Journal of Non-Crystalline Solids 443 (2016) 172–183

Contents lists available at ScienceDirect

Journal of Non-Crystalline Solids

journal homepage: www.elsevier.com/locate/jnoncrysol

Sub-micron fracture mechanism in silica-based glasses activated by permanent densification from high-strain loading☆

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ARTICLE INFO

Article history:
Received 25 February 2016
Received in revised form 8 April 2016
Accepted 15 April 2016
Available online 26 April 2016

Keywords:
Silica-based glasses
High-strain-energy fracture
Densification
Fragmentation
Microkernels

ABSTRACT

Several silica-based glasses were fractured at high strain energy via drop-weight testing on small specimens. A cylindrical specimen geometry was chosen to promote initially simple, axisymmetric, and uniform compressive loading. The imposed uniaxial compressive strain at impact was sufficiently high to qualitatively cause permanent densification. Produced fragments were collected for postmortem and a fraction of them, for all the silica-based glasses, consistently had distinct sub-micron-sized fractures (~300–1000 nm), designated here as "microkernels", on their surfaces. They would most often appear as a sub-micron pore on the fragment - apparently if the microkernel had popped out as a consequence of the local crack plane running through it, tensile-strain release, and the associated formation of the fragment it was on. No fractographic evidence was found to show the microkernels were associated with local failure initiation. However, their positioning and habit sometimes suggested they were associated with localized crack branching and that they could have influenced secondary fracturing that occurred during overall crushing and comminution and associated fragment size and shape creation. The size range of these microkernels is much too small to affect structural flexure strength of these glasses for most applications but are of a size and concentration that may affect their ballistic, shock, crush, and comminution responses when permanent densification is concomitantly occurring.

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1. Introduction

The mechanical response of glasses or ceramics used in armor systems from a ballistic impact is a complex consequence of many independent properties and geometrical parameters of both the target and projectile materials. That response in the target materials is influenced by fracture and plastic-like deformation processes that are functions of time and continually-changing, high-magnitudes of multiaxial stress states caused by the projectile's impact energy and any penetration. Shock propagation into the target, and its potentially-induced damage, is occurring concurrent with that project-target interaction.

Primary and post-primary fracture in brittle materials that occurs during either simple uniaxial or multiaxial loading are consequences of the imposition of sufficiently high First Principal tensile stresses and those tensile stresses exceeding some definition of tensile strength for that material. For predicting ballistic response of armor systems containing glasses or ceramics, modelers utilize an inputted tensile strength that is an important parameter for accounting for fracture processes within those brittle materials.

In a recently completed study by one of the authors [1], the internally initiated fracture of a borosilicate glass, caused by shock (a localized, yet high-strain-energy event), was examined along with the modeled estimation of the tensile stress associated with its formation. An image of that internally generated crack is shown in Fig. 1. That estimated tensile failure stress, assuming a material elastic response, was large - approximately 1.2 GPa. With the exception of some strengthened glasses, that 1.2 GPa failure stress is nearly an order of magnitude higher than the (tensile) failure stress of almost all commonly used silicate glasses fractured in bending.

It follows that the estimated (internal) flaw associated with a 1.2-GPa-failure in glass must be very small. The calculated, quasi-statically-generated Griffith flaw size [2] is ~600 nm using that tensile failure stress value, a reasonable fracture toughness of borosilicate glass of 0.75 MPa√m, and a stress intensity shape factor of 1.13 for a volume-located circular flaw [3]. Its size will be smaller if a (more likely) non-circular-shaped flaw was the tensile-stress-limiter with a lower bound of ~250 nm [3]. In contrast, the size of a half-penny surface crack limiting the same glass to 100 MPa in bending (which is a

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☆ This research was performed at the Oak Ridge National Laboratory (ORNL) and sponsored by Purdue University under the Material Science and Technology Division, Work-for-Others (WFO) Program, IAN: 14B658801, and DOE agreement: NFE-10-03121, with the U.S. Department of Energy. Additional support provided by the US Army Research Laboratory through Contract W911NF-14-2-0015 at the University of Tennessee.

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http://dx.doi.org/10.1016/j.jnoncrysol.2016.04.029
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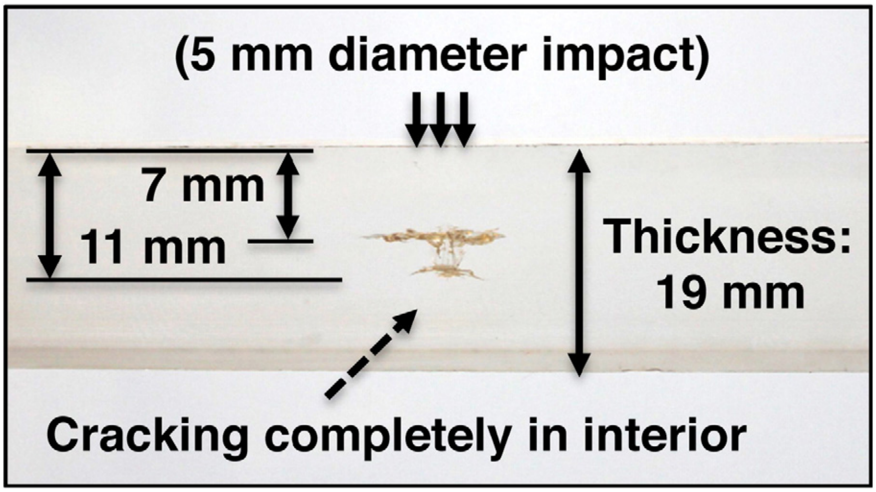

Fig. 1. Generated internal cracks in Borofloat glass resulting from laser shock.

relatively high bend strength for non-strengthened silica-based glasses) would be two orders of magnitude larger (~70,000 nm).

The fracture morphology of the 7-mm-deep lateral crack in Fig. 1 produced several interesting observations. It was carefully refractured to enable microscopy to be conducted directly and orthogonally on that lateral crack system. Several scanning electron microscopy (SEM) images of such are shown in Fig. 2. An unexpected tempered-glass-like fracture habit existed over approximately a 1-mm-diameter, and is shown in Fig. 2(a). There were multiple locations of failure initiation. The shock pulse was only a few nanoseconds in duration, and for a terminal crack propagation speed of ~1900 m/s, a crack would propagate about 10 μm in that time. Therefore there is a likelihood that multiple failure initiation sites could have occurred. Two observations are highlighted and shown in Fig. 2(b)–(d). Several discrete mirrors were evident in the microstructure shown in Fig. 2(a)–(b). An example of one shown in Fig. 2(c) with a calculation of the local stress using the estimated mirror radius size [4]. Its stress was estimated to be 1.7 GPa which is high like what was estimated from modeled tensile stress [1], but other measurements calculated a range of stresses down to approximately 900 MPa. The flaw at the center of the mirror radius in Fig. 2(c) could not be identified; however, its Griffith flaw size associated with 1.7 GPa is a few hundred nanometers. An example of a seam of localized heterogeneities, designed here as "microkernels" and shown in Fig. 2(d), were also observed within this microfracture region. Their presence appears to be associated with the front of a localized crack propagation bifurcation. Their size, perhaps not coincidentally, is equivalent to the approximated Griffith flaw size calculated for the example in Fig. 2(c).

The initial motivation of the present study was to determine if these microkernels could be exposed for further examination through (easier-to-conduct and less expensive) quasi-static fracture produced at high-strain energies. Several silica-based glasses were fractured at room temperature via drop weight testing onto small cylindrical specimens. The estimated imposed compressive strain at impact exceeded 1%. The

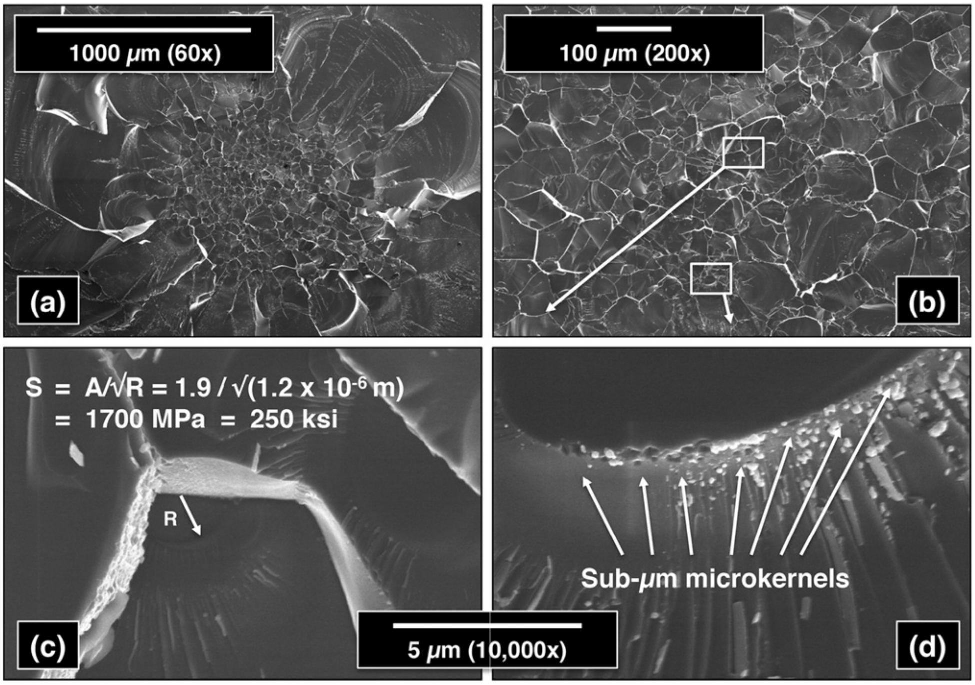

Fig. 2. Fracture morphology of the 7-mm-deep lateral crack shown in Fig. 1. Low magnifications (a) and (b) with zoomed in region showing (c) one of the many fracture mirrors, and (d) a seam of microkernels located where a local crack deflection had occurred. Shock wave direction was perpendicular to this surface.

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