Experimental investigation of the shearing resistance of SODA-Lime glass at pressures of 9 GPa and strain rates of $10^6 s^{-1}$

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Experimental Investigation of the Shearing Resistance of Soda-Lime Glass at Pressures of 9 GPa and Strain Rates of $10^6 s^{-1}$

T. Jiao[1, a)], C. Kettenbeil[2, b)], G. Ravichandran[2, c)] and R.J. Clifton[1, d)]

[1]*School of Engineering, Brown University, Providence, RI 02912, USA*

[2]*Division of Engineering and Applied Science, California Institute of Technology, 1200 E California Blvd, Pasadena, CA 91125, USA*

[a)]Corresponding author: Tong_Jiao@Brown.edu
[b)]ckb@caltech.edu
[c)]ravi@caltech.edu
[d)]Rodney_Clifton@Brown.edu

Abstract. Pressure-Shear Plate Impact (PSPI) experiments were conducted to measure the high-rate shearing resistance of soda-lime glass at pressures of 9 GPa and at shearing rates of approximately $10^6 s^{-1}$. Samples of soda lime glass, 5 μm thick, were sandwiched between pure tungsten carbide (WC) plates and impacted by pure WC flyers. Impacting plates were inclined to the direction of approach by an angle of 18º. Normal stress and shearing resistance of the sample were calculated from measured free surface velocities using 1D elastic wave theory. The experimental results show that, at a pressure of 9GPa, the shear stress increases almost linearly up to 1 GPa and then falls quickly to approximately 0.3 GPa — after which it decreases slowly to approximately 0.17 GPa. Comparisons with results of previous experiments on nominally identical samples, impacted to generate lower peak pressures, showed the peak shearing resistance to be much higher at higher pressures; however, the sharp fall in shearing resistance occurs at comparable shear strains (1.5-2).

INTRODUCTION

Experimental results have shown that at high pressures silica glass appears to transform from its amorphous state to crystalline stishovite [1]. As a first step in understanding the shearing resistance of soda-lime glass at higher pressures, Pressure-Shear Plate Impact (PSPI) experiments were conducted on this glass at pressures of 9 GPa and at shearing rates of approximately$10^6 s^{-1}$. These pilot experiments are part of a larger collaborative effort to investigate shearing resistance and phase transformations in soda-lime glass at much higher pressures, say greater than 50 GPa.

PSPI EXPERIMENTS

The setup of PSPI experiments is shown in Figure 1. A thin sample of soda-lime glass is sandwiched between pure tungsten carbide (WC) plates and impacted by a pure WC flyer. This impact assembly is inclined to the direction of approach by an angle of 18º. In order to measure the free surface velocity along the normal and transverse direction, the back surface of the rear plate was mirror polished and coated with a diffraction grating. Details of PSPI experimental procedures, including the combined normal and transverse displacement interferometers (NDI, TDI), have been given by Clifton and Klopp [2]. The experimental parameters are shown in Table 1. Soda lime glass, 5μm thick, is vapor-deposited on the rear face of the front plate. Then a 200 nm thick layer of SiO_2 is deposited as a protective layer to prevent soda-lime glass from absorbing moisture. The T-X diagram is shown in Figure 2.

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TABLE 1. Experimental Parameters

Shot No.	h_{sample} (mm)	h_{flyer} (mm)	h_{front} (mm)	h_{rear} (mm)	Φ (mm)	V_0 (m/s)	Tilt Angle (mrad)
1602	0.0052	6.385	3.951	5.898	50	194	0.5
1603	0.0052	6.389	3.971	5.919	50	188	0.4

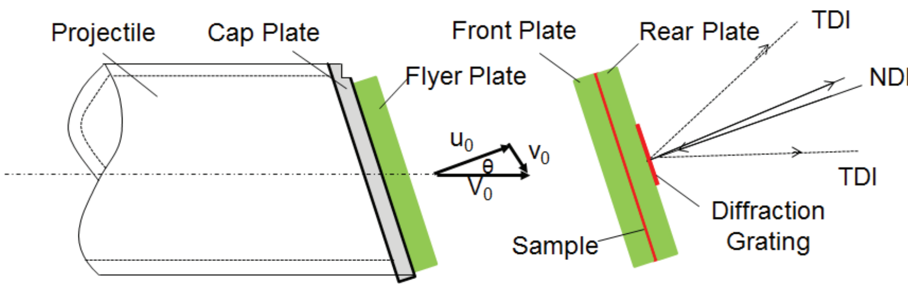


FIGURE 1. PSPI Experimental Setup

As shown in Figure 2, after impact a longitudinal wave (solid line) arrives at the sample first. It reverberates through the thickness of the sample until the normal stress becomes nominally uniform. After that, a shear wave (dashed line) arrives and subjects the sample to simple shear under nominally constant pressure.

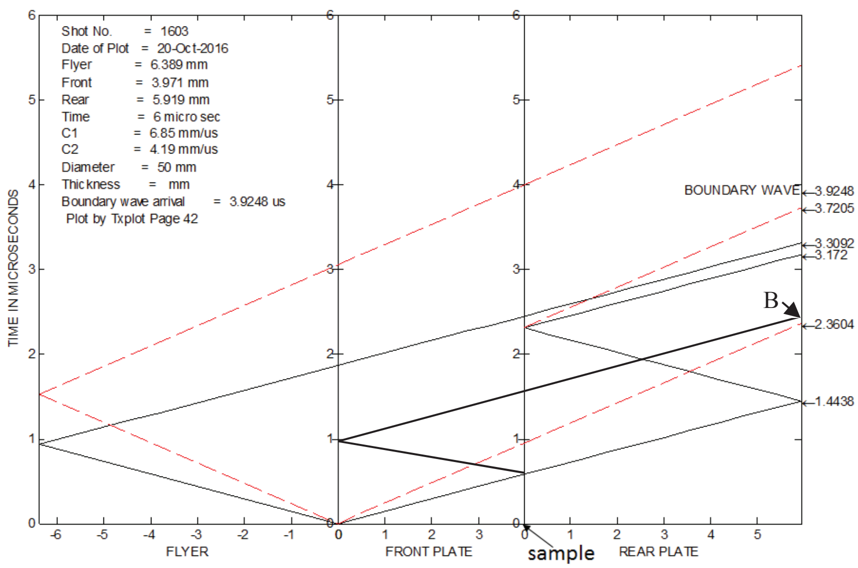


FIGURE 2. T-X diagram

EXPERIMENTAL RESULTS

Typical NDI and TDI traces are shown in Figure 3. The inset shows the magnified NDI fringes. Normal velocities and transverse velocities at the free surface, shown in Figure 4(a) and (b) are reduced from the raw traces of Figure 3.

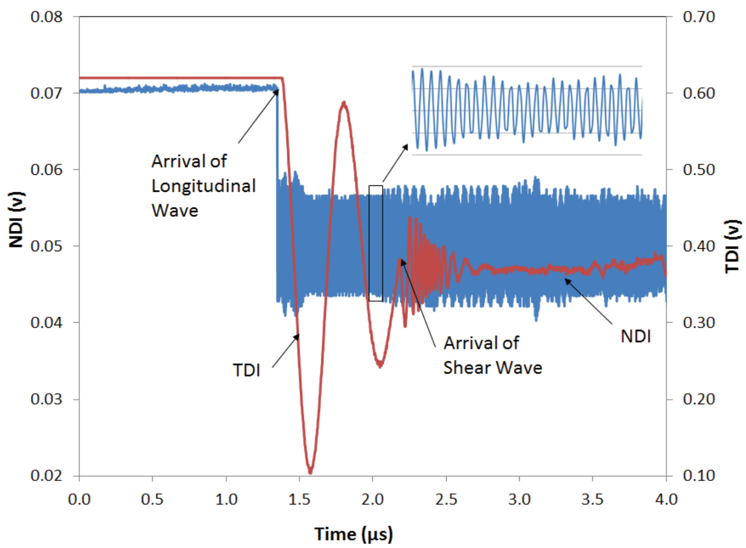
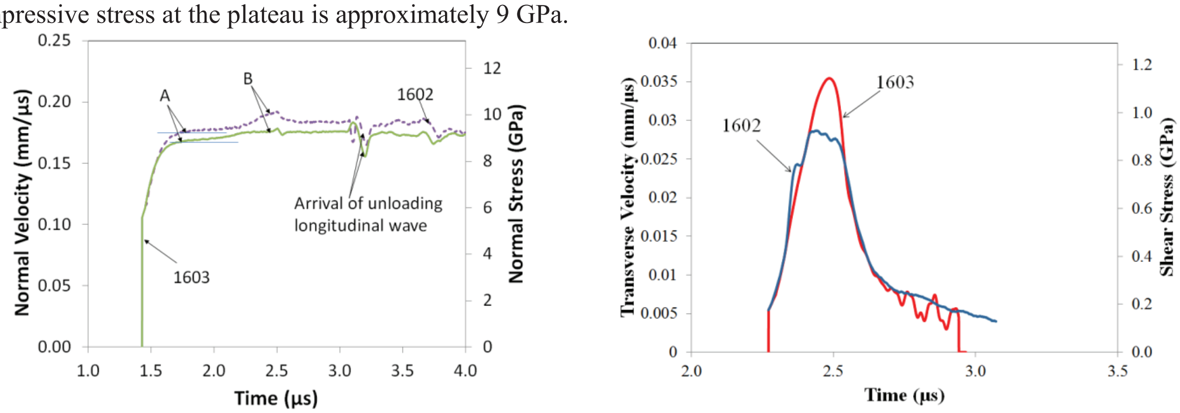


FIGURE 3. Typical NDI and TDI traces for shot 1603

Figure 4(a) shows the normal velocities at the free surface of the rear plate, with the normal stresses calculated from 1D elastic wave theory. At the arrival of the longitudinal wave, the normal velocity increases steeply initially, then slowly until a plateau is reached. For such a thin sample, the slowly rising segment of the profiles is too gradual to be described by impedance mismatch alone. Instead, these profiles indicate some nonlinear or inelastic behavior of soda-lime glass. Interestingly, after 0.5 µs (point A), the normal velocities increase gradually along a sigmoidal curve for approximately 0.25 µs before reaching a near plateau. At 2.5 µs (point B), both normal velocities show a small, roughly sinusoidal, blip. This blip is due to reflection of a longitudinal wave from the impact surface, as indicated by point B in Figure 2. Beyond point B the normal velocity remains at the plateau until the arrival of an unloading longitudinal wave reflected from the free surface of the rear plate. As shown on the right side axis, the compressive stress at the plateau is approximately 9 GPa.



(a) (b)

FIGURE 4. (a) Normal velocities at free surface; (b) Transverse Velocities at free surface

Figure 4(b) shows the transverse velocity at the free surface, with the calculated shear stresses shown on the right side. After the arrival of the shear wave, the free-surface transverse velocity increases sharply for approximately 0.25 µs and then plunges nearly to zero during approximately another 0.25 µs. As shown in Figure 5, The plunge in shear stress at the rear surface of the sample appears to coincide in time with the sigmoidal increase (point A) of the normal velocity. Figure 5 shows clearly that the time interval of approximately 0.25 µs, during which the gradual rise of normal stress occurs, coincides with the time during which the shearing resistance of the soda-lime glass decreases precipitously. During this time interval, from 1D elastic wave theory, the normal velocity at the rear face of the glass sample changes by

$$\Delta u^{+}\left(t-h_{rp}/c_{1}\right)=\frac{1}{2}\Delta u_{fs}\left(t\right) \qquad (0.1)$$

where the superposed $^{+}$ indicates the change in normal velocity at the sample/rear-plate interface, $u_{fs}\left(t\right)$ is normal velocity at the free surface, h_{rp} is the thickness of the rear plate of the target assembly and c_1 is the longitudinal wave speed in WC. After reverberations through the thickness of the glass have equilibrated the normal stresses on the two faces of the sample, this positive change in normal velocity on the $^{+}$ face corresponds to a negative change in normal velocity on the $^{-}$ face of the glass sample, indicating dilatation of the sample. At the same time the change in the normal stress is

$$\Delta\sigma_{11}=-\frac{\rho_0 c_1}{2}\Delta u_{fs}, \qquad (0.2)$$

which is negative (i.e. compressive). Thus, the material behavior shown in Figure 5 corresponds to shear-induced dilatation under small increase in compressive normal stress. This dilatation is occurring under nominally simple shear at a shear rate that is increasing as the shearing resistance is being lost.

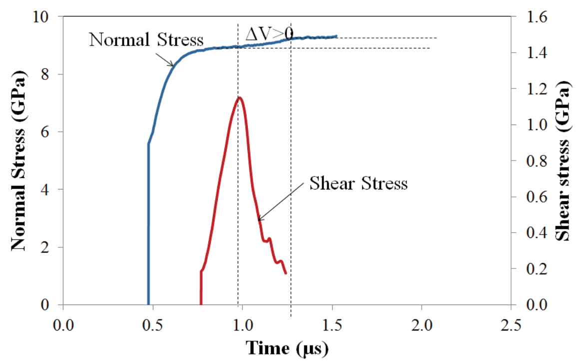


FIGURE 5. The history of normal and shear stress at sample/rear plate interface for shot 1603

The history of shear strain rate, and the stress-strain curve in shear, are shown in Figures 6(a) and (b). The average shear strain rate is approximately $7\text{x}10^{6}\text{s}^{-1}$. At pressures of approximately 9 GPa, the shear stress increases strongly up to 1 GPa and then falls quickly. The shear strain at which precipitous softening begins is 1.5 to 1.7.

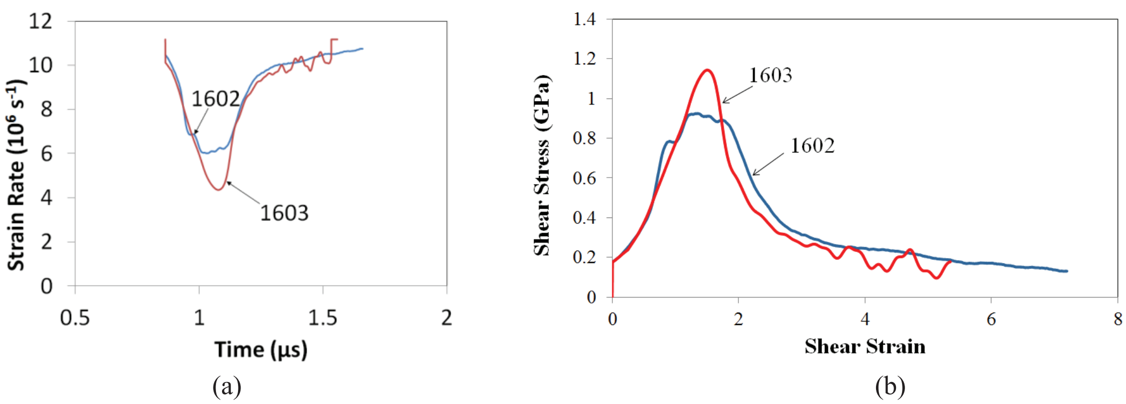


FIGURE 6. (a) History of shear strain rate; (b) Shear stress strain curves

Comparison of the experimental results with those reported previously [3, 4], is shown in Figure 7. The pressure and shear strain at failure follow each shot number. In previous studies [3, 4], the shearing resistance at pressure of 3.5GPa (shot 9703) is higher than that at 2.5GPa (shot 9701); while the shearing resistance at pressure of 5.7GPa (shot 9702) is the lowest. Sundaram didn't make any comments on this phenomenon, but the abrupt decrease of the shear stress at failure in shot 9702 indicates this lower shearing resistance could be attributed to some initial defects.

Although the pressure dependence of shearing resistance is not clear in previous studies [3, 4], Figure 7 clearly shows that the shearing resistance of soda-lime glass at pressures of approximately 9 GPa are almost double the shearing resistance at lower pressures. Samples used in these experiments are from the same company, and nominal thicknesses are 5 μm for both studies. One difference is that samples for the current work had a protective layer of 0.2 microns SiO_2 deposited on the rear surface of the sample. This difference allows the possibility that the SiO_2 layer reduces initial defects and thereby enables higher shearing resistance – although the more likely explanation appears to be increased shearing resistance due to higher pressure. For the 4 shots for which the sample fails (i.e. not shot 9701), the failure strains are comparable. Sundaram has attributed this kind failure to a bond-switching mechanism in which adjacent covalent Si-O bonds switch at large shear strains [3,4], causing the precipitous decrease in shearing resistance.

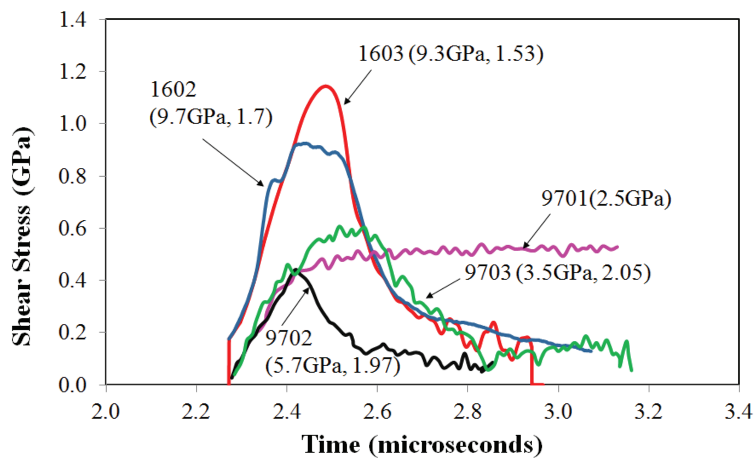


FIGURE 7. Summary of shearing resistance

CONCLUSION

PSPI experiments have been conducted to measure the shearing response of soda-lime glass at pressures of 9 GPa. The shear stress increases strongly up to 1 GPa and then falls quickly. Precipitous softening begins at shear strains from 1.5 to 1.7. In comparison with previously reported results at lower pressures, the shearing resistance continues to increase with increasing pressure while the shear strain at failure remains nearly the same.

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