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Crack shape studies in brittle porous materials

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The technique of ultrasonic fractography has been used to study crack interactions in a porous glass. Observations indicate the initial attraction of a crack to the porosity, the change of crack shape as the crack segments to bypass the pores and the production of fracture surface steps as the crack breaks away. This technique has great potential for the study of local changes in crack shape and velocity in brittle composite systems.

1. Introduction

It has been suggested [1–3] that the crack shape may be an important parameter in the fracture of brittle materials especially in cases where the crack front samples a variation in fracture toughness. Indeed, the increase in fracture surface energy observed in several brittle particulate composites [4] has been associated with the change in crack shape caused by impedance of the crack front by the second phase. In order to circumvent the particle, the strain energy of the system must be increased and this is reflected by a change of the crack front shape. The evidence for this shape change has been mainly deduced from fractographic observations such as fracture surface steps [4]. Unfortunately, this evidence is not systematic, especially for glassy materials and there is a need for a more sophisticated technique for crack shape analysis.

Ultrasonic fractography was developed by Kerkhof and co-workers [5] for the measurement of high crack velocities. The method involves transmission of a beam of transverse ultrasonic waves through a sample at the time of fracture. The oscillating shear wave produces a mode II stress intensity component on the crack front and modulates the crack path leaving a permanent ripple marking on the fracture surface. As the frequency of the imposed wave is accurately known, the spacing of the ripple marking facilitates determination of the crack velocity.

The height of the ripple markings is $< 1\,\mu$m. Because this technique leaves a permanent record of the crack front on a fracture surface, it is clear that systematic information could also be obtained on crack shape. In this paper, the use of ultrasonic fractography to study the interaction between a crack front and porosity in a porous glass is reported.

2. Experimental procedure

Two batches of S glass (55 wt% SiO_2, 15 wt% Al_2O_3, 30 wt% Na_2O) were produced by melting, fining and casting of the appropriate mixture of oxides or salts. The melting was performed at 1450° C in an electric glo-bar furnace. The first batch was fined for 6 h to allow the production of a dense glass. The second batch was fined for 2 h so that some residual porosity (gas bubbles) remained in the glass (~ 1 vol%). The cast billets were annealed at 450° C then diamond-machined into double cantilever beam (DCB) fracture specimens. The specimen dimensions were approximately 50 mm × 12 mm × 6 mm with side grooves of 2 mm depth and a notch of 20 mm down the mid-section of the beam. The samples were annealed at 450° C to remove machining stresses and then pre-cracked.

An Instron testing machine was used to fracture the samples. The water-cooled ultrasonic transducer was glued on the end of the sample opposite the notch using epoxy resin (Fig. 1). The frequency of

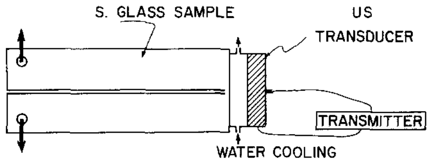

Figure 1 DCB fracture test for ultrasonic fractography.

the ultrasonic waves was 1.02 MHz and a 1 kW transmitter was used to drive the crystal. This testing geometry gives rise to a Doppler frequency shift but the crack speeds encountered in the DCB test were typically less than $50\,m\,sec^{-1}$ so avoiding the necessity of a frequency correction. The ultrasonic equipment is described in detail elsewhere [6].

Fractographic observations were made using an SEM and interference microscope. For electron microscopy the samples were coated with carbon and shadowed at a $\sim 5^{\circ}$ angle with gold. For interference microscopy, the samples were coated with a thin layer of gold.

3. Results

The dense S glass was observed using interference microscopy. The three-dimensional nature of the ultrasonic modulation is shown in Fig. 2. The height of the ripples was determined from these observations to be $\sim 0.7\,\mu m$.

The interaction between a crack front and a pore is shown in the composite SEM micrograph

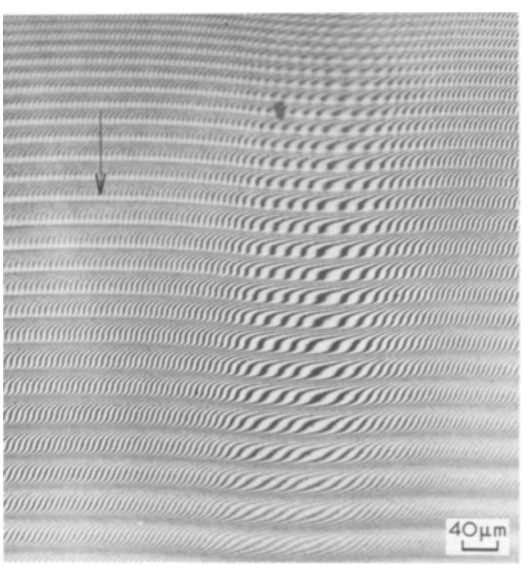

Figure 2 Interference micrograph of an ultrasonically-modulated fracture surface of dense S glass (crack direction arrowed).

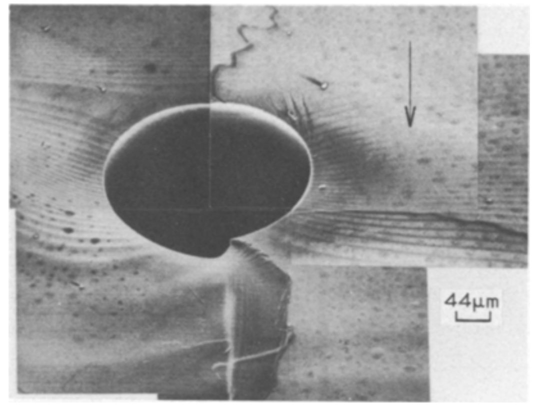

Figure 3 SEM composite micrograph of crack-pore interaction by ultrasonic fractography in porous S glass (crack direction arrowed).

(Fig. 3). It is evident that, as the crack approaches the void, there is a local increase in crack velocity (5 to $50\,m\,sec^{-1}$). This is the result of an increase in the mode I stress intensity factor as the crack enters the elastic field of the pore. This problem has been analysed by several authors [7–11] and is illustrated in Fig. 4 following Atkinson [8]. The stress intensity at the crack (K_I) divided by the stress intensity for a crack without the pore (K_I^0) is calculated and plotted. In this case the crack was approaching along the equator of the pore.

After the initial approach, the crack segments to by-pass the void but as the void represents a lower local elastic energy region the motion of the crack is impeded and the crack front changes shape. The local crack velocity appears to be a

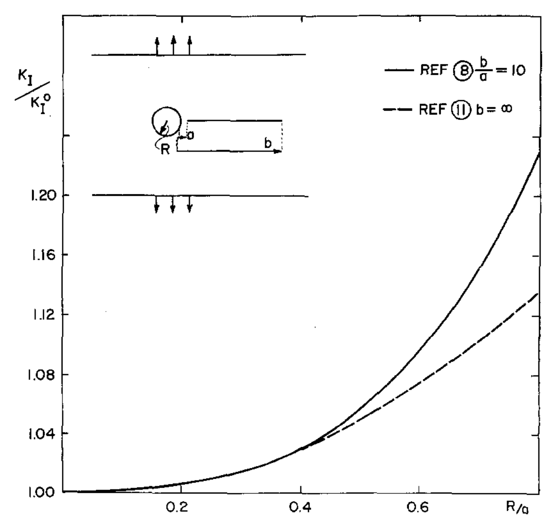

Figure 4 Increase in stress intensity for crack in vicinity of a pore.

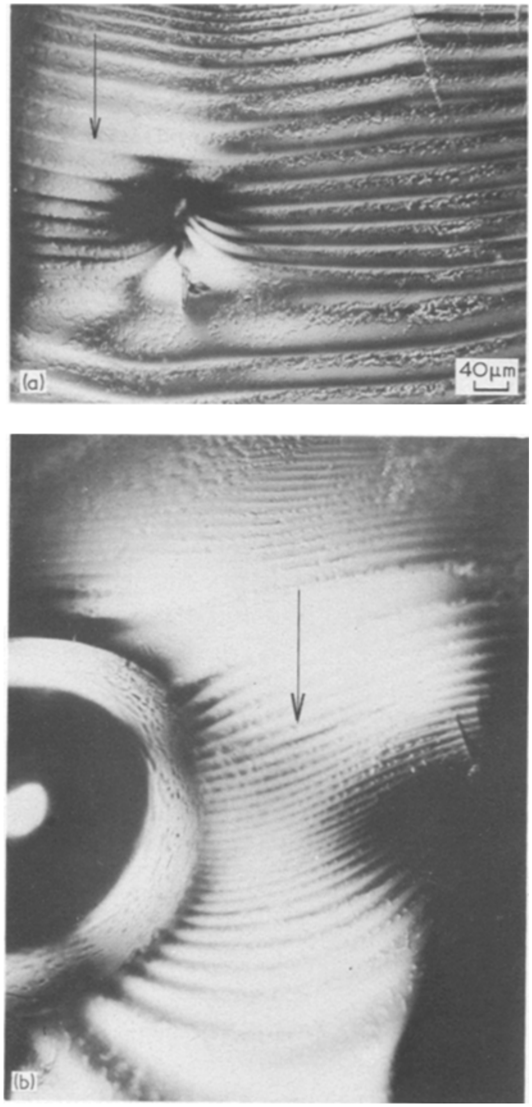

Figure 5 (a) Crack interaction with a very small pore (crack direction arrowed). (b) Ultrasonic ripple patterns as crack by-passes a pore in S glass (Nomarski interference), × 400 (crack direction arrowed).

minimum at the centre of the void. It is clear from Fig. 3 that the crack front is never "pinned" by void and the pore acts more as a "drag" force on the crack front. The work of Evans [2] based on elastic energy considerations, suggest that the crack front must be pinned in order to increase the fracture surface energy.

Finally, the crack breaks away from the void at a high velocity (~ 80 m sec^{-1}) leaving a fracture surface step at the rear of the particle. Presumably, the segmented cracks have interacted with the stress field of the pore and reach the rear of the pore in a non-co-planar configuration.

The resultant fracture "tails" have often been observed in porous or particulate composites. A secondary fracture is now required to complete the separation. It is interesting to note that some ripples are observable associated with this process. The low velocity within the step (~ 5 m sec^{-1}) indicates that the secondary fracture must occur sometime after the primary crack front has passed on, i.e. these "steps" must be left as ligaments behind the major crack front. Improved fractographic observations were made using the Nomarski interference technique and typical crack-pore interactions are shown in Fig. 5a and b.

From this work, it is clear that the technique of ultrasonic fractography can be used to study local crack shapes and give valuable information on local crack interactions.

Acknowledgements

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