DYNAMIC EFFECTS OF LIQUIDS ON SURFACE CRACK EXTENSION IN GLASS

T. A. Michalske*, V. D. Frechette** and R. Hudson**

*National Bureau of Standards, Washington, D.C.
** N.Y.S. College of Ceramics, Alfred Univ., Alfred, N.Y.

ABSTRACT

Crack growth in surface flawed glass bend bars was produced in aqueous environments. The recently discovered cavitation scarp, found to correspond to the onset of critical crack formation, was observed on fracture exposed surfaces of bend specimens. Wallner lines produced by superimposing a tuned-frequency sonic signal during cracking were used to map the growth of surface flaws to critical dimensions. Cavitation scarp formation was discussed in terms of critical stress intensity (K_{IC}) measurements for surface flawed beam specimens.

KEYWORDS

Crack growth; fracture; fractography; glass; critical stress intensity.

INTRODUCTION

Subcritical crack growth is a phenomenon by which a small crack in a stressed material can grow slowly until it becomes sufficiently large to result in catastrophic failure. In glass, water at the crack tip greatly increases the rate of subcritical crack growth. Previous studies (1-4) have documented the effect of water on subcritical crack growth by examining the crack velocity-stress intensity (log V vs K_I) relationship for various glasses in water. This relationship was shown to exhibit three distinct regions of crack propagation. Region I has been described as the period of environmentally controlled crack growth, Region II has been associated with the transport of environmental species to the crack tip and Region III has been identified with environmentally independent crack growth.

A recent fractographic study (5) of water aided crack growth in fracture mechanics specimens (edge cracked plates) has shown two types of fracture surface markings which are associated with the effect of water on crack propagation rates in glass.

The first surface marking is termed a cavitation scarp. A sharp ridge corresponding to an abrupt change in fracture plane is formed as a crack accelerates from Region II to Region III growth. The cavitation scarp is preceded by a group of fine ridges which terminate at the cavitation scarp. These ridges are termed transition hackle and are thought to correspond to the nucleation process preceeding cavitation. Crack velocity measurements showed that the cavitation scarp is associated with an order of magnitude jump in crack velocity (see Fig. 1). The crack velocity jump was explained in terms of a drag effect due to the presence of a viscous liquid at the crack tip which is abruptly terminated as the liquid and crack tip are separated by a stable cavitation bubble. Since the crack front undergoes an order of magnitude jump in velocity, the position of the cavitation scarp was suggested as a means to measure the crack length at the onset of catastrophic failure. The previous fractographic observations suggested a means for studying the interactions between developing surface flaws in glass and liquid environments.

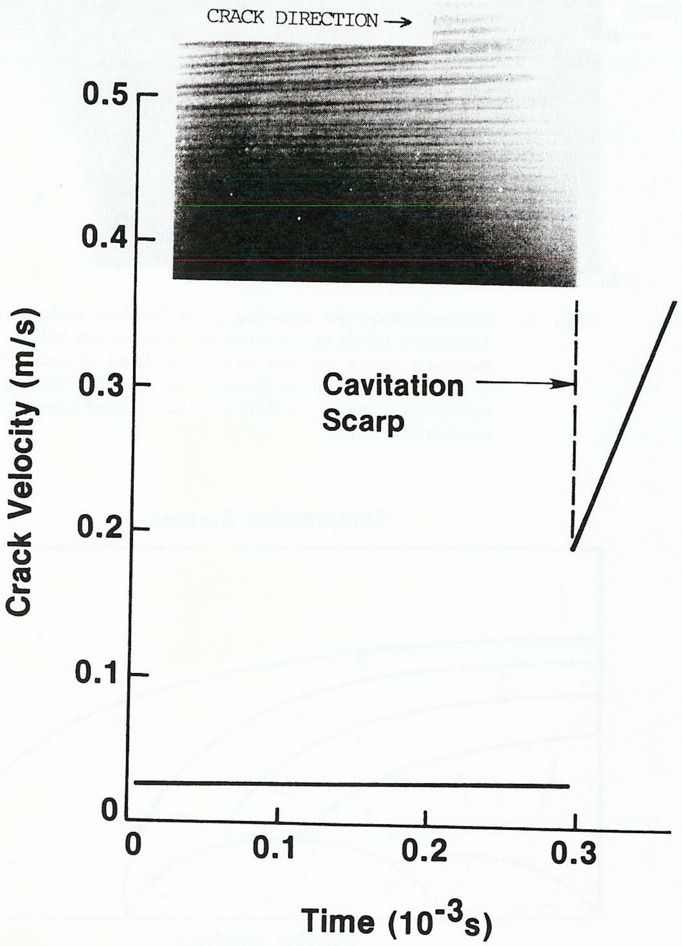

Fig. 1. Crack velocity vs time on either side of the cavitation scarp. Inset shows fracture surface markings accompanying velocity effects.

PROCEDURE

Specimens were soda-lime-silica bars measuring 6.3X9.5X76 mm. A single controlled geometry flaw was placed in each bar perpendicular to its long dimension. The flaws were created by a two step process (6). First, a small surface damage site was produced by indentation. The complex damage site generated by indentation was then matured by placing the specimen surface in local tension. By this process the damage site develops into a regularly shaped surface crack with a continuous crack front.

The bars were broken in four point bending using an Instron testing machine at a cross head speed of 0.05 cm/min.

Crack velocity was measured using a modification (7) to Kerkhof's (8) ultrasonic technique. A train of S-waves (shear waves) was imposed on the specimen during crack propagation. Postmortem measurements of the spacing between the Wallner lines caused by the S-waves were used to calculate crack velocities.

RESULTS

The fracture surface details which result when a surface flaw is accelerated to catastrophic failure in the presence of water are shown in Fig. 2. The photomicrograph shows the surface details labeled in the accompanying sketch. Taken in order of their development, the irregularly shaped damage site is seen first. Next, the regularly shaped flaw matured by application of local surface tensile stress is outlined by an arrest line. This boundary represents the flaw that existed prior to application of bending stress. Transition hackle is the next surface detail generated by the spreading flaw (Fig. 3 shows a higher magnification view of the transition hackle). The transition hackle is terminated at the cavitation scarp which forms an approximate semi-elliptical boundary around the origin area. Following the cavitation scarp, strong Wallner lines are seen on the now mirror-smooth crack surface. These Wallner lines are not symmetric about the origin flaw which suggests that critical crack growth (outside the cavitation scarp) did not proceed in a uniform manner but spread preferentially away from one side of the cavitation scarp. Closer examination of the crack surface details (see Fig. 4) show that after the subcritical crack spread from the origin flaw, the critical crack began from one side of the cavitation scarp and spread to the corner of the specimen where a strong Wallner line formed. Next, the critical portion of the crack front swept around to intersect the subcritical crack and finally sever the specimen. The intersection of the two crack fronts at the cavitation scarp is evidenced by two types of fracture surface markings. In Fig. 3 Wallner lines on the critical crack surface are seen to originate from transition hackle on the subcritical crack. In one specimen (see Fig. 5) a lancet of twist hackle pointing in the direction of local fracture shows an abrupt change in direction as it intersects the cavitation scarp.

Crack velocity measurements along the tensile surface showed that the cracks had accelerated to a velocity of 0.119 ± 0.05 m/s before cavitation occurred. It is also noted that crack velocity was nearly constant just prior to formation of the cavitation scarp. Crack velocity along the tensile surface immediately following the cavitation scarp began at about 0.8 m/s and rapidly accelerated toward the corner of the specimen. Prior to cavitation, the crack velocity was seen to vary with position along the expanding crack front; the highest velocity being along the tensile surface and the lowest at 90° to the tensile surface. Measurement of crack velocity at angles of 15° and 30° to the tensile surface showed that the crack front was moving 30% and 50% slower respectively than the crack front at the tensile surface.

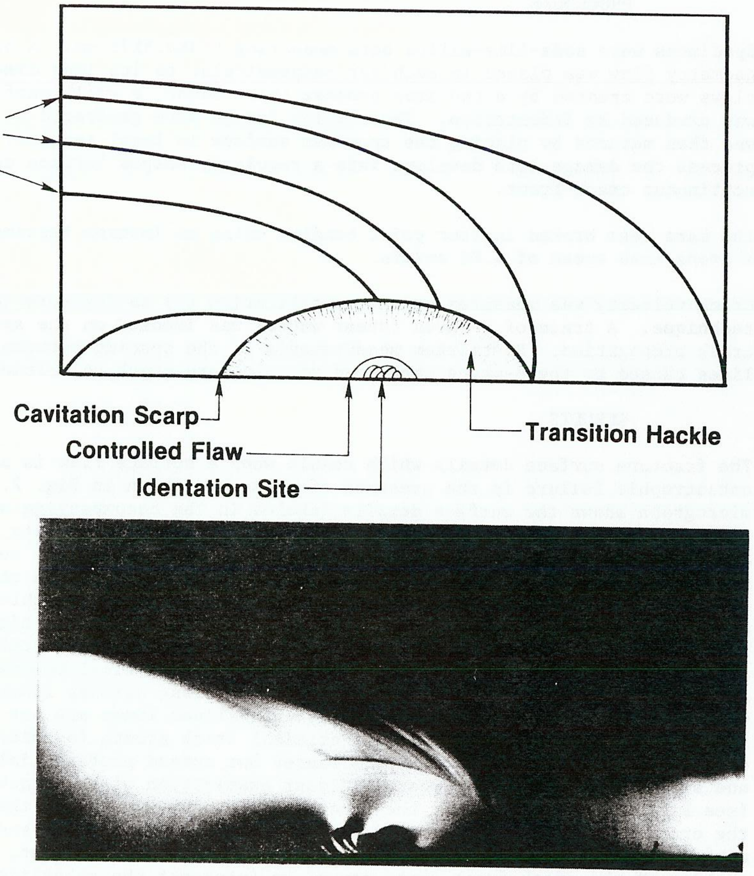

Fig. 2. Schematic: Exposed surface of glass fracture resulting from bending in water. Various surface details which were formed during crack growth are labeled. Photomicrograph: Enlargement of area in schematic. Reflected light; 20 X.

DISCUSSION

Results presented in the previous section show that many of the effects seen as large cracks accelerate to critical velocity in a water environment can also be observed on small surface cracks as they expand to critical dimensions. Both types of cracks accelerate to a plateau velocity then experience an order of magnitude jump in crack velocity at the cavitation scarp. However, in the case of the through cracks, cavitation appears to spread instantaneously across the crack front which causes the entire crack to go into the catastrophic mode. Surface flaws seem to cavitate over only a limited portion of the crack front and the critical crack spreads only from that area. It is reasoned that localized cavitation in expanding surface flaws is a result of variation in crack velocity

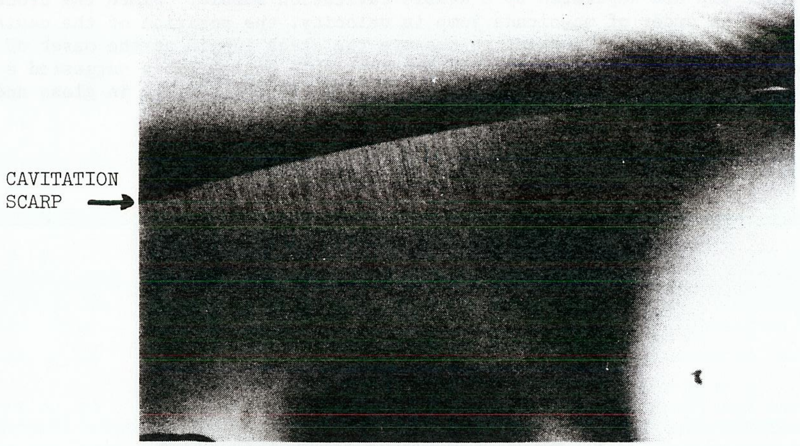

Fig. 3. Photomicrograph showing fine hackle ridges on the fracture surface preceeding the cavitation scarp. Wallner lines on the crack surface outside the cavitation scarp originate at hackle ridges. Reflected light, differential interference contrast; 60X.

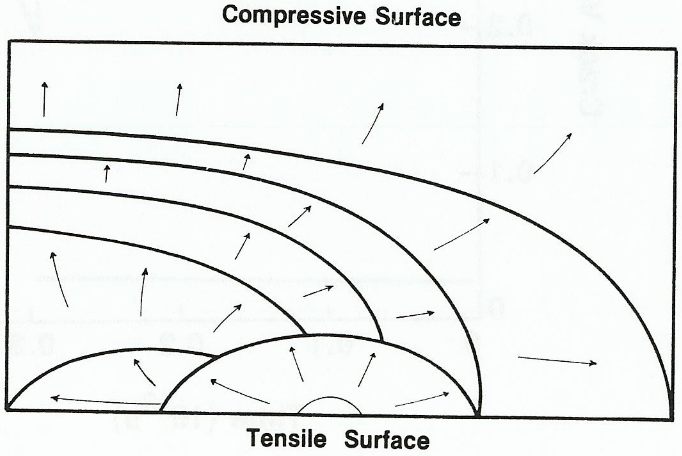

Fig. 4. Schematic showing development of surface flaw by application of bending stresses in water environment. Arrows indicate direction of local fracture.

along the crack front. Because the negative pressure of the liquid in the crack tip region is dependent on the crack velocity, the high velocity portion of the crack front can have sufficient negative pressure to support cavitation while the slower moving portion of the crack front cannot support such an effect. Thus cavitation would occur first near the tensile surface of the specimen since velocity is highest there due to an increase in stress intensity from surface effects and the stress gradient associated with bending. Once the critical crack has been initiated, its velocity and acceleration are so much higher than the subcritical crack that the critical portion of the crack is able to sweep around the entire specimen before the remainder of the crack front can reach catastrophic velocity.

It was also seen that the velocity immediately preceding the cavitation scarp (termed the critical velocity) was higher in the case of surface flawed specimens than for fracture mechanics specimens. (The critical velocity measured in edge cracked plates was 0.036 ± 0.004 m/s where as the critical velocity measured for surface flawed bars was 0.119 ± 0.05 m/s.) This velocity difference may be discussed in terms of the cavitation model developed in a previous paper (5). The expression for the velocity at which cavitation becomes possible is given by:

$$V_{\text{Cavitation}} = \frac{\frac{2\gamma}{r} + P_2}{2\mu\alpha^{-2}\,(X_2^{-1} - X_1^{-1})} \qquad (1)$$

where γ is the surface tension of the liquid, μ is the viscosity of the liquid, r is the radius of a cavitation bubble which just fits in the crack opening, P_2 is atmospheric pressure, α is the half angle of crack opening and the quantities X_1 and X_2 represent the positions of the open end of the crack and the cavitation bubble respectively. Either an increase in the crack opening angle or a decrease in the crack length could contribute to a higher crack velocity for cavitation. It should also be noted that this expression for the critical velocity was developed for a crack with constant crack front length where as the surface flaw has an expanding crack front which may also influence the cavitation behavior.

Fig. 5. Photomicrograph showing abrupt change in crack path at cavitation scarp. Reflected light, differential interference contrast; 60X.

Because of the order of magnitude jump in crack velocity at the Region II/III transition, it was suggested (5) that the cavitation scarp could be used to measure the crack length at the onset of catastrophic failure in fracture mechanics specimens. Results of this study suggests that the crack length at the cavitation scarp in surface flawed bend specimens is representative of the point of critical velocity only when measured along the tensile surface where cavitation first occurs. Measurement to the cavitation scarp along other directions represents the intersection between the subcritical and critical crack fronts and is not associated with any particular velocity of the expanding flaw. Thus critical crack length measurements to determine the critical stress intensity (K_{IC}) should be made from the fracture origin to the primary area of cavitation on the expanding surface flaw.

SUMMARY

Controlled geometry surface flaws in Na_2O-CaO-SiO_2 glass bars were extended to critical dimensions in water by application of bending stresses. Fracture surface details (transition hackle and cavitation scarp) previously shown to be associated with liquid cavitation and an order of magnitude jump in crack velocity were observed on the crack surfaces of bend bars. Examination of the fracture generated surfaces showed that liquid cavitation and the jump in crack velocity occurred only at the highest velocity portion of the expanding flaw and that the critical crack spread from that region to sever the specimen. The limited region of liquid cavitation was explained in terms of a stability criterion for the cavitation bubble. It was also noted that the measured critical velocities in surface flawed bend specimens were significantly higher than those measured for fracture mechanics specimens.

Results from this study suggest that critical flaw dimensions, as marked by the cavitation scarp, should only be measured to the region where cavitation first occurred.

REFERENCES

Schonert, K., Umhauer, H. and Klemm, W., (1969) Proc. of the 2nd International Conference on Fracture, 474.
Wiederhorn, S.M., (1967) J. Am. Ceram. Soc., 50, (8) 407-414.
Weidmann, G.W. and Holloway, D.G., (1974), Phys. Chem. Glasses 15, (5), 116-122.
Richter, H., (1977), The Physics of Non-Crystalline Solids, 618-624.
Michalske, T. A. and Frechette, V.D., J. Am. Ceram. Soc., accepted for publication.
Frechette, V. D. and Hudson, R., To Be Published.
Michalske, T. A. and Frechette, V.D., Int. J. Fracture, accepted for publication.
Kerkhof, F., (1966), Kurzzeitphysik, 408.