RESPONSE OF THE POLYMERS KEL-F, POLYSULFONE, HIGH DENSITY POLYETHYLENE AND POLYMETHYLMETHACRYLATE TO SHOCK LOADING AND RELEASE FROM 0.3 TO 2.4 GPa
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The Bauer PVDF stress-rate gauge has been used to study the response of the cited polymers from measurements at the impact surface and "in-situ" at sample thicknesses of 1.5 and 3 mm. The PVDF stress-rate dependent piezoelectric output combined with appropriate signal recording techniques allow accurate recording over the broad range of stress rates encountered during shock compression of polymers. Strong viscous response effects are observed. The release velocity is found to increase strongly with pressure, and the release-rate history is recorded with PVDF as a continuous function of pressure.

1. INTRODUCTION

Polymers have been extensively studied under high pressure shock compression¹; most of the data, however, have been obtained at relatively high pressures. At low pressures, Schuler, et al² have shown the strong viscoelastic behavior of PMMA and developed theory to describe the behavior. In spite of the technological importance of polymers there are relatively few data on their low pressure responses. The present paper gives a brief report of the shock-loading and release behaviors of the four cited polymers. Use of the PVDF stress-rate gauge provides detail of strong viscoelastic responses as well as precise shock-and release-wave behavior.

2. EXPERIMENTAL TECHNIQUE

Impact-loading experiments, precisely controlled in velocity and tilt, were conducted on each polymer at pressures from 0.3 to 2.4 GPa on the Sandia research compressed-gas gun³.

2.1 Mechanical arrangement

The shock-loading experiments used a symmetric impact loading of the target with PVDF at the impact surface and "in-situ" at sample thicknesses of 1.5 and 3 mm. The impactor, target and backer materials were all the same material in a given experiment. Precise impact velocity measurements, accurate time-resolved pressure measurement, and an accurate transit time measurement through the polymer sample, were used to determine the shock compression response of each polymer.

The impact loading was provided by a 1-kg aluminum projectile with a polymer facing, thicknesses of

2.5 to 3.9 mm, a free rear surface to provide well defined shock-loading and release with a predetermined pulse duration, and impact velocities of 0.13 to 1.3 km/sec.

The flexible nature and poor bonding properties of the polymer samples as well as the extraordinary response sensitivity of the PVDF gauge required that special assembly procedures be used for the sample construction. All polymer samples were machined and lapped. The fluorinated polymers were then prepared for bonding by an etching process that removes the fluorine from the surface layer. Each sample dimension was carefully measured ($\pm .0005$ mm) and weighed ($\pm .0005$ gram) for density calculations and bonded to PVDF gauges on an optically flat press.⁴ Care was taken to apply only enough pressure to achieve a thin epoxy bond (.002 to .005mm). Excess pressure will deform the sample and potentially crack the epoxy bond after curing.

2.2 Electrical arrangement

The electronic recording system consisted of 1-GHz bandwidth Tektronix DSA 602 digitizers connected to low-loss, coaxial transmission cables (Andrews LDF5-50A) 12.2 meters in length, that measured the electrical current produced from the PVDF during shock compression. These digitizers provide the stable baseline needed to accurately carry out the measurement.

The piezoelectric current-mode response provides the minimum inductance circuit required for the GHz signals and gives a direct measure of stress-rate, an extraordinarily sensitive description of material response.⁵ Stress-versus-time responses are obtained from the charge derived from numerical integration.

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The electrical circuit consists of a precision current-viewing resistor (CVR) across the electrodes of the gauge that is connected in parallel to the two low-loss cables with two disposable RG-223 jumper cables 0.6 mm in length. The standard method of recording the PVDF signals is with two Tektronix DSA 602 digitizers, one connected to each gauge sampling at the maximum rate of 500 ps/point, while a third DSA 602 operated in two-channel mode at increased sensitivity provides a common time base between the two PVDF gauge locations and accurately records the lower stress rates. The proper selection of CVR resistance⁶ allows the voltage amplitude to be reduced to an acceptable level; typically resistances of 0.010-0.2 Ohm are used.

Figure 1 Mechanical and electrical configuration for shock compression measurements.

PVDF offers many unique features for measuring shock compression profiles.^{7,8} The Bauer PVDF stress-rate gauge⁵ used to record the shock response of these polymers is a piezoelectric polymer film that, appropriately treated, exhibits piezoelectric properties suitable for a wide variety of applications.

2.3 Materials sources

Kel-F 81 1.5" bar, Afton Plastics, Lakeland MN. Polysulfone UDEL P-1700 resin, 1.25" bar, Union Carbide Corp., New York, NY. High density polyethylene, Marlex HMN 6060 resin, 1/2" sheet, Phillips Chemical Company, Bartlesville, OK. Polycast Poly II 1" sheet, batch #951105Q, Polycast Technology Corporation, Stamford CT.

3. RESULTS

3.1 Shock response

During the abrupt shock loading imposed on each of the polymers, the typical loading response is a shock

followed by a region of lower stress due to viscous relaxations slowly increasing the pressure to equilibrium values. The rise time of the shock portion of the stress pulse is less than the transit time of the shock wave through the PVDF (typically 6-10 ns). This has previously been referred to as thick-gauge mode in the context of the Sandia quartz gauge, where the sensing element is thick, relative to the stress pulse rise time.^{9,10} The relaxations observed are typically hundreds of nanoseconds in duration with correspondingly low stress rates and currents, as seen in Figure 2.

Figure 2. Shock induced PVDF piezoelectric polarization measured in current mode and resulting stress wave profile (Inset shows sensitive second channel).

The typical dual sensitivity method of recording employs a primary channel to capture the shock jump, and one or more sensitive channels (10:1 to 100:1 sensitivity ratios are used), to monitor small-amplitude deviations from the base line, which correspond to small stress rates. The dual recording is shown in Figure 2. After reverberations within the gauge, the pressure recorded by the PVDF reaches an "instantaneous" in-material pressure, and the current slowly returns to the baseline as the material viscous behaviour equilibrates to an "equilibrium" pressure state that occurs typically within hundreds of nanoseconds, see Table 1. (Figure 3 illustrates a gradual pressure rise for nearly 1 microsecond.) The recorded data on both channels are combined for times after which the shock-induced current pulse has returned to the region of sensitivity

recorded by the baseline channel by overlaying the primary and baseline channels, after finding a common point that allows for amplifier overdrive recovery.

Observed stress-time relationships of the polymers consist of an initial shock jump in the polymers to an "instantaneous" stress-time state, followed by viscous relaxations. This behaviour is typically observed in polymeric materials and has been extensively studied in the PMMA.²

3.2 Viscous response

The observed stress vs. time profiles clearly show the strongly viscous response features typical of polymeric materials.² The analysis of viscous behaviour is complex and requires considerable effort and possibly further experimentation. Figure 3 shows a typical impact surface and propagated wave profile measurement made in high density polyethylene. A release wave from the impactor rear surface arrives at the impact gauge shortly after the "in-situ" gauge is released from the backer rear surface. The inset shows the PVDF current-time recording of release-rate behavior which provides a time resolved record of stress rate of release.

Illustrated are estimates of the instantaneous and equilibrium stresses at the impact surface, compared with the propagated-wave profile through 1.5 mm of high density polyethylene. It is clear that viscous effects are

very strong, and in some cases, equilibrium behavior is not achieved in the time scale of the measurement. Some inconsistency has been observed with the sample thickness, which may result from lack of uniformity in the polymer samples or nonsteady wave propagation.

Figure 3. Impact surface and propagated wave profiles in high density polyethylene show initial shock jump followed by viscous relaxations. Inset shows the PVDF current-time recording of release-rate behavior and resulting release wave profile. A reflected shock from "in-situ" PVDF is seen at 1.5 μ sec on the impact gauge.

3.3 Release response

The polymers are studied under shock-loading in detail, followed by a shock un-loading or release from

Table 1. SUMMARY OF IMPACT EXPERIMENT MEASUREMENTS

Exp.#1	Impact velocity (km/sec) ²	Shock velocity (km/sec) ³	Release velocity (km/sec)		Impact Surface Stress (GPa)		Propagated wave Stress (GPa)		$\sigma=\rho_0 Uu$ (GPa)
			impactor	backer	inst. ⁴	equil. ⁵	inst. ⁴	equil. ⁵	
<u>Kel-F</u> ($\rho_0=2.139$ gm/cm ³ $\pm 0.5\%$)									
2364-1.5	0.130	2.020	---	2.369	0.24	0.28	0.22	0.27	0.281
2365-3	0.136	2.059	---	---	0.29	0.31	0.27	0.31	0.299
2346-1.5	0.766	2.665	4.051	4.194	2.22	2.39	2.17	2.43	2.183
2347-3	0.783	2.647	---	4.178	2.00	2.21	2.20	2.33	2.218
<u>Polysulfone</u> ($\rho_0=1.233$ gm/cm ³ $\pm 0.5\%$)									
2353-3	0.213	2.484	2.774	3.122	0.27	0.29	0.24	0.29	0.326
2352-1.5	0.218	2.456	2.974	---	0.28	0.31	0.25	0.29	0.330
2358-3	1.196	3.293	---	---	2.17	2.41	1.89	2.10	2.428
2366-1.5	1.217	3.139	---	3.97	2.35	2.58	2.26	2.54	2.357
<u>Polycast</u> ($\rho_0=1.183$ gm/cm ³ $\pm 0.5\%$)									
2372-1.5	0.190	2.915	---	3.355	0.30	0.33	0.30	0.33	0.327
2381-3	0.198	2.990	4.635	3.290	0.32	0.35	0.30	0.34	0.350
2370-3	1.132	3.350	7.15	6.05	2.16	2.40	1.93	2.23	2.243
2369-1.5	1.136	---	---	---	---	---	2.04	2.30	---
<u>High Density Polyethylene</u> ($\rho_0=0.955$ gm/cm ³ $\pm 0.5\%$)									
2385-3	0.221	2.730	3.250	3.555	0.24	0.27	0.21	0.25	0.288
2386-1.5	0.928	3.439	5.120	5.071	1.41	1.54	1.38	1.51	1.524
2380-3	1.302	---	---	---	---	---	2.22	2.43	---

¹ Experiment number-nominal sample thickness in millimeters. ² Projectile impact velocity measurement, 0.1% accuracy. ³ Average shock velocity measurement through sample, 0.8% accuracy for 1.5mm sample, 0.4% accuracy for 3mm sample. ⁴ PVDF instantaneous stress ⁵ PVDF equilibrium stress

pressure where not only the release wave velocity is identified, but a continuous release-rate versus time profile is recorded, as seen in Figure 3. The release wave (adiabatic sound speed) velocity is observed to increase strongly with pressure, typical of a compressible polymeric material,² and gives the local slope of the pressure versus volume relationship for each material as shown in figure 4 for Polycast (UVIUA PMMA), high density polyethylene and polysulfone. Further study is needed to quantify the rich details of the release behavior observed with the PVDF stress-rate gauge, but the present work allows for preliminary modeling of the studied polymers under shock compression and release.

Figure 4 Shock velocity versus particle velocity shows polymeric release behavior as a function of stress. High density polyethylene data are solid markers for clarity.

4. DISCUSSION

The polymer shock response data show good agreement with independent researchers reported work and provides details of strong viscoelastic responses. The release speed versus particle velocity relationship has not been previously reported except for the PMMA response by Schuler et al². The present data show higher velocities, perhaps due to thinner samples.

The release-rate measurement as a continuous function of pressure is a new technique which presents a new capability to study details of release behavior.

The PVDF measures the pressures caused by initial reverberations due to impedance mismatches of the PVDF and the host material. Analysis of these initial pressure states is expected to give a first approximation of the Hugoniot for 25 μm thick biaxially stretched PVDF.

5. CONCLUSION

The collection of shock response data in the present work give a unique set of low pressure data on the cited polymers. The PVDF recording sensitivity is uniquely useful. More work is needed to develop a better understanding/interpretation of the shock loading and release behavior of these polymers.

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