MEASUREMENTS OF THE CONDUCTIVITY OF SHOCKED POLYMETHYLMETHACRYLATE

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Abstract. Shock polarization and changes in conductivity have been observed in previous electrical investigations of the shock behaviour of crystalline materials. For this reason a differential system has been designed by LLNL to separate these effects in their investigations of the conductivity of sapphire under shock. The measurement removes voltages produced in the shock electrical field allowing determination of those induced by resistance changes. Polymers are, at present, under mechanical investigation at RMCS and experiments are reported in which the thermoplastic polymethylmethacrylate (PMMA) is shocked in the range up to 10 GPa in order to observe its electrical response. The variations in induced field and in the material conductivity are reported.

INTRODUCTION

The response of polymethylmethacrylate (PMMA) to shock loading has excited interest as an example of a thermoplastic below its glass transition temperature. Barker and Hollenbach showed that up to 2.2 GPa, PMMA displays nonlinear behavior, and quote a Hugoniot elastic limit (HEL) of 0.7 GPa (1). This value was determined since the shock velocity became dependent upon the thickness of the sample, (reducing by a maximum of 2%). They suggested that this was due to the strain-rate sensitivity of the material in its plastic response above 0.7 GPa. No obvious change in slope in the particle velocity-time curves was noted, although there was a significant rounding of the upper part of those curves as the maximum particle velocity was reached. This would likely be the result of the nonlinear nature of the shock velocity-particle velocity curve due to the viscoelastic behavior of PMMA. Schuler and Nunziato (2) also report an HEL of 0.75 GPa, derived from analysis of shock-reshock experiments. Below the estimated HEL, the rise of the reshock part of the pulse was fast, indicating that loading was elastic in nature. Above 0.75 GPa, the slope of the reshock was shallower, suggesting that inelastic deformation was taking place.

Shear strength measurements performed in PMMA show an initial increase in shear strength to 7.5 GPa before dropping to near zero (3, 4). Gupta has also detected a drop in shear strength, although he has placed it somewhat lower, around the HEL (5). It is interesting to note that temperature measurements using either thermocouples or thin copper film gauges show a marked increase in temperature at 2.0 GPa (6). Here, results were explained in terms of the onset of a shock-induced, exothermic reaction, possibly due to bond breaking. A similar threshold has been noted by Hauver during measurements of the shock-induced electrical polarization of PMMA (7). Rosenberg and Partom (8) used strain gauges in PMMA to deduce residual temperatures after complete release from shock loading and the tensile strains induced at the spall plane. Here they demonstrated that the measured strain (after complete release) could be related to the residual temperature.
The classic study of Carter and Marsh (9) shows breaks in the shock velocity-particle velocity curves which (they suggested) constituted a phase transformation in the polymers they tested. This is also observed to occur in PMMA and thus it may be of interest to probe the electrical behaviour around this value which is at 26 GPa (9). This is one of the goals of this work.

There are many questions still unanswered concerning the response of the material. One of these relates to the induction of electrical fields across the front when shocked. Polarization has proved a feature of previous electrical investigations of shock behaviour. The deformation process introduces defects which can induce electronic states in the band gap of an insulator. Such changes have been observed in shocked sapphire (10).

To differentiate polarization from resistance change behind the shock, a differential circuit (fig. 1) has been designed for investigations into the conductivity of sapphire under shock (10). The measurement removes voltages produced in the induced shock field allowing determination of those induced by resistance changes. This method thereby avoids the additive measurements of polarization and resistance change previously reported by other groups.

EXPERIMENTAL

The experiments were carried out using 50 mm and a 75 mm bore diameter, single stage guns and a 35 mm bore, (final stage) two stage gun. Impact velocity was measured to an accuracy of 0.5% using a sequential pin-shorting method and tilt was fixed to be less than 1 mrad by means of an adjustable specimen mount. Impactor plates were made from lapped tungsten alloy, copper and aluminium discs and were mounted onto a polycarbonate sabot with a relieved front surface in order that the rear of the flyer plate remained unconfined. Targets were flat to better than 5 μm across the surface. Stress profiles were measured with commercial manganin stress gauges both embedded into the specimens (Micro--measurements type LM-SS-125CH-048).

For the measurement of conductivity change in the sample, the method used for the experiments on sapphire (10) was adapted.

However, Lysne (11) has developed models for dielectric relaxation in polymers that suggest that interpretation of signals attributed to polarisation or to conduction are frequently confused. It will be seen that this may be the case in this investigation.

FIGURE 1. Circuitry for measuring resistance of target. After Weir et al. (10).

FIGURE 2. Experimental arrangement for experiments. a) Longitudinal stress gauge mounting positions with rear PMMA plate. b) Flyer hits target. Electrodes penetrate distance L and are D apart.

Each test was conducted by drilling two 1 mm diameter holes into the surface of the sample. These holes were 3 mm apart and 2 mm from the surface at which a conducting flyer would impact. They were thus located within the region that the lateral releases from the edge of the sample could not penetrate during the loading time of interest. Equally, the electrodes did not penetrate the entire sample. The holes were drilled 2 mm from the impact face so that they did not short to the conducting flyer plate. The drills used for this task were flat-bottomed. Care was necessary to avoid cracks opening up as the brittle polymer was drilled.

The arrangement of the sample and flyer are shown schematically in figure 2. The electrodes were formed by placing flat-ended brass rods into the drilled holes with a low viscosity epoxy around them. By this means the hole is completely filled if correct degassing techniques are used to eliminate bubbles. Two electrodes were placed in
each sample which were connected to a differential power supply.

The electrodes were then soldered to 10 mm thick copper shims which were then taken out laterally for connection to the positive and negative poles of the differential power source. The surface of the tile has a copper electrode of thickness 25 μm bonded to it which is earthed to remove any possibility of any stray charge on the flying plate. The earth plane is defined to be a point on the metal gun framework adjacent to the sample mounting.

In all experiments, the shock wave would thus travel for a distance after impact and then sweep the length of the electrode. Clearly, any damage introduced by drilling would be encountered by the shock but this was discounted as shot to shot reproducibility was good. The PMMA target was machined and lapped on its front surface to remove any surface inhomogeneities and to ensure a flat impact face. There were no voids visible in the microstructure under optical examination.

RESULTS AND DISCUSSION

![Figure 3](image)

**FIGURE 3.** Two pairs of traces for the positive and negative electrodes. There are two experiments, at nominally the same impact stress, shown for comparison. One pair is dark and the other dotted. Note similar features illustrating reproducibility.

Figure 3 shows a pair of experiments showing induced voltages on the electrodes under nominally the same conditions. The two sets of traces are shown to emphasise the reproducible nature of the experiments. In both cases a copper impactor hits a PMMA target at a velocity of ca. 550 m s⁻¹ inducing stresses of ca. 2 GPa. This represents one of the thresholds in behaviour noted earlier (for in this case, the onset of temperature rise in the material). The voltages induced on the conducting electrodes at these stresses are the order of mV. Note that there is a rise and then fall at the start of the trace (of ca. 1 μs) which is believed to be induced before the arrival of the wave at the electrodes. The voltage then drops to a plateau for 2 μs until a release enters from the rear of the flyer plate perturbing the system. The other traces observed in the following study are typical of this form.

![Figure 4](image)

**FIGURE 4.** Traces on positive and negative electrodes for the impact of a 3 mm thick tungsten alloy flyer plate travelling at 805 m s⁻¹. The shock induces a negative spike of ca. 10 mV before it reaches its base. The positive electrode is dark whilst the negative is dotted.

The histories of fig. 4 show a similar form. This time the stress has been increased to a value ca. 3.5 GPa. The initial negative polarisation signal is increased in magnitude to its value at the lower stress. As the wave encounters the end of the electrode, the trace steady and both remain at zero until around 2 μs. At this time releases from the rear of the flyer plate enter the target interacting with the electrodes and the compressed material around them.

It is interesting to note that here, and in fig. 3, the signals show diverging positive and negative branches at ca. 2.8 μs, reminiscent of what is expected to occur should conduction begin. This time corresponds to the arrival of the compression wave at the free rear surface of the target and as the wave front reflects, the signal magnitude increases at both electrodes. This may reflect
increased shocked area as the legs have been reached.

The next shots showed similar results at higher stress to those shown earlier. No conduction was observed to occur but the polarisation signal increased in value although keeping the same sign.

**FIGURE 5.** Traces on positive and negative electrodes for the impact of a 2 mm thick tungsten alloy flyer plate travelling at 1787 m s⁻¹. The shock induces a negative spike of ca. 15 mV before it reaches its base. The positive electrode is dark whilst the negative is dotted. The signals both rise as the shock sweeps the electrode. A dashed free electrode was also included to investigate the polarisation signal.

Fig. 5 shows results of traces taken from one of the higher stress experiments conducted. This was at 10.1 GPa. The shock induces a negative spike of ca. 15 mV before it reaches the electrodes’ base. The positive electrode is dark whilst the negative is dotted. Traces are seen to rise slowly over the microsecond of loading but then the signals digress under action from release interactions. The signals both rise as the shock sweeps the base of the electrodes. A feature of fig. 5 is a signal recorded on a free, unbiased electrode introduced into the sample along with the other two to track the polarisation. Note the magnitude of the voltages induced which are found on the right-hand scale. The signal at this stress is of order 100 mV and is negative. Thus the magnitude of the induced signal measured has increased an order of magnitude in the series of experiments reported.

Other experiments were done at higher stresses but none more than 10.8 GPa. Thus the goal of reaching the break in $U_s - U_p$ (9) was not achieved. At these stresses, the polarisation signal was smaller and the stress plateaux were at the level of the very first shots done.

**CONCLUSIONS**

A series of experiments have been described in which the method of Weir et al. (10) has been adapted for measurements of the conductivity of ionic solids which behave as insulators under ambient conditions.

PMMA was chosen since previous electrical measurements had tracked its dielectric properties (7). In none of the experiments conducted (up to a value of 10.8 GPa) did the material conduct. It was only in the very highest stresses achieved that the signals at the electrodes rose at all. This suggests that the material is indeed a good insulator. It was not possible to reach some of the higher mechanical thresholds but further work is planned to address these issues.

Induced electrical fields across the shock front were measured at all levels studied and these were not observed to change direction with increasing stress in the range considered although their magnitude increased by an order of magnitude.

**REFERENCES**


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