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Soda-lime Glass Behavior Under Laser Shock

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Abstract. Understanding and modeling the behavior of glass is an issue for certain aeronautical, military and civil applications. For example, parts of satellites and shuttles are made of glasses. During their lifetime, they are subjected to potentially damaging high velocity impacts. To determine the behavior of these structures during and after impact we used instrumented laser driven shock loading performed on high power intensity laser facilities. Transverse shadowgraphs of the front wave propagating inside the transparent material are collected at different times. These shadowgraphs provide information regarding the shock wave velocity. PDV or VISAR measurements provide time-resolved free surface velocity to determine material velocity when the shock wave breakout occurs. For some laser shots, shock wave corresponds to elastic wave then Hugoniot elastic limit may be determined. Under high pressure conditions glass permanently densifies and traces of such a plastic deformation are looked for on the path of the shock wave. Those experimental data are necessary to characterize the material behavior under such conditions and to model the mechanical behavior of glass structures. In this presentation we will present experimental results obtained for soda-lime silica glass samples loaded by laser induced shock.

INTRODUCTION

Glasses such as fused silica, soda-lime,... are a part of our everyday lives. These materials appear in electronics, housing, windshields of vehicles like cars, planes. They may also be found in less common applications such as laser driven shock experiments like Inertial Confinement Fusion (ICF), where optical devices or windows of vacuum chambers can be damaged by high velocity metallic solid or liquid fragments produced by spallation or micro-spalling [1]. In aerospace applications, shuttle windows and solar panels of satellites may be impacted by high-speed debris such as micro-meteorite or pieces of broken satellites [2]. These high velocity impacts are characterized by high strain rate. To assess and reduce risks of damage that may cause the destruction of the structure, the behaviors of glass under high strain rate conditions must be predicted by models relying on experimental data.

In this context, we have conducted experimental investigations of soda-lime glass behavior under laser driven shocks. Experimental diagnostics include Photonic Doppler Velocimetry (PDV) and Velocity Interferometer System for Any Reflector (VISAR) techniques to measure free surface velocity of glass samples and transverse optical shadowgraphy to observe shock and release waves propagation in the transparent target. These techniques provide complementary results which allow for the measurement of both the shock wave and material velocities and the Hugoniot Elastic Limit (HEL), which is useful for the development and validation of models devoted to multi-scale simulation (e.g. Dynamic Molecular, Discrete Element Method, Finite Element Method).

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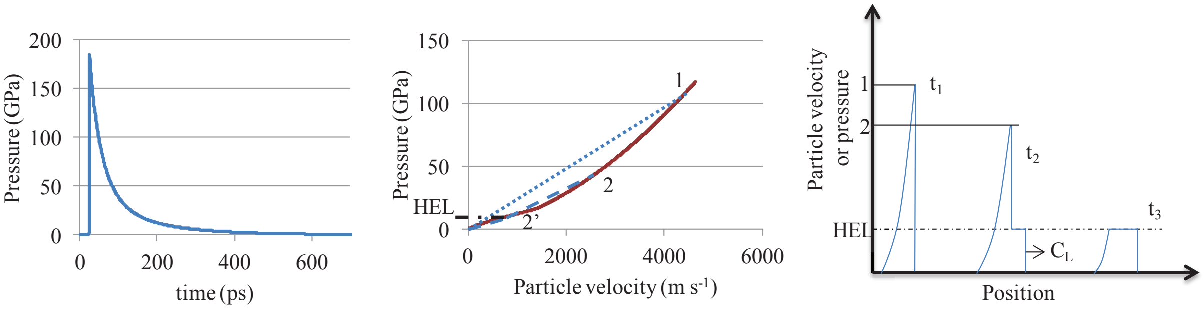
EXPERIMENTAL PROCEDURE

Laser shots have been performed in the Laboratoire pour l'Utilisation des Lasers Intenses (LULI, UMR 7605, Ecole Polytechnique, Palaiseau, France) on the ELFIE facility. The samples are 160 to 2800 µm-thick soda-lime glass with a density of ρ=2.512 g cm^{-3}. An aluminum layer is deposited both at the irradiated face of the glass sample as an ablator for the laser-matter interaction and at the opposite face as a reflective surface for VISAR measurement. The thickness of these layers is about 1 µm. A high power pulsed laser beam of 1.06 µm wavelength, 350 fs duration, and 10 J maximum energy is focused onto the target. The irradiated spot is circular with a diameter of 1.3 mm. The setup is placed in a vacuum chamber to avoid laser breakdown in air before reaching the target surface. The laser irradiation causes the vaporization of the thin layer of aluminum into a plasma cloud, which expansion toward the laser source induces a compressive pulse into the solid target.

A skew PDV system [3, 4, 5] and VISAR [6] device allow time-resolved measurement of the velocity of the free surface, the one opposite to the loaded surface. Transverse shadowgraphy [7] provides successive images of the shock wave propagation into the thicker transparent samples [8], which allows us to estimate the mean velocity of the shock wave. This technique also allows for the observation of the expanding cloud of debris coming out from the back face of thinnest targets damaged under laser shock. Acquisition time is 5 ns for each image in order to avoid any motion blur. The amplitude of the pressure load and its temporal shape are inferred from one-dimensional computation of laser-matter interaction, using the measured laser intensity profile as an input for the Lagrangian code ESTHER developed by the CEA.

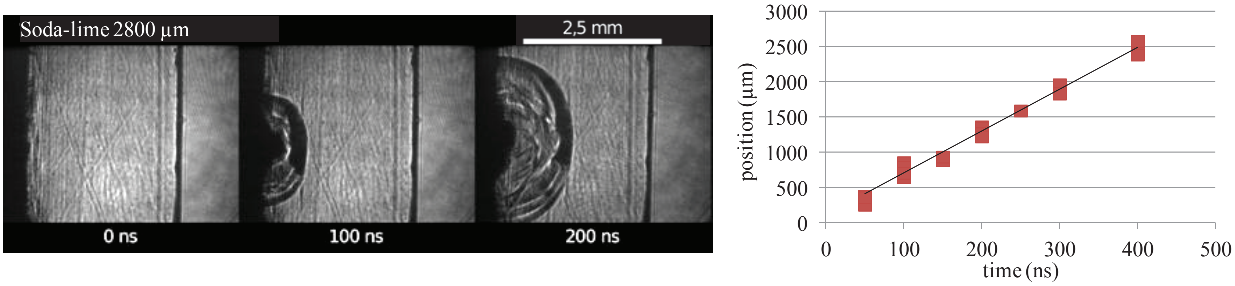
RESULTS AND DISCUSSION



(a) (b) (c)

FIGURE 1. (a) Temporal shape of a pressure load corresponding to a 0.160 PW cm^{-2} intensity laser shot. (b) Hugoniot curve (in red) of the soda-lime glass from the de Resseguier model [9]. The dotted line represents the Rayleigh curve from initial state (0) to a stable state (1). The dashed line represents the Rayleigh curve for an unstable shock from the initial state (0) to the final state (2) via the HEL state (2'). (c) Schematic spatial shapes of the pressure load in glass sample at three successive times.

Figure 1 (a) shows the temporal shape of the pressure load inferred from the ESTHER computation code. The pressure pulse, about 180 GPa in magnitude, corresponds to a 0.160 PW cm^{-2} intensity laser shot. The shock wave is followed by a progressive release. For all experiments, intensities of laser shots are above 0.160 PW cm^{-2}. Thus, corresponding pressure loads near the irradiated surface are higher than 180 GPa. These pressure states are in the stable part of the Hugoniot curve of glass where pressure is about the one of the state 1 represented on the Fig. 1 (b). In the first micrometers from the irradiated surface, the shock wave is stable and spreads into the sample. The corresponding spatial shape is schematically represented in Fig. 1 (c) at t_1 time. The release wave, faster than the shock wave, quickly softens the pressure load. It reaches the unstable part of the Hugoniot curve around the state 2 represented on the Fig. 1 (b). The shock wave then splits up into two waves. The first wave is the elastic precursor, which propagates at the C_L velocity. In the case of 1D shock wave propagation, this wave brings the matter from the initial state to the Hugoniot Elastic Limit (state 2' on the Fig. 1 (b)). The elastic wave is followed by a plastic shock wave, which transforms the sample from the state 2' to the maximum pressure state around state 2. These waves are always followed by the release wave that spreads slower than the elastic precursor but faster than the plastic wave. The corresponding spatial shape is schematically represented in Fig. 1 (c) at t_2 time. Finally, the release wave softens the plastic wave. The triangular initial shock wave becomes an elastic wave represented in Fig. 1 (c) at t_3 time.

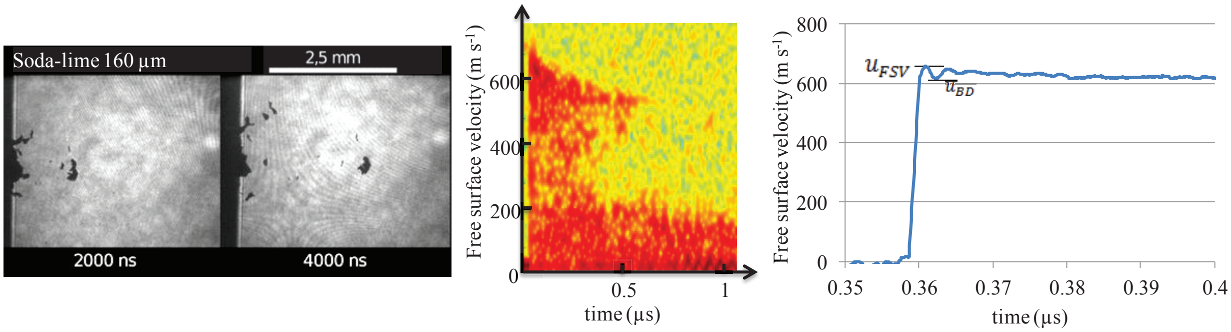


(a) (b)

FIGURE 2. (a) Time resolved shadowgraphy of the shock wave propagation at 0 ns, 100 ns and 200 ns into a 2.8 mm-thick soda-lime glass sample subjected to a 1.87 PW cm^{-2} intensity laser shot. (b) Diagram of the shock wave position versus time into soda-lime samples subjected to 1.7 PW cm^{-2} intensity laser shots.

As explained above, a shock wave produced by a femtosecond laser shock quickly becomes an elastic wave. Below the HEL, the velocity c_L of all waves is constant. The evolution of the position of the waves versus time allowed to determine this velocity. Figure 2 (a) presents shadowgraphs of a 2800 µm-thick soda-lime glass sample subjected to a 1.87 PW cm^{-2}-intensity laser shock. The first picture represents the sample before the laser shot, the second and the third ones are taken at 100 ns and 200 ns after the arrival of the laser on the target respectively. Several laser shots at a laser intensity of about 1.7 PW cm^{-2} were performed; the systematic position measurement of the elastic wave versus time is reported in Fig.2 (b). The slope of the line corresponds to the elastic wave velocity c_L=5970 m s^{-1} as measured by conventional means such as ultrasonic echography.

For the laser shots on 2.8 mm-thick samples, the thickness of the sample is larger than the diameter of the laser spot on the irradiated surface. Thus, the shock wave becomes spherical during its propagation and cannot be considered as a 1D shock anymore. To determine the HEL with the Rankine-Hugoniot equations and particularly the momentum conservative equation (Eq. 1), similar experiments have been performed on much thinner, 160 µm-thick soda-lime glass samples. This thickness allows us to disregard such 2D effects that could come from the radial energy distribution and is sufficient to decay the pressure profile of the shock wave that becomes an elastic wave due to the following release wave effect. Velocity of the free surface has been measured and is shown in Fig. 3 (b). The maximum free surface velocity when the shock breaks out allows us to determine the HEL.



(a) (b) (c)

FIGURE 3. (a) Shadowgraphs showing flying debris of aluminum at 2 µs and 4 µs after the beginning of the irradiation of the front face of the target and corresponding PDV (b) and VISAR (c) measurements of the aluminum layer and debris ejected from a 160 µm-thick soda-lime glass sample subjected to a 0.160 PW cm^{-2}-intensity laser shot.

When the elastic wave breaks out at the free surface of the sample, the aluminum layer starts moving at u_{FSV}=643 m s^{-1}. This value corresponds to twice that of the glass behind the incident 1D elastic wave. The HEL may be determined with the momentum conservative equation through the following equation (Eq. 1):

$$P_{HEL} = \rho c_L \frac{u_{FSV}}{2} = 4.8\ GPa \tag{1}$$

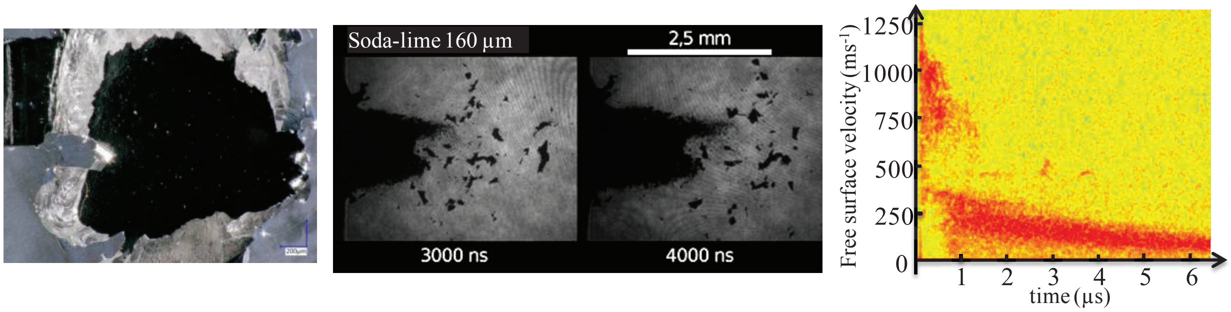
where ρ is the glass density, c_L is the longitudinal elastic wave velocity and u_{FSV} is the velocity of the free surface when the shock wave breaks out. The 4.8 GPa value is consistent with the ones quoted by Alexander [10].

When the shock wave breaks out at the free surface, a release wave goes back into the sample. The interaction between this reflected release wave and the incident unloading wave generates tensile stresses near the Al/glass interface that initiate separation of the aluminum layer. The strength leading to Al/Glass debonding can be determined using Eq. 2.

$$\sigma_R = \rho c_L \frac{u_{FSV} - u_{BD}}{2} = 0.3\ GPa \tag{2}$$

where ρ is the aluminum density, c_L is the sound wave velocity in aluminum and u_{BD} is the velocity of the free surface when the aluminum layer reaccelerates. The debonding strength is lower than the spall strength of the glass [11]. In this configuration, and due to the loss of reflectivity of the free surface reflectivity, the spall strength cannot be determined for higher intensity laser shots.

Nevertheless, for powerful laser shots, thin glass targets are perforated and glass is sprayed (Fig. 4 (a)). An expanding cloud of debris is observed (Fig. 4 (b)). The distribution of velocities is measured (Fig. 4 (c)) and will be used to validate the fragmentation model. Highest velocities between 750 m s^{-1} and 1250 m s^{-1} correspond to aluminum debris followed by slower glass debris gradually ejected at less than 300 m s^{-1}.



(a) (b) (c)

FIGURE 4. Optical observation (a), shadowgraphs (b) showing flying debris of aluminum and glass at 3 µs and 4 µs after the beginning of the irradiation of the front face of the target, and PDV measurement (c) of debris ejected behind a 160 µm-thick soda-lime glass subjected to a 1.78 PW cm^{-2}-intensity laser shock.

CONCLUSION

The dynamic behavior of soda-lime glass under laser shock condition has been investigated with complementary diagnostics. The elastic wave velocity is about 5970 m s^{-1}, as determined with transverse observation of the shock wave propagation in thicker samples. The HEL, about 4.8 GPa, is calculated from the free surface velocity measured with VISAR. PDV measurements and post mortem observation of samples and debris recovered will allow us to study fragmentation process and validate models.

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