An overview on the effect of manufacturing on the shock response of polymers

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Abstract. Scatter and non-linearity of the Hugoniot in the Uₛ-uₚ plane has been seen in a number of polymers including poly(methyl methacrylate) (PMMA), the polymer considered here. In this study the plate impact technique has been used to investigate the shock response of PMMA between particle velocities of 0.13 and 0.77 mm μs⁻¹. From this data no scatter was seen between our data and the experimental data of Barker and Hollenbach, and Carter and Marsh. Also a linear Hugoniot in the Uₛ-uₚ plane was found, with the equation Uₛ = 2.99 + 0.92uₚ. The non-linearity observed by Barker and Hollenbach was not present in this data, probably due to the non-linearity occur at particle velocities of below 0.13 mm μs⁻¹, within their experimental data. Grüneisen gamma has also been briefly considered using a shock reverberation experiment but more work is needed before a value can be ascertained.

1. Introduction

Polymers are widely used within the field of shock physics for applications such as gauge protection [1, 2] as well as a window material for interferometry [3]. Consequently, it is important to understand this high strain rate behaviour because in such regimes a slight discrepancy can greatly alter the interpretation of data. In particular, it seems reasonable to assume that discrepancies in the shock response could arise in different commercially sourced material due to alterations in the manufacturing procedure.

Barker and Hollenbach investigated the shock response of PMMA, and found scatter in the experimental data when compared to previous studies [3]. To counteract this they used only material from a single supplier as this presumably would be more reproducible in the future. It was found that PMMA had a non-linear Hugoniot over the investigated shock conditions. However it should be pointed out that the non-linear behaviour is only apparent in the experimental data below 0.2 mm μs⁻¹. A Hugoniot elastic limit was found to be approximately 0.7 GPa, which was later supported by Schuler and Nunziato [4].

Carter and Marsh also studied PMMA with the work collated with other polymers in reference [5]. It was found that the ultrasonic measurements for c_B did not match up with the ascertained values of c₀ from the linear experimentally derived Hugoniot. This was thought to be due to the initial compression being two-dimensional in nature (compression between polymer chains) before becoming three-dimensional in nature (compression along the polymer chain backbone).
Table 1. Elastic material properties for PMMA.

| $\rho_0$ (g cm$^{-3}$) | $c_L$ (mm $\mu$s$^{-1}$) | $c_S$ (mm $\mu$s$^{-1}$) | $c_B$ (mm $\mu$s$^{-1}$) | $v$ |
|-------------------------|--------------------------|--------------------------|--------------------------|-----|
| 1.19                    | 2.72±0.02                | 1.37±0.02                | 2.43±0.03                | 0.36|

2. Experimental Method

2.1. Material Properties

Elastic properties for PMMA were obtained via ultrasonic techniques with the measured values shown in table 1. The longitudinal and shear sound velocities ($c_L$ and $c_B$ respectively) were obtained using a 1 MHz Panametrics 5077R transducer in the pulse-echo and transmit-receive configurations. The bulk sound speed ($c_B$) was calculated using equation (1), with Poisson’s ratio ($v$) calculated from other elastic constants.

$$c_B = \sqrt{c_L^2 - \frac{4}{3}c_S^2}$$ (1)

2.2. Plate impact technique

Experiments involved using 50 mm diameter, 5 m barrel, single stage gas gun to accelerate flyer plates to velocities of between 170 and 870 m s$^{-1}$ (measured using a series of light gates). The materials used for the flyer plates were aluminium and copper. A simplified experimental set up is shown in figure 1. Impact surfaces were machined flat and parallel to tolerances of < 10 μm, with the assembled target held in place using a sacrificial barrel extension such that alignment was assured to < 2 mrad [6]. For these experiments manganin pressure gauges manufactured by Vishay Micro-Measurements® of type LM-SS-125CH-048 were used in the longitudinal orientation. This allowed the passage of the shock wave to be monitored, with calibration of gauges following the work conducted by Rosenberg et al. [7], with shock variables calculated using the impedance matching technique [8].

Figure 1. Simplified diagram of experimental setup.
A shock reloading experiment was also conducted to experimentally derive the value of Grüneisen gamma, following the method by Winter et al. [9] and Roberts et al. [10]. In this experiment the shock is reverberated between two higher impedance materials (copper was chosen in this case), shown in figure 2; as any reloading would be off-Hugoniot it was subsequently sensitive to Grüneisen gamma. ANSYS Autodyn® models were used, in conjunction with the experimental data, to obtain a value of Grüneisen gamma.

![Figure 2. Schematic of PMMA ring up experiment.](image)

### 3. Results and Discussion

The experimental data from the conducted shots are displayed in table 2 and shown graphically in figure 3. It can be seen that the currently gathered data is comparable with the relevant data from Barker and Hollenbach [3] and Carter and Marsh [5]. A linear Hugoniot equation of form \( U_S = 2.99 + 0.92u_p \) was found which incorporates the experimentally gathered data from ourselves, as well as the data gathered by Barker and Hollenbach, and Carter and Marsh up to \( u_p \) values of 1 mm \( \mu s^{-1} \). Unlike Barker and Hollenbach’s data the Hugoniot is linear in nature. However, as it can be seen with the experimental data from Barker and Hollenbach the two lowest \( u_p \) values are the cause of their Hugoniot’s non-linearity. This behaviour is also expected from our PMMA due to the difference between \( c_B \) and \( c_0 \), but more low \( u_p \) experiments would need to be performed to confirm this.

Figure 4 shows the experimental data plotted in the pressure-volume plane. It can be seen that the experimental data agrees with the calculated Hugoniot \( (P = \rho_0 U_S u_p) \) until a value of between 2.0 and 3.0 GPa. This deviation most likely demonstrates a strengthening behaviour in the PMMA within this region [11].

All of this data suggests that there is inherently less scatter in the shock response of PMMA than suggested by Barker and Hollenbach. This may be due to manufacturing techniques being considerably improved so that the material supplied is more consistent than perhaps it had been previously. It could also be that the non-linearity in the PMMA Hugoniot at the low end exaggerated this scatter of the data.

Using the technique described in reference [10], with the set up shown in figure 2, a shock reloading experiment was performed on PMMA to obtain a value of Grüneisen gamma. Figure 5 shows the experimental data compared to the ANSYS Autodyn® model traces obtained.
Table 2. Experimental results for the PMMA.

| Velocity (ms$^{-1}$) | Flyer Thickness (mm) and Material | $U_S$ (mm$\mu$s$^{-1}$) | $u_p$ (mm$\mu$s$^{-1}$) | Volume (cm$^3$g$^{-1}$) | $\sigma_x$ (GPa) |
|----------------------|----------------------------------|--------------------------|--------------------------|--------------------------|------------------|
| 175                  | 10 Al                            | 3.11                     | 0.13                     | 0.81                     | 0.48             |
| 333                  | 10 Al                            | 3.23                     | 0.26                     | 0.78                     | 0.99             |
| 345                  | 10 Al                            | 3.20                     | 0.27                     | 0.77                     | 1.01             |
| 496                  | 10 Al                            | 3.19                     | 0.39                     | 0.74                     | 1.58             |
| 665                  | 10 Al                            | 3.41                     | 0.52                     | 0.72                     | 2.15             |
| 690                  | 10 Cu                            | 3.69                     | 0.62                     | 0.70                     | 2.89             |
| 702                  | 10 Cu                            | 3.59                     | 0.63                     | 0.70                     | 2.93             |
| 868                  | 10 Cu                            | 3.71                     | 0.77                     | 0.67                     | 4.11             |

Figure 3. Experimental data in the $U_S$-$u_p$ plane.

Figure 4. Experimental data in the Pressure-volume plane.
via varying the Grüneisen gamma value. A lagrangian mesh with a cell size of 10 μm by 20 μm was employed. The copper material model was obtained from the ANSYS Autodyn© material library, with the PMMA from the conducted experiments. Both materials were assumed strengthless in nature. A close match between the experimental and modelling data can be seen for the first shock state plateau; subsequently divergence does occur as time increases becoming evermore prevalent. This is most likely due to the fact that no strength model was employed on the PMMA in the region where strength deviation behaviour was seen (figure 4). This is an interesting result, showing that even a small deviation in model parameters can alter the model massively, especially in shock reloading experiments. More work will be conducted in the future to investigate the strength behaviour to complete the ANSYS Autodyn© model.

4. Conclusion
By using the plate impact technique and manganin gauges the shock response of the polymer PMMA has been investigated. A linear Hugoniot in the \( U_S-u_p \) plane was found to have the equation \( 2.90 + 0.92u_p \), which agreed with the majority of data from both Barker and Hollenbach as well as Cater and Marsh. Potential non-linear behaviour in the \( U_S-u_p \) Hugoniot is expected at \( u_p \) values of below 0.2 mm \( \mu s^{-1} \), however, more experiments would need to be conducted to confirm this assumption. From this data it seems that there is less scatter within the data than previously assumed, possible due to a more consistent manufacturing process. A Grüneisen gamma experiment has been performed but more work is needed to understand strength behaviour before a value of Grüneisen gamma can be estimated.

Acknowledgments
The authors would like to thank Mr Andrew Roberts for experimental help.

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