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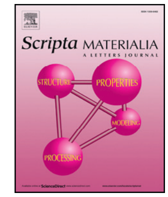

Glass fracture by focusing of laser-generated nanosecond surface acoustic waves

David Veysset [a,b,*], Steven E. Kooi [a], Ryadh Haferssas [a,c], Mostafa Hassani-Gangaraj [d], Mohammad Islam [a,c], A.A. Maznev [a,b], Yevheniia Chernukha [e], Xiaoguang Zhao [f], Keiichi Nakagawa [g,i], Dmitro Martynowych [a,b], Xin Zhang [f], Alexey M. Lomonosov [h], Christopher A. Schuh [d], Raul Radovitzky [a,c], Thomas Pezeril [d], Keith A. Nelson [a,b]

[a] *Institute for Soldier Nanotechnologies, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[b] *Department of Chemistry, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[c] *Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[d] *Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[e] *Institut Molécules et Matériaux du Mans, UMR CNRS 6283, Université du Maine, 72085 Le Mans, France*
[f] *Department of Mechanical Engineering, Boston University, Boston, MA 02215, USA*
[g] *Department of Bioengineering, The University of Tokyo, Tokyo 113-8656, Japan*
[h] *Prokhorov General Physics Institute RAS, Moscow, Russia*
[i] *Department of Precision Engineering, The University of Tokyo, Tokyo 113-8656, Japan*

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ABSTRACT

Dynamic fracture of borosilicate glass through focusing of high-amplitude nanosecond surface acoustic waves (SAWs) at the micron scale is investigated in an all-optical experiment. SAWs are generated by a picosecond laser excitation pulse focused into a ring-shaped spot on the sample surface. Interferometric images capture the SAW as it converges towards the center, focuses, and subsequently diverges. Above a laser energy threshold, damage at the acoustic focal point is observed. Numerical calculations help us determine the time evolution of the stress distribution. We find that the glass withstands a local tensile stress of at least 6 GPa without fracture.

The dynamic fracture of glassy materials is of great importance for a wide range of technologic applications, from cracked mobile device screens or car windshields hit by rocks on the road to the International Space Station's windows subjected to space debris impacts [1]. Glasses, despite being intrinsically among the strongest man-made materials, are vulnerable through their defects, which can reduce the static tensile strength by orders of magnitude [2]. While the theoretical tensile strength limit of silica glass is about 20 GPa [3], experimentally-measured static tensile strength can be as low as 0.1–0.2 GPa in bulk specimens [4]; in nanoscale specimens that sample few or no flaws much higher tensile strengths exceeding 10 GPa can be measured [5]. When dealing with high strain rate situations (e.g. an impact of a micrometeorite on a spacecraft), static material properties offer only limited insight into materials resistance to crack initiation and propagation [6]. Dynamic fracture of silicate glasses on the microsecond time scale has been extensively studied in shock spallation experiments under plate [7–10] or laser-induced shock [11]. These measurements, in which spallation is caused by tensile stresses in release waves, reveal a much higher tensile strength under dynamic loading, typically in the few GPa range. For example, the reported spall strength of soda lime glass ranges from 2.2 to over 5 GPa [7,9,11]. The interpretation of tensile strength measurements in plate impact experiments is complicated by the fact that the material is initially subjected to compression; above ~4 GPa many studies report an apparent structural degradation under compression ("failure waves") [8–10,12–14], which reduces the subsequently measured tensile strength on release. It is evident that the dynamic strength of glass is not a material constant; rather, it depends on the duration of the tensile stress and on the entire loading history. Whereas laser shock experiments on metals such as aluminum and copper [15] indicate that under very short (sub-nanosecond) shock pulses, the spall strength approaches the theoretical limit for those materials, it remains an open and practically relevant question whether the theoretical limit can be approached for silicate glasses.

In this work, we describe a methodology for studying glass failure on the nanosecond time scale using focusing laser-generated surface acoustic waves (SAWs). High amplitude SAWs have already been

* Corresponding author at: Institute for Soldier Nanotechnologies, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.
E-mail address: dveysset@mit.edu (D. Veysset).

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proven capable of causing fracture in brittle materials [16,17]. In those prior works [16,17] fracture was caused by the formation of "surface shock waves" accompanied by a sharp increase of the stress at the surface; the measurements could only provide a lower bound estimate of the peak stress value. In a recent study [18], we proposed an alternative approach, based on focusing SAWs. The short SAW propagation distance (100 μm) prevents shock front formation, and the high stress that occurs where the SAWs are focused is essentially achieved in the linear elastic regime. These measurements are very different from traditional shock spallation studies in that the tensile phase of the SAW pulse lasts only a few nanoseconds and is not preceded by a significant pre-compression. In experiments on gold-coated glass, we observed failure of the gold coating and, at higher laser energies, of the glass substrate. However, the early failure of the gold layer prevented measurements of the SAW pulse profile at high amplitudes and complicated the interpretation of the observations of the glass damage. In the current work, we report experiments in a modified arrangement, wherein a gold coating is still used to generate SAWs but their focusing occurs on a bare glass substrate. Above a certain SAW amplitude threshold, glass failure at the focal point and the formation of a crater due to the ejection of the fractured material are observed. Numerical calculations matching experimentally measured displacement profiles in the focused SAW allow us to characterize the dynamics of the stress distribution in the sample.

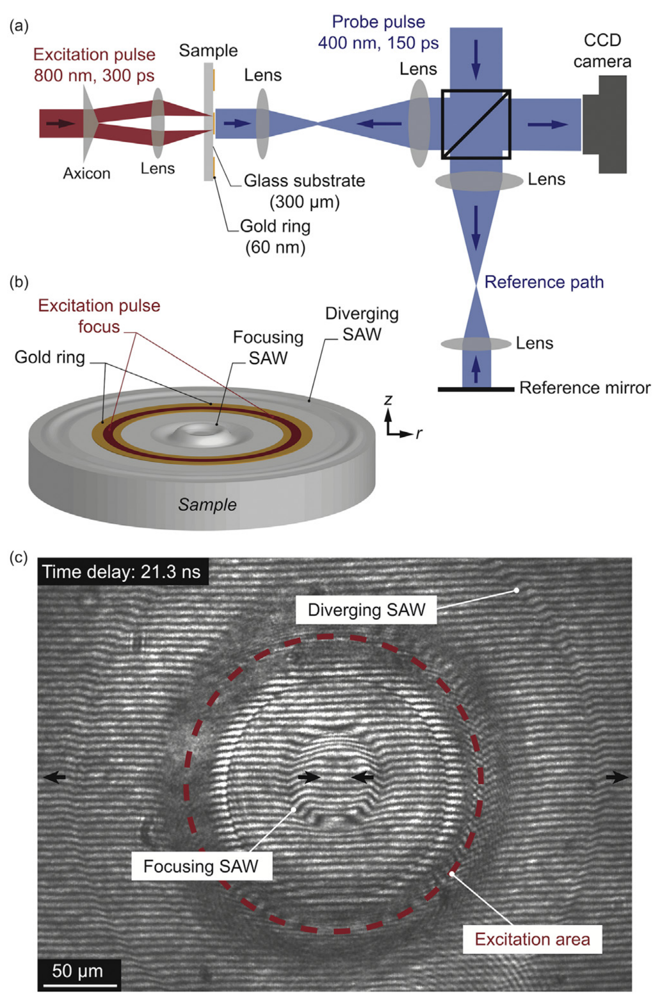

Fig. 1. (a) Experimental setup. The excitation beam is shaped as a ring with an axicon/lens combination. Interferometric imaging is achieved using a Michelson interferometer. (b) Schematic of the sample configuration. The excitation pulse is focused on the gold ring, generating focusing and diverging surface acoustic waves. (c) Interferometric image showing surface displacement caused by focusing and diverging SAWs. This image was taken for a laser energy of 0.25 mJ with a delay of 21.3 ns between the excitation and the probe pulses. Thedashed ring indicates the laser excitation area. Circular fringes appearing at the bottom of the image comes from a defect on one of the imaging optics. See supplementary material for images taken before laser excitation and post mortem.

The experimental setup, shown schematically in Fig. 1, follows the design developed by Veysset et al. [18]. A laser excitation pulse, derived from a Ti:sapphire amplifier, with a 300-ps duration, 800-nm wavelength and adjustable energy (from 0.15 mJ to 1.50 mJ), was focused onto the surface of a 300 μm-thick borosilicate glass substrate (D263 Schott) to ablate a 160 nm-thick metallic ring. The metallic ring, henceforth referred to as the gold ring, consisted of 10-nm chromium, in contact with the glass, and 150-nm gold. The gold ring had an inner diameter of 160 μm and an outer diameter of 240 μm (see supplementary material for sample fabrication). The laser focus was shaped as a 200 μm-diameter, 5 μm-wide ring using a 0.5° conical prism (axicon) and a 3 cm focal-length lens, as described by Pezeril et al. [19] and Veysset et al. [20,21] Multiple rings were fabricated on the same substrate and the sample was translated to move the laser focus to a new ring for each laser shot, with the laser focus and ring overlapping as in Fig. 1b each time. Imaging of the sample surface was achieved using a variably-delayed, 150-fs duration probe pulse reflected from the surface of the sample. The probe pulse, derived from the same amplifier system, was frequency-doubled to 400-nm wavelength. Interference fringes of equal thickness obtained using a Michelson interferometer configuration were recorded by a CCD camera.

For each laser shot, stress waves were produced following ablation—therefore destruction—of the metallic film and a single image was recorded with a set time delay between the excitation and the probe pulses. Because of the ring shape of the excitation, focusing and diverging surface waves were generated and propagated on the surface of the bare glass (see Fig. 1b and c). Bulk waves were also generated but were not imaged in the present configuration. As the surface was displaced under SAW propagation, the phase of the reflected pulse shifted (the phase shift is denoted as $\Delta\varphi$) causing fringes to shift on the CCD image (see Fig. 1c). By measuring the fringe shift, we could determine the corresponding out of plane surface displacement $u_z(r)$ through the relationship $u_z = \lambda\Delta\varphi/4\pi$, where $\lambda = 400\ nm$ is the probe pulse wavelength. After each shot, the sample was positioned to a new ring and different time delay and laser energy could be set.

We recorded images such as that shown in Fig. 1c for multiple time delays and laser energies and extracted the surface displacements along a ring diameter. More details regarding the image analysis can be found in Veysset et al. [18]. Fig. 2a presents surface displacement profiles showing the propagation of the focusing SAW for 7 delays at a laser energy of 0.25 mJ, corresponding to a laser fluence of 4.5 J/cm^2. The SAW focused around 30 ns after being generated and subsequently diverged. Fig. 2b shows the surface displacements obtained for a laser energy of 0.75 mJ. Around this laser energy, the image quality was degraded at longer times and the surface displacements closer to the focus or right after the focus could not be accurately extracted. Fig. 2c shows the peak-to-peak amplitude of the SAW taken at a delay of 12.7 ns for varying laser energies and shows that the SAW amplitude started to saturate at laser energies above 1 mJ.

In our previous work, with the same experimental design but with the sample surface uniformly coated with a gold film, the large amplitude of the SAW at the focal point caused delamination and damage of the film at low laser energy (~0.1 mJ) and glass substrate fracture at high laser energy (~2 mJ) [18]. The film damage obscured the imaging of the SAW at higher laser energies making it impossible to evaluate the absolute surface displacements leading to glass fracture. Here, with no metal film inside the ring, we observe surface displacements even at high laser energies and, after sample examination under laser-scanning confocal microscope and atomic force microscope, can confirm visible glass fracture at laser energies above 0.75 mJ. The substrate visibly fractured at the center in about 10% of the cases for a laser energy of 1.00 mJ and in 100% of the cases for a laser energy of 1.50 mJ (see Fig. 2c,