocity is associated with. The first, which originated with Mott (1), associates it with the longitudinal wave velocity. The second, which was postulated by Poncelet (2) and Yoffe (3), associates it with the transverse wave velocity; and the third, which was advocated by Broberg (4) and Craggs (5), associates it with the Rayleigh's surface wave velocity.

Among these three, Mott's theory seems to be most widely accepted. According to this theory, the terminal velocity should be a certain fraction of the longitudinal wave velocity. Also, it implies that the terminal crack velocity is not dependent on surface properties such as surface energy but only on the mass density and elastic moduli of the bulk material.

At the Swampscott Fracture Conference, however, Schardin (6) reported measurements for glasses having a variety of compositions, and showed that observed maximum crack speeds do not correlate as well with sound velocities as they do with a quantity defined as the square root of the ratio between microhardness and mass density. Since hardness is known to be related with the surface energy, he suggested that the surface energy might influence the limiting fracture velocity. More recently this idea was emphasized by Kerkhof (7), who estimated the surface energy of various glasses from interatomic distances, and derived a linear relationship between the limiting fracture velocity and the square root of the ratio of surface energy to mass density.

* Department of Applied Physics, University of Tokyo, Bunkyo-ku, Tokyo.

Since it can be shown that the surface energy is approximately proportional to Young's modulus, it is difficult to decide whether surface energy really affects the limiting crack speed, when materials with different Young's moduli are compared. Therefore, it was interesting for the authors to study crack speed in the same material as it was held in different environment.

The present study was based of course on the idea that surface adsorption may reduce the surface free energy of a solid. This is a thermodynamic phenomenon that requires quasi-static equilibrium, so there remained some doubt as to whether enough molecules from the environment can arrive at the tips of very fast cracks to have an effect.

Fig. 1 shows a schematic diagram of the experimental apparatus. The specimens were sheets of soda-lime glass picked from a commercial lot. The fracture phenomena were photographed with a Beckman-Whitley high-speed camera at a rate of $3-6 \times 10^5$ frames/sec. In order to make the time of crack initiation uniform, each specimen was polished in a dilute hydrofluoric acid solution. This strengthening treatment helped to produce a concentric crack pattern, which improved measurement of crack sizes.

The polished specimens were held vertically by a rectangular frame, which was placed in a metal vacuum chamber. Cracks were started by hitting the specimens with a small electrically triggered hammer, which also triggered the camera when it hits the specimen. The atmosphere inside the chamber was controlled through standard vacuum and gas supply systems. Tests were done at pressures down to 10^{-4} Torr, and after introducing various pure gases such as hydrogen, helium or carbon dioxide. Since the time required for crack propagation was so short (less than about 10^{-4} sec), a pressure of 10^{-4} Torr was adequate to prevent a significant amount of surface contamination during a test. Tests were also carried out in the room atmosphere and in water.

Fig. 2 shows an example of crack propagation in a glass plate. The wide shadows at the middle of the picture show the hammer and the conductive paint. Such symmetric crack patterns were quite convenient for determining maximum crack velocities. Fig. 3 shows the frame following next to Fig. 2. Time interval between these two frames is 5μ sec.

Table 1 summarizes our measurements of velocities for different environmental conditions. It may be seen that there is no perceptible change compared to the results for room conditions, which agree quite well with results obtained by other authors for soda-lime glass. For specimens immersed in water the contrasts of the pictures were lowered because of the similar refractive indexes of glass and water, so the errors of the measurement increased. However, it seems safe to conclude that no detectable influence of water on the maximum crack speed was found. Fig. 4 is presented to illustrate the equal growth rates of cracks in different environments.

The fracture velocities listed in Table 1 were obtained with surface-treated specimens of high-strength, and of little fluctuation in the time of crack initiation. By reducing the time delay between impact and the flash illumination, crack propagation in specimens of rather low strength could be sometimes photographed (8). Table 2 lists the results obtained with such specimens. The maximum velocities observed were under the limiting value of about 1.5 km/sec, so in this case some influence of a surrounding gas on the crack velocities seems to be present. It should be noted that, assuming other conditions are constant, the presence of a surrounding gas which reduces the surface energy of glass appears to increase the crack velocity. Therefore, surface energy and fracture velocity have a negative correlation, whereas Kerkhof's theory predicts a positive correlation between these quantities.

According to Mott, crack velocity \dot{c} may be described by an equation of the following form.

$$\dot{c} = \dot{c}_m \left(1 - \frac{C_0}{c}\right)^{\frac{1}{2}} \quad (1)$$

where \dot{c}_m = limiting crack velocity, C_0 = Griffith's critical crack size and c = instantaneous half size of a growing crack. By a mathematical refinement, Dulaney and Brace (9) obtained another expression as given by

$$\dot{c} = \dot{c}_m \left(1 - \frac{C_0}{c}\right) \quad (2)$$

From the Inglis stress concentration relationship, it is possible to rewrite Eq. (1) and (2) in terms of σ^* , the stress at the crack tip, and of the surface energy γ as follows:

$$\dot{c} = \dot{c}_m \left\{1 - \left(\frac{8E}{\pi r}\right) \frac{\gamma}{\sigma^{*2}}\right\}^{\frac{1}{2}} \quad (3)$$

$$\dot{c} = \dot{c}_m \left\{1 - \left(\frac{16E}{\pi r}\right) \frac{\gamma}{\sigma^{*2}}\right\}^{\frac{1}{2}} \quad (4)$$

where E denotes Young's modulus and r the radius of the crack tip.

Plotting the normalized crack speed \dot{c}/\dot{c}_m on a non-linear scale against γ/σ^{*2} , Eq. (3) and (4) can be represented by two straight lines as shown in Fig. 5. Three dotted lines there indicate the mean of the velocities listed in Table 2. From the intercepts of these dotted lines with the normalized velocity axis, it is possible to determine the ratio of γ/σ^{*2} among each medium. Although the slopes of the lines to represent the crack speed equations are more or less arbitrary, it is obvious that this ratio of γ/σ^{*2} is independent on the slopes. Table 3 gives the ratio of γ/σ^{*2} thus obtained and ratio of surface energies for soda-lime glasses tested in various media. It seems rather surprising that the tendency for the surface energy to change with the medium that was found for static tests is also observed for such dynamic tests.

As a summary of the present results it may be pointed out that:

1. No environmental effects on the terminal crack velocities in glass were observed.
2. For crack velocities markedly smaller than the terminal value, some environmental effects appeared to be present.
3. It is possible to explain both of these results in terms of the generally accepted theory of crack velocities.

References

- (1) N. F. Mott: *Engineering*, 165, 16 (1948)
- (2) E. F. Poncelet: "Fracturing of Metals", Amer. Soc. for Metals (1948)
- (3) E. H. Yoffe: *Phil. Mag.*, 42, 739 (1951)
- (4) K. B. Broberg: *Arkiv för Fys.*, 18, 159 (1960)
- (5) J. W. Craggs: *J. Mech. Phys. Solids*, 8, 66 (1960)
- (6) H. Schardin: "Fracture", MIT-Wiley, New York, p. 297 (1959)
- (7) F. Kerkhof: *Naturwissenschaft*, 50, 565 (1963)
- (8) M. Takahashi and S. Hyodo: *Jap. J. Appl. Phys.*, 3, 127 (1964)
- (9) E. N. Dulaney and W. F. Brace: *J. Appl. Phys.*, 31, 2233 (1960)

TABLE 1

Observed Maximum Values of Glass Crack Velocities

Medium	air	vacuum	carbon dioxide	hydrogen	water
Pressure (Torr)	760	10^{-4}	1 ~ 7	2 ~ 5	760
Number of Measurements	16	16	6	15	6
Velocity (km/sec)	1.52 ± 0.02	1.54 ± 0.04	1.50 ± 0.05	1.53 ± 0.04	1.55 ± 0.08

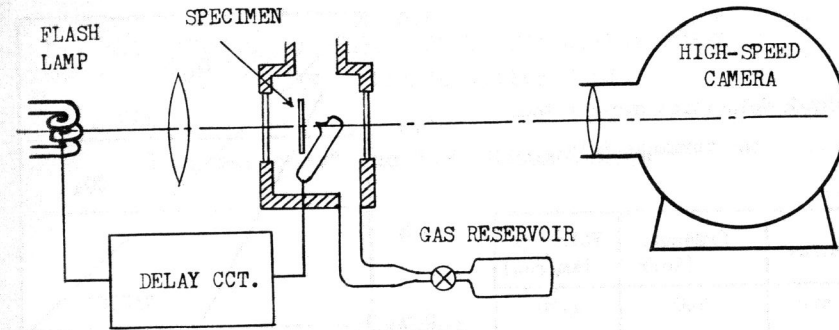


FIG. 1 : Experimental Arrangement.

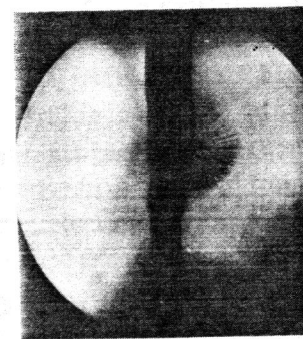


FIG. 2

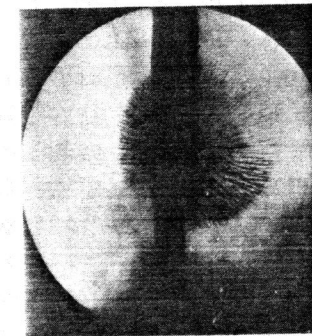


FIG. 3

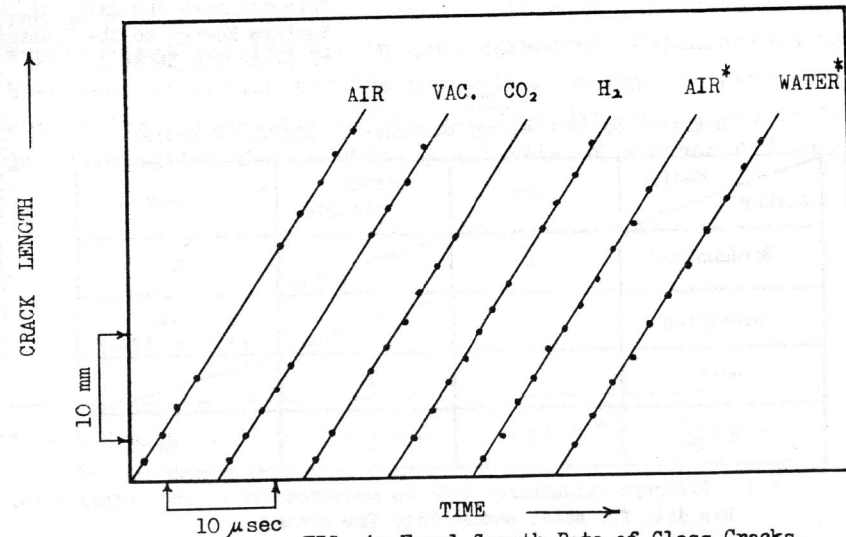


FIG. 4: Equal Growth Rate of Glass Cracks.

TABLE 2.

Crack Velocities smaller than the Terminal Value.

Medium	Pressure (Torr)	Velocity (km/sec)
air	760	1.30
air	760	1.39
vacuum	2.0×10^{-4}	1.08
vacuum	4.4×10^{-4}	1.03
vacuum	8.2×10^{-4}	1.04
He	12.4	1.24
He	7.2	1.43
CO ₂	6.4	1.28
CO ₂	5.4	1.22
H	1.4	1.39

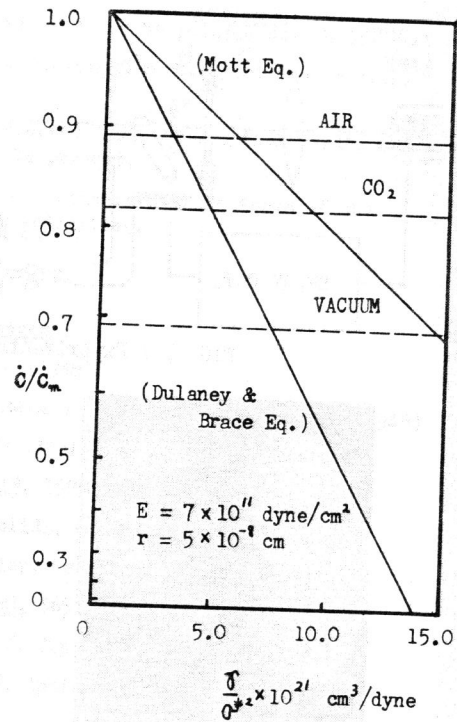


FIG. 5: Relation of Normalized Crack Velocity with the Ratio of Surface Energy to the Square of Crack Tip Stress.

TABLE 3.
Ratio of Surface Energy of Glass in Different Media.

Medium	air	carbon dioxide	vacuum
Author			
Berdennikov	1*		4.2
Schoening	1		3.0 (1.7 ~ 12.1)
Culf	1	1.9	
γ/σ_s^2	1	1.6	2.4

* : Although Berdennikov made no measurements at room conditions, his data for water should hold for wet air.