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More on the behavior of soda lime glass under shock loading

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Abstract

A series of plate impact experiments with soda-lime glass specimens was performed in order to further investigate the complex behavior of this material in the 0–8 GPa range of shock loading. Using commercial manganin gauges we followed the stress histories and their different shapes as the stresses increase from 3.5 to about 8.0 GPa. In particular, we find that there are meaningful differences between the shapes of these signals at pressures below about 4.0 GPa, in between 4.0 and 6.0 GPa and above 6.0 GPa. We also gather more data on the fractured glass behind the fracture wave front, from our measured stress histories, and offer a new way to determine the Hugoniot elastic limit of this material, as well as other brittle solids.

Keywords: Fracture waves; Soda lime glass; Manganin gauges; Hugoniot elastic limit

1. Introduction

The dynamic response of soda-lime glass (SLG) to shock wave loading has been investigated for several decades by many researchers (see for example [1–5]). The scientific interest in this material has been considerably increased since the discovery of the fracture wave (FW) phenomenon in SLG by Razorenov et al. [6], using free-surface velocity measurements. The effect of this slow-moving front on the shear and spall strengths of the glass has been quantitatively determined by using manganin gauges, as shown in [7,8], respectively. The recent articles [9–11] cover much of the data accumulated in the last decade and it is clearly evident that there are still some discrepancies between the data of different workers and their interpretations. These controversies are the result of the complex behavior of SLG in the 0–10 GPa range of shock pressures where elastic and inelastic waves are followed by the FW fronts. In the works of Kanel et al. [9,10], several glass plates, glued together, were used to separate these waves and find better estimates for the stress ranges where these different response modes take place in the glass. The work of Grady and Chhabildas [5] highlights the complexity of the SLG behavior in the 4–7 GPa range, and in the work of Simha and Gupta [11] an effort is made to account for this behavior with a time-dependent constitutive model.

The purpose of the work presented here was to further investigate the behavior of SLG in the 0–8 GPa range in order to shed more light on these peculiarities and, hopefully, to dissolve some of the controversies that appeared in the above cited works.

2. Experimental

Soda lime glass specimens 5–10 mm thick were used as target plates that were impacted by either SLG or aluminum flyer plates in our 64 mm single-stage gas gun. The density of these plates is 2.5 g/cm^3 and their longitudinal sound speed is 5.8 mm/μs. Manganin stress gauges (manufactured by Micro-Measurements) were embedded in the targets and impact velocities were measured (to within 1%) with thin shorting pins. Manganin gauges were calibrated in our lab under both loading [12] and unloading conditions [13]. These gauges are encapsulated in a relatively thick (50 μm) glass-reinforced epoxy resin that creates an interlayer of about 60–80 μm of a soft material around the gauge when it is embedded between two specimen plates. This layer affects the rise time of gauge

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response and, as a result, some of the more important features of the stress wave are lost through a stress reverberation process in this interlayer. In order to overcome this difficulty we embedded the gauges, in most of our experiments, at the back of the SLG specimen to which a thick polymethylmetacrylate (PMMA) backing plate was glued. As the acoustic impedance of PMMA is very close to that of the epoxy encapsulation, the stress reverberations on the rising part of the trace are eliminated. Thus, the inherent features of glass response are not distorted by gauge embedment. This back-surface gauge configuration is also ideal to study the FW properties through its interaction with the release wave propagating back to the specimen right after the shock wave reaches the SLG–PMMA interface.

The two configurations (fully embedded and back surface gauge) are shown schematically in Fig. 1. One should note that with the back-surface technique we measure the stresses entering the PMMA backing rather than those in the specimen, and a correction factor has to be used if one is interested in the actual shock stress traversing the SLG specimen. This correction factor α is given by the following expression:

$$\alpha = (Z_1 + Z_2)/2Z_2 \quad (1)$$

where Z_1 and Z_2 are the acoustic impedances of glass and PMMA, respectively. These impedances are easy to calculate for the elastic range of the relevant materials, but are more difficult to define in case that the shock wave in glass is beyond its elastic limit. For the elastic range of glass we find that α is about 2.3 and we shall use this value also for stresses just above the elastic limit.

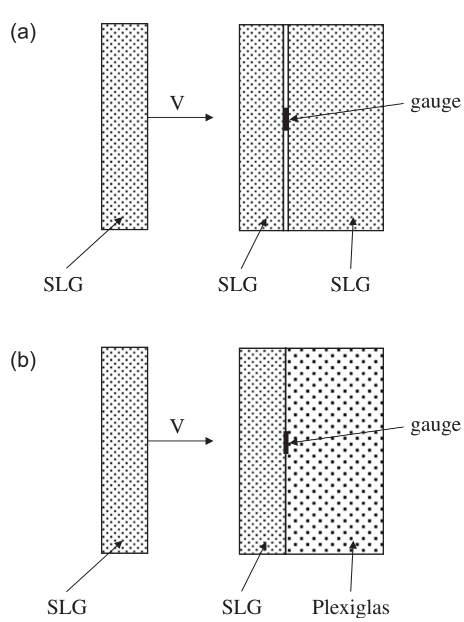

Fig. 1. The two experimental configurations: (a) fully embedded gauge and (b) back-surface gauge.

3. Results and discussion

3.1. Back-surface gauges

As mentioned above, most of the experiments in this study were performed with the back-surface technique. Fig. 2a shows schematically the shock and FWs in glass and the interaction of the release wave (from the glass/Plexiglas interface) with the slow FW front. This interaction is manifested by the recompression signal measured by the gauge, as shown schematically in Fig. 2b. Our first aim was to confirm the published value of about 4.0 GPa for the stress threshold of FW initiation in soda-lime glass (see [10,11], for example). We performed two symmetric experiments at impact velocities of 520 and 650 m/s, which resulted in stresses around 4 GPa in the glass, respectively. Fig. 3 shows the resulting gauge traces from these experiments. Using the value of $\alpha = 2.3$ we find that the shock levels in the glass in these experiments were 3.9 GPa and about 4.5 GPa. One can clearly see the reflected recompression in the higher shock trace (about 1.2 μs after shock arrival), which is a clear indication for the FW front moving behind the main shock. The timing of this recompression determines the velocity of the FW front, if one assumes that it originates at the impact plane at the instant of impact. We find a value of 1.43 mm/μs for the

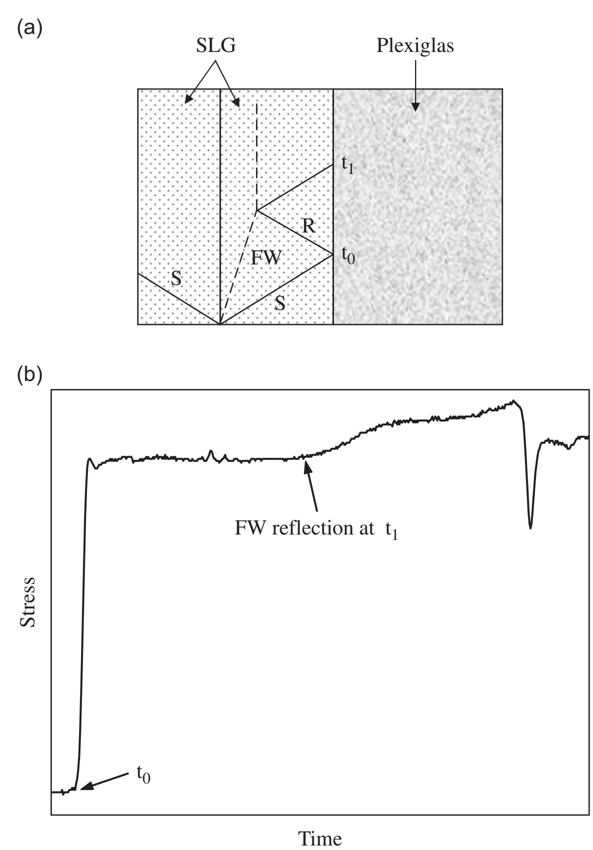

Fig. 2. (a) Schematic x–t diagram for the back-surface gauge. (b) The resulting stress record including the recompression signal.