

Shock Response of Polymethylmethacrylate

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Abstract Polymethylmethacrylate (PMMA) from two suppliers is subjected to shock loading up to 2 GPa to develop understanding of the effect of manufacturing process on the shock response. The particle velocity, shock velocity, and longitudinal and lateral stresses are measured simultaneously and independently using photon Doppler velocimetry and manganin gauges. The particle velocity measurements agree with data in the literature. The calculated shear stress was seen to deviate from linear behavior at approximately 2 GPa, which is consistent with other experiments. Overall, the selection of material is shown to have up to a 10 % effect on shock properties, but the average difference is less than 2 %, which indicates that the varying the PMMA supplier may not have a dramatic effect on test using PMMA as a window or gap material.

Keywords Polymethylmethacrylate · Hugoniot · PMMA · Shock loading · Manganin gauges · Photon doppler velocimetry

Introduction

Polymethylmethacrylate (PMMA) is widely used in dynamic high pressure experiments as a window material and in explosive characterization tests, e.g. gap tests, as a shock mitigation material. Although there has been considerable work in

the literature characterizing PMMA, often the pedigree of the materials tested is not discussed. There was considerable effort to characterize a particular PMMA material—Rohm and Haas UVA Type II—as windows for shock experiments [1]. However, this material is no longer manufactured, and the question has arisen as to whether new PMMA materials intended for use as attenuators or windows in shock experiments need to be characterized or if the detailed calibration performed on a separate material is sufficient.

The shock response of PMMA has been reported extensively in the literature since the 1960s [1, 2]. Several authors [1, 2] have observed that the relationship between particle velocity and shock velocity is not linear, particularly at low particle velocities, where the shock velocity has a much steeper slope than expected. This has been attributed to the forces between chains of the polymer being at least an order of magnitude less than those along the polymer backbone, which results in two-dimensional, microscopic deformation as the distance between the polymer chains is compressed [2]. When the chains have moved sufficiently close together that the forces are on the order of those required to compress the backbone, the particle velocity—shock velocity response becomes linear [2].

The high rate shear strength of PMMA is of interest for applications where loading is not unidirectional. The relationship between the Hugoniot stress, σ_x , and the shear strength, τ , is:

$$\sigma_x = P + \frac{4}{3}\tau \quad (1)$$

where P is the hydrostatic pressure. However, more recently, the shear strength has been determined by measuring the lateral stress, σ_y , in the sample [3–7]:

$$2\tau = \sigma_x - \sigma_y \quad (2)$$

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In PMMA, the lateral stress has been observed to decrease following the shock front indicating a strengthening of the material, possibly due to the viscoelastic/viscoplastic response of PMMA [6]. Experiments at higher pressures have indicated a dramatic decrease in shear strength, which the authors attributed to rising temperature behind the shock front [7]. Since the temperature in PMMA has been shown to rise dramatically above 2 GPa [8, 9], this may be responsible for the deviation from elastic behavior and subsequent dramatic drop in shear stress above 7.5 GPa [7]. The rise in temperature was attributed to a potential exothermic reaction [8].

In this paper, two PMMA materials, namely Rohm and Haas Type II UVA and Polycast Poly II UVT, are subjected to shock loading up to 2 GPa to understand the difference in shock properties between the two materials. The particle velocity and shock velocity results are compared with data for a variety of PMMA experiments in the literature. Additionally, the longitudinal and lateral stresses are determined from in-material manganin gauge measurements and are discussed in relationship to shear stresses from Millett and Bourne [6] and Bat'kov et al. [7].

Experimental Approach

Two PMMA materials have been considered in this study. The first material is Rohm and Haas Type II UVA sheet, which was material tested by Barker and Hollenbach for the original interferometer window calibration experiments [1], that had been stored in the laboratory for several decades. The second material is Polycast Poly II UVT, MIL-PRF-6425E sheet material that is being considered as replacements for the Rohm and Haas material in shock experiments. All of the samples were machined from the plate and tested perpendicular to the plate direction. The density for each material was measured using Archimedes' method.

Plate impact experiments were conducted on both materials. For two experiments, RH2 and RH3, a normal displacement interferometer [10, 11] was used to measure the particle velocity at an internal interface within the PMMA, as shown in Fig. 1a. The interferometer was constructed on an optical table with a Coherent Sapphire laser at 532 nm and New Focus 1601FS-AC 1 GHz detectors. A 50 mm diameter single stage light gas gun was used to propel the nominally 41 mm diameter, 4.6 mm thick flyer plate to impact the 41 mm diameter sample. The sample was comprised of two plates nominally 4.5 mm thick. A thin aluminum coating was vapor deposited on the interface between the two samples, and the NDI system was focused on this reflective coating near the center of the sample.

In the remaining experiments, velocimetry and gauges were used to make independent measurements of shock

parameters, as shown in Fig. 1b. A 100 mm diameter single stage light gas gun was used to propel the projectile to impact the sample. The 88 mm square flyer plate was mounted in a sabot, and held at the edges so as not to interfere with the experiment. The impact velocity was measured using shorting pins mounted on the gun barrel such that they did not interfere with the passage of the sabot and designed to provide an electrical signal when in contact with metal sabot. The flyer plate was nominally 5 mm thick and impacted a nominally 3 mm thick, square driver plate. The input longitudinal manganin gauge was mounted between the driver plate and the sample close to the center of the experiment. The nominally 12.5 mm thick, square sample was cut in half to allow for placing the lateral manganin gauge, which was placed approximately 6 mm from the driver plate—sample interface. The transmitted longitudinal manganin gauge was glued between the sample plate and an nominally 12.5 mm thick, rectangular backer plate. The two longitudinal manganin gauges, input and transmitted, were used to measure the stress and the time of arrival at two locations in the material, which was used to calculate the shock velocity. Finally, a lateral manganin gauge was used to measure transverse stress.

Photon Doppler velocimetry (PDV) was used on the aluminum coated, driver plate-sample internal interface to measure the particle velocity, excluding RH1. The aluminum coating was vapor deposited on the front surface of the half of the sample using a mask to limit it to the center of the rectangle. The PDV was focused toward slightly offset of the center of the sample due to the presence of the lateral manganin gauge. These experiments were intended to provide independent measurements of three of the five shock parameters and to allow for determination of shear stress in the material through comparison of the lateral and longitudinal manganin gauge stresses.

PDV measurements were made using a conventional system generically described by Strand [12]. The Doppler interferometers were Third Millennium Engineering F177A-AC ModBlocks, which were coupled to an Agilent DSXO9000 series oscilloscope for digitization. This oscilloscope recorded measurements at 40 GSamp/s with a 16-GHz bandwidth, although the PIN optical/electrical detector within the F177A-AC ModBlocks was limited between 35-kHz and 10-GHz bandwidth. The 35-kHz lower-limit cutoff resulted from AC coupling of the detectors, which precluded measuring velocities below 0.025 m/s. Inside each Doppler unit was a tap coupler that split off 1 % of the light to be used as an unshifted reference.

Laser light for each system was supplied by a single 2-W IPG ytterbium fiber laser (ELR-2-1550-LP-SF) that was split 4 ways, providing approximately 0.5 W of 1550-nm light per.

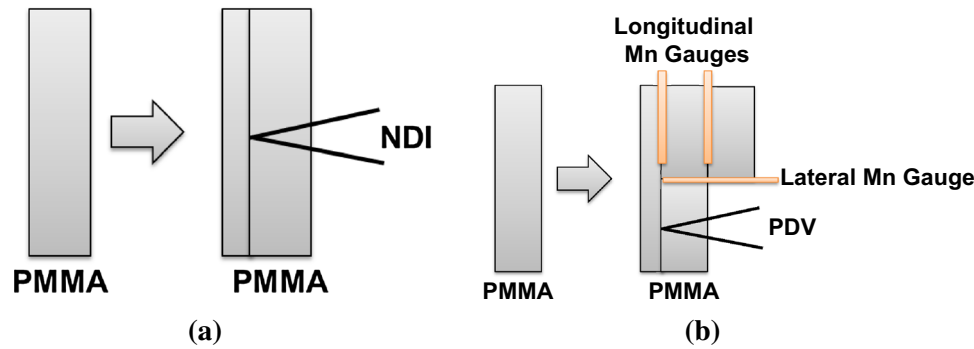


Fig. 1 Schematic of plate impact experiment with **a** normal displacement interferometer and **b** photon Doppler velocimetry and longitudinal and lateral manganin gauges. The gauge elements for the

longitudinal gauges are near the center of the experiment, and the gauge element for the lateral gauge is approximately in the middle of the sample thickness

Doppler channel. Light was carried to the samples inside Corning SMF28 fiber, which was terminated with an AC photonics pigtail with a graded index-of-refraction lens (1CL15A300LSD01). This lens projected the light onto the target, through vacuum, illuminating a 0.5 mm diameter spot on the target surface.

All signals were post-processed using the Sandia National Laboratory—developed Matlab-based SIRHEN analysis package to obtain velocity spectrograms. Segments of the signals were processed using 512 time points in the Fourier transform, which resulted in a temporal resolution within the spectrogram of 20 ns for the system. Extraction of velocities from the spectrograms was accomplished by fitting the individual time points of the spectrograms with a Gaussian distribution, from which the peak value was related.

The longitudinal manganin gauges were Micromasurements LM-SS-210AW-048/SP60, and the calibration used to convert change in resistance (R) to stress is that derived by Rosenberg et al. [13, 14]. The gauges exhibit an elastoplastic response, so the calibration is done in two parts depending on the stress level:

$$\sigma = 51.3 \frac{\Delta R}{R_0} \quad \text{for } \sigma < 1.5 \text{ GPa} \quad (3)$$

$$\sigma = 39.45 \frac{\Delta R}{R_0} + 0.278 \quad \text{for } \sigma > 1.5 \text{ GPa} \quad (4)$$

The lateral manganin gauges were Micromasurements J2M-SS-580SF-025, which are T-shaped gauges to reduce the time for the shock wave to transit the gauge. The calibration has been developed by Chapman et al. [15]:

$$\sigma = 51.3 \frac{\Delta R}{R_0} \quad \text{for } \sigma < 1.1 \text{ GPa} \quad (5)$$

$$\sigma = 5.307 + 43.693 \frac{\Delta R}{R_0} - 12260 \sqrt{5.832 \times 10^{-7} \frac{\Delta R}{R_0} + 1.7576 \times 10^{-2}} \quad (6)$$

for $\sigma > 1.1 \text{ GPa}$

Results and Discussion

Five plate impact experiments have been conducted on the two grades of PMMA as shown in Table 1, where the calculated parameters are in italics. For most of the experiments, a symmetric impact configuration was used. For RH6 and Poly4, soda lime glass was used as the impactor to increase the pressure in the sample PMMA, where the density of the glass is 2.490 g/cm³, the longitudinal sound speed is 5.79 km/s, and the shear sound speed is 3.43 km/s. Shock velocity was determined from the arrival time at the two longitudinal manganin gauges placed nominally 12 mm apart shown in Fig. 1. If one of the gauges failed before the shock arrived, then the shock velocity was determined from the measured pressure and particle velocity, as in Poly4.

Particle velocity was measured independently using a PDV system looking at an internal interface in the PMMA, and, as such, capturing the in-material particle velocity. A representative spectrogram from the Poly2 experiment is shown in Fig. 2. The velocity correction when using a PMMA window with a 1550 nm PDV system has been found to be on the order of 1 %, which is sufficiently small so as to not affect the reported particle velocities in Table 1 [16]. The fitted particle velocity traces for all experiments, where they are available, are shown in Fig. 3. The times have been shifted so that the rise for each experiment starts at approximately the same time for ease in comparison of the various experiments. The incomplete release seen in Poly4 and RH6 is due to the impedance mismatch between the soda lime glass impactor and the PMMA sample. The single value of particle velocity reported in Table 1 was determined by averaging the particle velocity in the plateau region of each trace. For experiments where the impact velocity and particle velocity were independently measured (Poly1-3 and RH5), the particle velocity was also calculated from half of the impact velocity and compared to the particle velocity measured with PDV. The variation

Table 1 Planar impact experiments conducted on Rohm and Haas (RH) and Polycast (Poly) PMMA, where values for particle velocity, u_p , shock velocity, U_s , and stresses are listed

Exp.	Impact velocity (m/s)	Impactor	ρ (g/cm ³)	u_p (km/s)	U_s (km/s)	σ_x (GPa)	σ_y (GPa)	2τ (GPa)
RH1	138	RH PMMA	1.19	<i>0.062</i>	2.81	0.21	0.143	0.063
RH2	<i>146</i>	RH PMMA	1.19	0.073				
RH3	<i>156</i>	RH PMMA	1.19	0.078				
RH4	292	RH PMMA	1.19	<i>0.145</i>	3.11	0.54	0.31	0.23
RH5	617	RH PMMA	1.19	0.31	3.22	1.19	0.651	0.54
RH6	592	Soda Lime Glass	1.19	0.48	3.29	1.87	0.994	0.88
Poly1	168	Poly PMMA	1.21	0.083	2.87	0.28	0.19	0.09
Poly2	307	Poly PMMA	1.21	0.15	3.03	0.51	0.30	0.21
Poly3	616	Poly PMMA	1.21	0.31	3.27	1.19	0.65	0.54
Poly4	591	Soda Lime Glass	1.21	0.47	3.58	2.03	1.12	0.91

Values in italics were calculated using $P = \rho_0 U_s u_p$

Fig. 2 Representative PDV spectrogram for the Poly2 experiment showing the Gaussian fitting of the individual time points as the solid black line

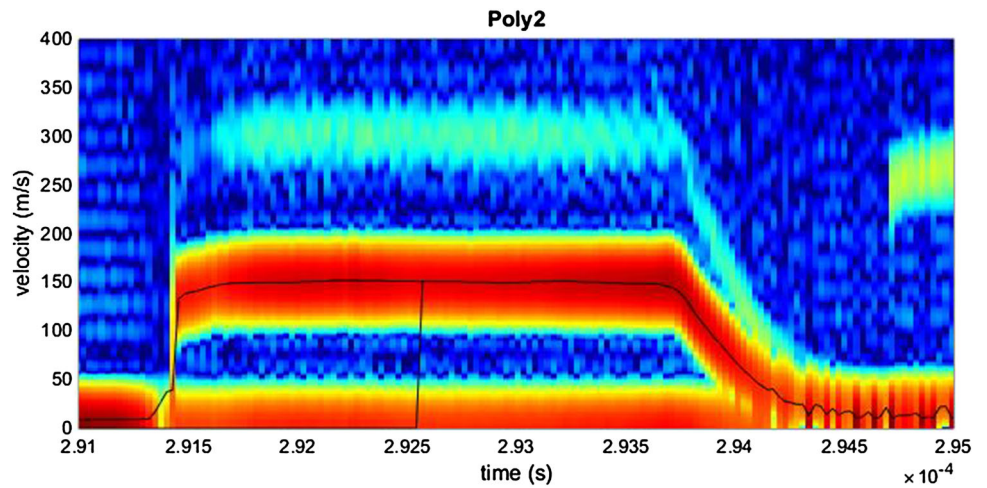
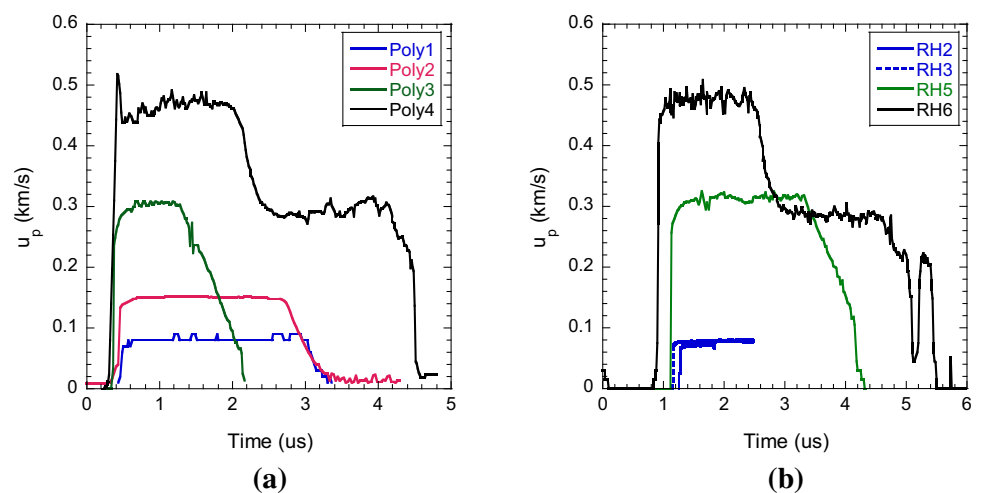


Fig. 3 Particle velocity measurements from **a** Polycast and **b** Rohm and Haas PMMA



between these two values ranged from 0.5 to 2 % indicating that there may be sources of error in either the impact velocity measurement or the PDV measurement which are not accounted for by the window correction.

The shock velocities versus particle velocities for the experiments in this study are shown in Fig. 4a. Generally, the two materials are in good agreement with each other, with the exception of the Poly4 experiment, which shows a significant increase in shock velocity over the Rohm and Haas material. For this experiment, the shock velocity was not able to be measured experimentally due to the failure of the transmitted manganin gauge, and, as such, was determined from the measured particle velocity and input stress from the manganin gauge. It is difficult to say from the data set whether the Polycast has a significantly different response from the Rohm and Haas material at higher impact velocities, and additional experiments would be required.

It can be seen that the relationship is not linear at low impact velocities, particularly for the Rohm and Haas material, which was also observed by Barker and Hollenbach [1]. Due to the maximum impact velocity for the Polycast material, it is difficult to see if the non-linearity holds, and additional, higher impact velocity experiments, would be needed to validate this claim. This is attributed to the two dimensional nature of the local deformation due to the higher strength of the polymer chain backbone compared to compression of the space between chains [2].

In Fig. 4b, the experimental shock and particle velocities from this study are shown in conjunction with data from the literature for PMMA. Barker and Hollenbach [1], Carter and Marsh [2], and Reinhardt and Chhabildas [17] all used the Rohm and Haas material for their studies. It can be seen that there is variation in the data, but there do not appear to be systematic differences between different

materials. Polynomials were fit to all of the available PMMA data:

$$U_s = 6.486u_p^3 - 7.823u_p^2 + 3.549u_p + 2.703 \quad (7)$$

for $u_p \leq 0.4$ km/s

$$U_s = 1.365u_p + 2.766 \quad \text{for } u_p > 0.4 \text{ km/s} \quad (8)$$

The equations are not intended to represent any particular physics, but were selected to determine the error in shock response from varying materials. On average, there is less than 2 % difference between any given experimental data point and the curve fit, which may be expected simply from differences between laboratory facilities and experimental error, indicating that the particular PMMA material has insignificant effect on the shock response, which is in agreement with the observations of Kister et al. [18]. The maximum difference between an experimental data point and the curve fit was 10 %. This is very encouraging because it gives some confidence when using available literature data for a new PMMA supplier, rather than conducting a complete experimental shock characterization. At the most, a few experiments that confirm the fit may be all that is required for a new material.

The Hugoniot stress in the materials, Fig. 5, was measured with a manganin gauge mounted approximately 3 mm from the impact surface and sandwiched between two pieces of PMMA. The times have been shifted so that the rise for each experiment starts at approximately the same time for ease in comparison of the various experiments. There is significant rounding of the shock pulse, which is attributed to the viscoelastic nature of the material [1]. The rise time decrease with increasing impact velocity. The values appended to the individual traces within the graph indicate the average stress for the plateau region.

The lateral stress traces from both the Polycast (a) and Rohm and Haas (b) are presented in Fig. 6, where the values next to each curve are the input stresses as

Fig. 4 Shock velocity versus particle velocity for **a** RH and Poly and **b** in comparison with data from the literature [1, 2, 6, 16, 18–21]

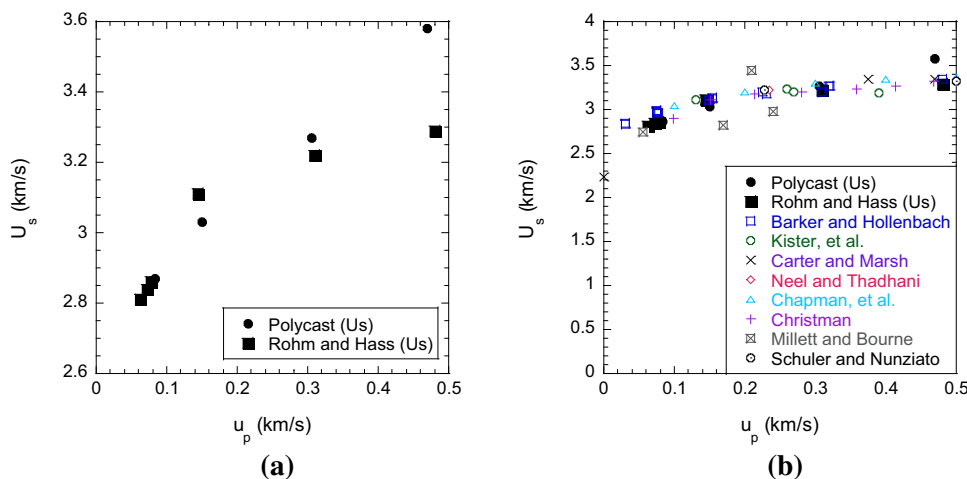


Fig. 5 Longitudinal stress gauge measurements from **a** Polycast and **b** Rohm and Haas PMMA measured approximately 3 mm inside the PMMA from the impact surface, where the *numbers* appended to the individual traces indicate the average stress at the plateau

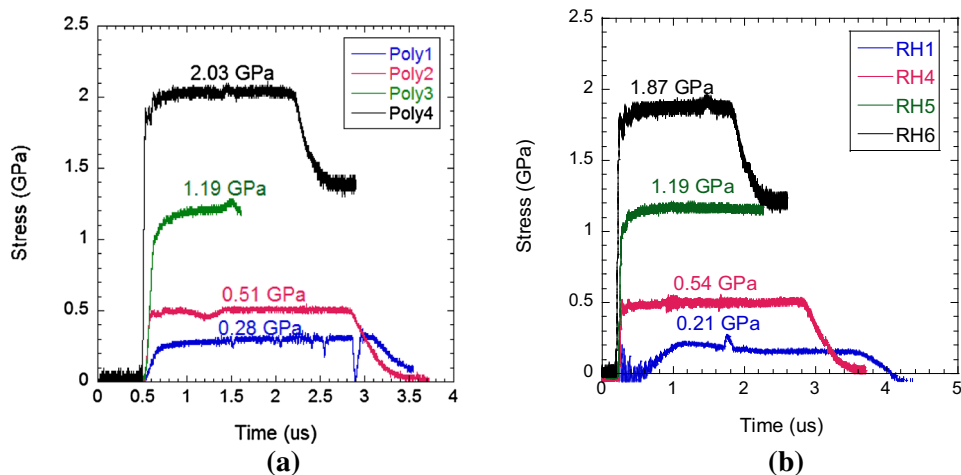
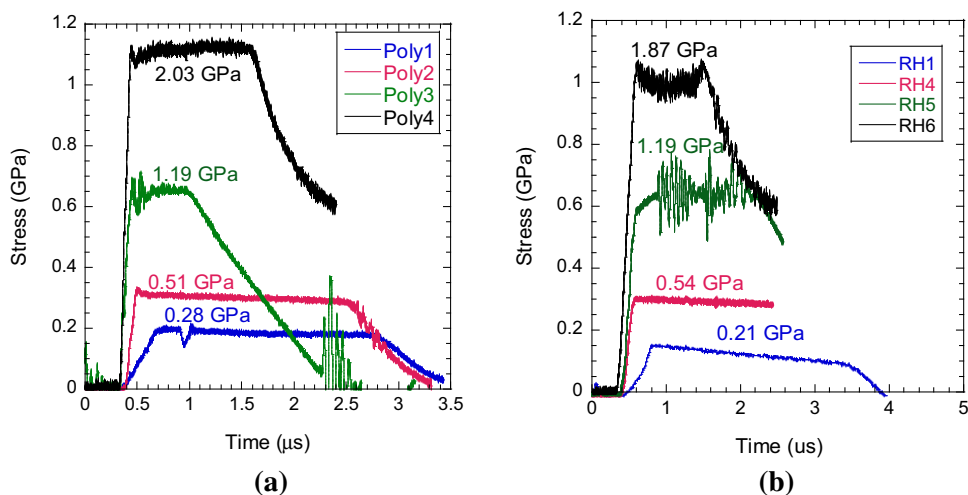


Fig. 6 Lateral stress gauge measurements from **a** Polycast and **b** Rohm and Haas PMMA, where the *numbers* indicate the average input stress at the plateau and can be referenced to Fig. 3



referenced in Fig. 5. In both materials, the stress rises to a plateau value before release. The large oscillations in both Poly3 and RH5 are attributed to electrical noise, most likely due to failure of the input gauge. It is obvious that the rise time decreases with increasing input stress, or impact velocity. The average lateral stress at the plateau and the calculated shear stress are given in Table 1. Similar to Millett and Bourne [6], who observed a decrease in stress behind the shock front of approximately 0.02 GPa, the two lowest impact velocity experiments (Poly1, Poly2, RH1, and RH4) also exhibit a decrease in shock strength of approximately 0.02 GPa, which implies that the strength of the PMMA is increasing behind the shock front. A similar decrease in lateral stress is observed in data from Gupta and Gupta [3], but it is not commented upon by the authors. This increase in strength has been attributed to the viscoelastic/viscoplastic nature of PMMA [6]. However, the higher impact velocity experiments did not show a similar

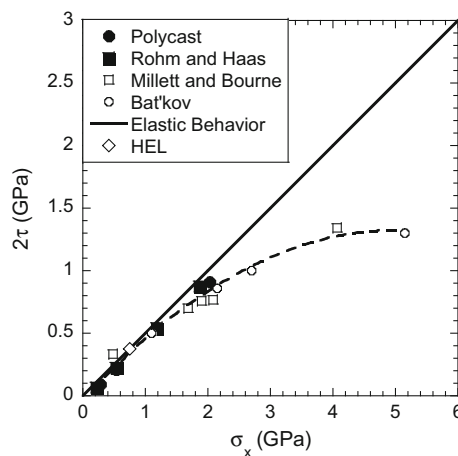


Fig. 7 Shear stress versus normal stress in comparison with data from Millett and Bourne [6] and Bat'kov [7]. The *dotted* line is a second order polynomial fit to data from this study in combination with that in the literature

decrease in stress behind the shock front, which is in contrast to the results from Millett and Bourne [6], who saw the decrease in most experiments including those at higher impact velocity.

In Fig. 7, the data from this study is compared with that from Millett and Bourne [6] and Bat'kov [7] as presented in [6]. The solid line is the elastic behavior [6] and the open diamond is the Hugoniot elastic limit (HEL) as reported by Barker and Hollenbach [1]. It can be seen that our data is in good agreement with that of previous researchers, and a single polynomial has been fit to all of the experimental data in the graph, shown as the dotted line. The deviation from linear behavior appears to start around 2 GPa, which is in agreement with the temperature measurements of Bloomquist and Sheffield [8, 9].

Conclusions

In this study, the shock response of Rohm and Haas UVA Type II, a legacy material, and Polycast Poly II UVT, which is being considered as a new standard PMMA, were characterized up to 2 GPa. The in-material particle velocity was determined using PDV, and the shock velocity was independently measured from arrival time at two manganin gauges. A fitted curve to all available shock velocity-particle velocity data showed an average difference between experiment and fit of 2 % and a maximum difference of 10 %. This indicates that minimal characterization experiments are required on a new PMMA material if this experimental error is acceptable. However, it should be noted that both PMMA materials in this study were cast plates and a larger difference may be encountered when the PMMA has undergone a significantly different processing history than that in the study.

The longitudinal and lateral stresses were measured using in-material manganin gauges. The longitudinal stresses showed significant rounding followed by a plateau stress. The two stress measurements were used to determine the shear strength in the material, which was shown to agree with literature data and possibly indicate a deviation from linear elastic behavior around 2 GPa. The deviation was correlated with temperature measurements from the literature, which show a dramatic increase in temperature at the same pressure.

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