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Applying fractography and fracture mechanics to the energy and mass of crack growth for glass in the mirror region

Richard C. Bradt *
Metallurgical and Materials Engineering, The University of Alabama, Tuscaloosa, AL 35487-0202, USA

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Abstract

The mirror region following the fracture initiation site is considered by applying fracture mechanics principles along with experimental observations of the crack velocity at the formation of the mirror mist boundary. Several issues regarding this crack growth in glass are addressed after considering the terminal velocity of crack growth and the mirror mist boundary information on silicate glasses. A strain energy release rate criterion is applied to estimate the kinetic energy of an advancing crack in glass at the mirror/mist boundary. This energy is then utilized to estimate the effective mass of the crack at the mirror/mist boundary. It is compared with material volumes in the vicinity of the crack.

Keywords: Crack velocity; Effective crack mass; Mirror/mist boundary; Strain energy release

1. Introduction

When a crack propagates in glass it leaves a distinctive pattern of fractography at the origin and throughout the initial growth period. The features of that region are known as the mirror, the mist and the hackle. Fig. 1 below after Chandan et al[1] shows the latter of these features, the hackle on matching fracture surfaces of a broken bend strength specimen where the edges have been beveled to remove any edge chips or flaws and therefore to leave the most serious flaw on the bottom flat of the specimen. The fracture mirror regions on these two matching faces are actually too small to be readily visible at this magnification, but the straight line hackle features which focus back to the initiation site do enable one to locate the position of the fracture origin at the bottom edge of the specimen.

Although the three fracture surface regions are often visible optically on many low strength glass specimens it is more convenient to view the fracture origin on a scanning electron microscope. In Fig. 2 below, after Quinn[2] which is a broken cylindrical rod, the mirror and mist regions are more clearly presented, but at the expense of reducing the length of the hackle.

In his review article Quinn[3] thoroughly addresses the history of the observation and interpretation of the fracture mirror region. Those items will not be fully reviewed again here, but rather the mirror region will be applied to address the crack acceleration and velocity when it reaches the point that it forms the mirror/mist boundary. It will suffice to note that the mirror is a very smooth region of very high crack velocity acceleration. For further insight to the mirror region, the Quinn[3] review is recommended. The mirror has been profiled using atomic force microscopy by Wiederhorn et al.[4] in the fifth Alfred Fractography Conference and is further discussed there, particularly with respect to its smoothness. The subsequent mist region which is a sort of dimpled band-shaped region of crack front instability leading the formation of the hackle lines has been studied and profiled by Ball et al.[5] This article will utilize the feature that is known as the mirror/mist boundary for kinetic energy and crack mass estimates from the fractography coupled with other measurements. Although much more is possible, additional features will have to be left for a later manuscript.

2. The empirical equation of the mirror/mist boundary in glass

Although mirrors and mirror–mist boundaries are also present in high strength crystalline ceramic fracture surfaces, they were initially observed and reported, apparently

* Tel.: +1 205 348 0663; fax: +1 205 348 2164.
E-mail address: rcbradt@eng.ua.edu

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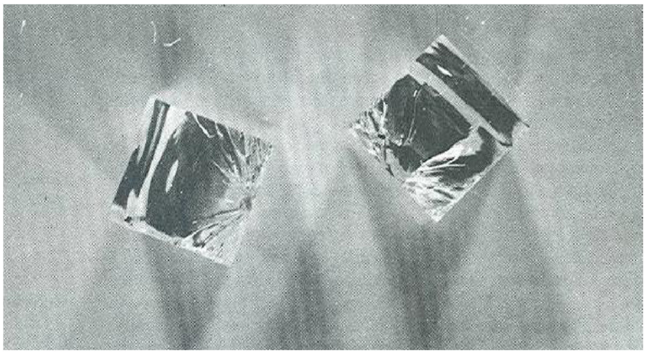

Fig. 1. The fracture surface markings on a 1 cm square strength specimen, after Chandan et al.[1] Note the distinctive hackle lines that radiate from the fracture origin on the matching faces.

independently, by Shand,[6] Johnson and Holloway,[7] and Orr[8] about a half century ago for glass. They found that the size of the mirror followed the empirical relationship with the strength:

$$\sigma_f R_{m/m}^{1/2} = A_{m/m}, \quad (1)$$

where σ_f is the fracture stress or the strength of the glass specimen, the $R_{m/m}$ is the radius of the mirror/mist boundary and $A_{m/m}$ is a quantity that is known as the fracture mirror constant. Different composition glasses have different mirror constants. The quantity known as the mirror constant has the same units as stress intensity and fracture toughness, namely MPa m$^{1/2}$. Eq. (1) has been applied by Michalske[9] to a wide range of different researchers' results for strengths of fused silica (50 MPa–3 GPa) and observed that this empirical equation describes the strengths. Kerper and Scuderi[10] have similarly assembled data for Pyrex (Corning 7740). It is depicted in Fig. 3 below. There is no doubt that the above empirical equation describes the strength and mirror/mist boundary relation very well. As a related point, Mecholsky[11] has extended the form of Eq. (1) to the mist/hackle boundary and also to crack branching as well. Although this equation was discovered by empirical graphical approaches, there is something about it that is very fundamental, even though it has never been derived from first principles.

It is the extending crack through the mirror region and at the mirror/mist boundary that will be of primary interest, so

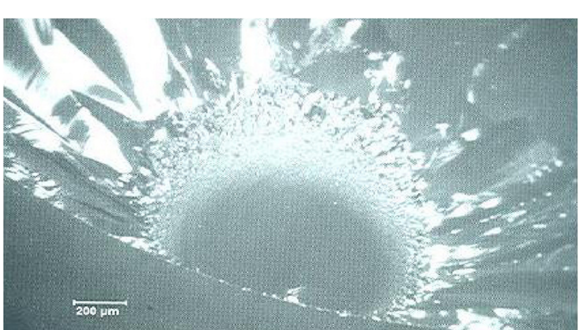

Fig. 2. The fracture origin on a broken glass rod illustrating the smooth mirror area about the fracture origin and also the mist region before the beginning of the hackle lines, after Quinn[2].

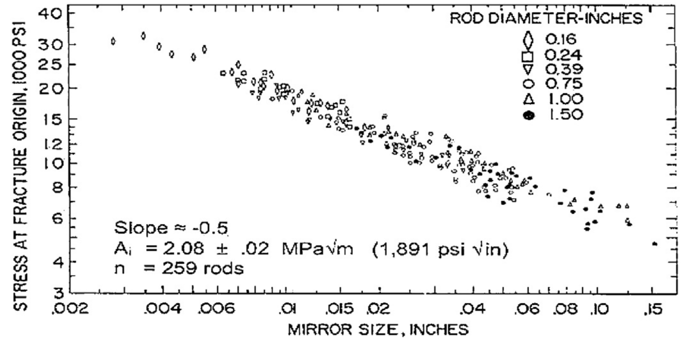

Fig. 3. The strength results for borosilicate PYREX, Corning 7740 glass rods presented on a fracture mirror/mist radius vs strength logarithmic plot. The slope is – ½. After Kerper and Scuderi.[10]

it is convenient to rearrange Eq. (1) to express the mirror/mist boundary radius, $R_{m/m}$ as:

$$R_{m/m} = \frac{(A_{m/m})^2}{(\sigma_f)^2}, \quad (2)$$

which, as has been previously pointed out by Bradt,[12] suggests that the mirror/mist radius is related to the strain energy and the strain energy release rate, for the σ_f^2 term is included in the expression for the stored elastic strain energy in the specimen at fracture, which is ½ (σ_f^2/E). If one treats the advancing crack front at the mirror/mist boundary as a circle, which is an approximation to the ellipses that often form, then the crack length $L_{m/m}$ at the mirror/mist boundary is approximately:

$$L_{m/m} = \frac{\pi 2 R_{m/m}}{2} = \pi R_{m/m}. \quad (3)$$

This dimension will be applied as the mirror/mist boundary crack length later in this manuscript.

3. The crack velocity at the mirror/mist boundary

At a previous fractography meeting at Stara Lesna in 2001, Richter[13] reported measurements of the crack velocity in soda lime glass in the mirror region. He used the stress wave fractography technique that he developed with Kerkhof and which is reported in detail by Kerkhof and Richter,[14] Richter[13] determined the crack velocity from fracture surface stress wave modulations on the fracture surface and reported the results in the form of a K_I–V diagram. Results are reported in Fig. 4 with the location of the mirror/mist boundary noted by the arrow marked mist at about $K_I = 2.10$ MPa m$^{1/2}$ and with the stress wave modulations visible just beyond the value of K_{IC} for this soda lime silicate glass of ∼0.75 MPa m$^{1/2}$ on the ordinate.

There are several important points about these crack velocity measurements by Richter.[13] Once fast crack growth initiates at K_{IC}, then as indicated by the logarithmic velocity scale, the crack accelerates very rapidly and asymptotically to the terminal velocity before it reaches the familiar mirror/mist boundary. Although the logarithmic scale makes it difficult to exactly ascertain the velocity at that point, the terminal crack velocity has been considered by a number of different authors, including Schardin