Measurement of the response of an elastomer at pressures up to 9 GPa and shear-rates of $10^3 - 10^6 \text{s}^{-1}$

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Abstract. Pressure-shear plate impact (PSPI) experiments have been conducted to study the mechanical response of an elastomer at high pressures and high strain rates. The previously determined isentrope has been extended to 9 GPa. At this pressure, the high-strain-rate shearing resistance of polyurea is approximately 500 MPa — comparable to, or greater than, that of high strength steels and at much lower density. A new symmetric pressure-shear plate impact (SPSPI) configuration has been developed in order to enable the direct measurement of the thickness-averaged nominal strain rates of the sample — as well as the tractions on both of its interfaces with linear elastic plates. This enhancement is made possible by using a symmetric configuration for which the velocity of the mid-plane of the sample is known from symmetry to be one-half of the impact velocity. One dimensional elastic wave theory is used to obtain tractions and particle velocities at the sample/anvil interface from the measured rear-surface velocities. In this way, nominal strain-rate histories are obtained for both longitudinal and shear strains.

1. Introduction
The authors have reported previously on the high strain rate response of polyurea in pressure-shear plate impact experiments (PSPI) designed to determine its isentrope and shearing resistance at high strain rates and at pressures ranging from the tensile regime up to 3 GPa [1,2]. Herein new results are reported on polyurea’s isentrope and its shearing resistance at pressures up to 9 GPa.

Table 1. Summary of PSPI experiments.

| Shot No. | $h_{\text{sample}}$ (mm) | $h_{\text{front}}$ (mm) | $h_{\text{rear}}$ (mm) | $h_{\text{flyer}}$ (mm) | Angle (°) | $v_0$ (m/s) | Tilt Angle (mrad) |
|----------|--------------------------|-------------------------|------------------------|-------------------------|-----------|-------------|-------------------|
| 1103     | 0.6                      | 4.016                   | 4.026                  | 4.021                   | 0         | 204         | 0.58              |
| 1104     | 0.4                      | 3.616                   | 5.941                  | 5.931                   | 0         | 195         | 0.3               |
| 1201     | 0.097                    | 3.582                   | 5.578                  | 7.411                   | 18        | 183.5       | 0.30              |
| 1202     | 0.09                     | 3.590                   | 5.656                  | 11.476                  | 18        | 172.7       | 0.59              |
| 1203     | 0.086                    | 3.588                   | 5.898                  | 10.565                  | 0         | 175.0       | 0.15              |

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2. Experimental results

2.1. PSPI experiments

In order to reach pressures as high as 9 GPa, a hard, high-impedance material — pure tungsten carbide — is used for the flyer plate and the front and rear plates of the target assembly. A polyurea sample is cast between these two plates. Details of PSPI experimental procedures, including the combined normal and transverse displacement interferometers (NDI, TDI), have been given by Klopp and Clifton [3]. New high pressure experiments are summarized in table 1.

![Figure 1. Normal velocities of 1103 &1104.](image1)

![Figure 2. Quasi-Isentrope of polyurea up to 9 GPa.](image2)

Shots 1103 and 1104 are normal impact experiments used to measure the isentrope up to 9 GPa. The samples are approximately 0.6 mm and 0.3 mm thick, respectively. Normal velocity-time profiles for these experiments are shown in figure 1. Because the acoustic impedance of polyurea is much smaller than that of pure tungsten carbide, the normal velocity history at the free surface shows multiple reverberations as the velocity rings up to the projectile velocity. Each step during the ring-up corresponds to a round trip of a weak shock wave propagating through the thickness of the sample. Because the change in entropy for a shock wave is proportional to the third power of the pressure increase across the shock, the ring-up process can be regarded as essentially isentropic. The height of each step can be used to calculate the stress level. The width of each step can be used to estimate the wave speed at a corresponding average stress level. Therefore, by analyzing the ring-up process, one can obtain the isentrope of the material [1].

![Figure 3. Shearing resistance in PSPI experiments.](image3)
Jiao, Clifton and Grunschel [1,2] have successfully used a “Lennard-Jones” type potential to described the isentrope of polyurea up to 3 GPa. When the new experimental results are included, the isentrope can again be described by the Lennard-Jones-like potential [4]:

\[ P = -A(J^{-N} - J^{-M}) \]  

(1)

where \( N=6, M=3 \) are predicted exponents for block co-polymers [4], \( J \) is the specific volume, \( P \) is the normal stress, and \( A=0.871 \text{ GPa} \) (evaluated by fitting data from shots 1103 and 1104) is a material parameter corresponding to six times the cohesive energy. Figure 2 shows that the isentrope calculated from equation (1) agrees quite well with experimental results.

Shots 1201 and 1202 were conducted to measure the shearing resistance at pressures of approximately 9 GPa. The inclination angle in both experiments is 18º. From the measured velocities, the stress-strain curves in shear can be deduced. In figure 3 the shear stress-strain curves measured in shots 1201 and 1202 are compared with those obtained previously at lower pressures. This figure clearly shows that the shearing resistance of polyurea increases strongly with increasing pressure. At pressures of 9 GPa, shear stresses are approximately 500 MPa. This exceptional strength for such a low density material is compared with that of other materials in figure 4.

**Figure 4.** Strength to Weight Ratio of Various Materials; points labeled in italics are points added to original figure in [5].

Figure 5 shows the normal velocities measured at the free surface of the rear plate in shots 1201 and 1202. The increase in normal velocity at approximately 3 \( \mu \)s is a result of the release wave reflected from the rear surface of the target. This wave returns to the sample and rings down the normal stress in the sample. The multiple reflections of these release waves results in the initial increase in the particle velocity at the rear surface of the target. After some ringing, the normal velocity levels off at a plateau that is higher than the one reached before the arrival of the first unloading wave. The second plateau corresponds to a compressive stress of approximately 2 GPa at the sample/rear-plate interface. After the unloading wave in the rear plate has made another roundtrip through its thickness (i.e. at approximately 4.4 \( \mu \)s), the compressive stress begins to reduce to zero. During the period when the compressive stress is at 2 GPa, the front and rear plates continue to separate. Whether this separation is associated with opening of cavities, either within the sample or at
an interface with its bounding plates is unknown. Shot 1203 is a normal impact experiment that was conducted to see whether or not the observed extension at constant compressive stress could be a consequence of the shear loading. That connection appears unlikely as the measured normal velocity for the normal impact experiment, also shown in figure 5, shows very similar extension under constant compressive stress.

![Figure 5](image)

**Figure 5.** Normal velocities measured in shots 1201-1203.

### 2.2. Symmetric PSPI experiments

In a PSPI experiment with the sandwich configuration, the shear strain is obtained through the integration of the strain rate over the loading history. In order to calculate the strain rate, the particle velocity at the front-plate/sample interface is obtained by assuming that the stress at that interface is the same as at the rear-plate/sample interface. For most materials this assumption is quite acceptable as the shear (normal) stress becomes nominally uniform through the thickness after a few reverberations of shear (longitudinal) waves through the thickness of the sample. However, a direct determination of the particle velocity at the front-plate/sample interface would clearly increase confidence in the inferred nominal strain–rate history. Such a direct determination is possible with the new symmetric pressure-shear plate impact (SPSPI) configuration shown in figure 6.

![Figure 6](image)

**Figure 6.** Symmetric pressure-shear plate impact setup.

Two thin layers of polyurea, with nominally the same thickness, are cast on both the flyer and anvil plates. By making the flyer and anvil assemblies symmetric, the boundary condition at the impact face becomes one of imposed velocity at a velocity $V_0/2$ where $V_0$ is the projectile velocity. As a result, the stresses are symmetric with respect to the impact plane so that stresses on the flyer-plate/sample interface are the same as those inferred, from elastic wave theory, for the sample/anvil interface by measuring the motion of the rear surface of the anvil. Thus, tractions and particle velocities on both faces of the two-part sample are obtained directly from NDI and TDI records. Slipping on the impact
face between the two-half samples seems unlikely in view of the small ratio of shear traction to normal stress (i.e. less than 0.06). Because the normal stress rings up faster than the shear stress, the most likely time for slipping is when the shear stress reaches its maximum value. The transverse velocity-time profile shows no indication of an anomalous increase in nominal strain-rate at any time, as would be expected if slip were to begin. In any event, the reported shearing resistance is the shear stress at the rear face of the two-part sample — regardless of whether or not slip occurs at the impact face. Values for that shear stress are the same as for the previous PSPI experiments on the one-part samples. Future tests will probe the possibility of slipping by trying to enable the measurement of transverse velocity during shear wave unloading. Another difference between PSPI and SPSPI is that in PSPI experiments the shear wave arrives after the longitudinal wave reverberates to reach an equilibrium compressive stress state. However, in an SPSPI experiment, both the longitudinal wave and shear wave begin to load the sample at the same time. Therefore, the beginning part of the shear deformation in the sample is under increasing compressive stress.

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| Shot No. | \( h_{p,\text{anvil}} \) (mm) | \( h_{\text{anvil}} \) (mm) | \( h_{p,\text{flyer}} \) (mm) | \( h_{\text{flyer}} \) (mm) | \( v_0 \) (m/s) | Tilt Angle (mrad) |
|----------|-------------------------------|-----------------------------|--------------------------|--------------------------|----------------|------------------|
| 1301     | 0.069                         | 4.051                       | 0.074                    | 4.043                    | 188            | 1                |
| 1302     | 0.098                         | 4.032                       | 0.086                    | 8.075                    | 178            | 0.3              |

Impact conditions for two experiments are shown in table 2. Normal velocity profiles measured at the rear surface of the target assemblies for these two experiments are shown in figure 7. The reflected longitudinal wave shown arriving at approximately 3.5 µs is the unloading wave arriving from the free surface of the flyer (and of the anvil in shot 1301). After unloading reverberations through the thickness of the sample, the flyer and anvil separate and the anvil moves away with the momentum captured from the flyer. Interestingly, neither of these experiments shows the second, higher plateau that was observed when similar experiments were conducted in PSPI sandwich configurations. Although the lack of appearance of the second plateau could be related partially to longer ring down times due to the greater sample thickness, the extension at constant compressive stress in PSPI tests is now thought to be influenced by failure of the polyurea/WC bond in the PSPI experiments, not solely to bulk failure of polyurea.

Strain-rate histories for both compressive and shear strains are shown in figure 8. Compressive stress-strain curves for the SPSPI experiments are shown in figure 9. The initial straight-line section, corresponding to the initial jump in particle velocity is obtained by modeling the initial response of the material as linear elastic. Maximum compressive stresses of approximately 8 GPa are reached in both experiments. With the new SPSPI configuration the nominal strain rates are obtained reliably throughout the loading history. Thus, for the stress-strain histories shown in figure 8, one can reliably interpret both the loading (shown as solid curve) and unloading response (shown as dashed curve). The resulting uniaxial-strain hysteresis shown in figure 9 is quite small, probably because much of the compressive response is related to the response of the material to change in specific volume.

Shear stress-strain curves obtained from the SPSPI experiments are also shown in figure 9. Separation between the straight line segments in figure 9 is an indication that the elastic shear wave precursor is attenuated more when it propagates through the thicker sample. Separation between the two curves reflects the slower ring up of the normal stress for the thicker sample of shot 1302. Because the pressure increases more slowly for shot 1302, the strong pressure sensitivity of the
shearing resistance of polyurea leads to a slower increase in shear stress. In both shots the maximum shear stress is approximately 500 MPa. Thus, the exceptionally high shearing resistance reported for simple shear at constant pressure in PSPI experiments is also observed in the SPSPI experiments at comparable pressures.

Figure 7. Normal velocities in SPSPI experiments

Figure 8. Strain rates in SPSPI experiments

Figure 9. Compressive and shear stress-strain curves obtained from SPSPI experiments.

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