CONF-890811--20

Received by OSTI

MAR 27 1989

DETONATOR RESPONSE MEASUREMENTS WITH A STANDARDIZED PIEZOELECTRIC POLYMER (PVDF) GAUGE

SAND--88-1519C

DE89 008678

Larry M. Moore
Explosive Projects and Diagnostics Division, 2514
R. A. Graham
Shock Wave and Structural Physics Division, 1153
R. P. Reed
Field Measurements Division, 7116
Sandia National Laboratories
P. O. Box 5800
Albuquerque, New Mexico 87185

and

Larry M. Lee
Ktech Corporation
901 Pennsylvania NE
Albuquerque, NM 87110

Time-resolved measurements of pressure profiles from the detonation of explosive devices can provide critical information on device performance. The special problems presented by the small size of the piezoelectric polymer gauges and nonplanar impacts are studied over a range of impact conditions. The response of PVDF gauges under precisely controlled impacts shows highly reproducible results to pressures of 20 GPa. Under approximately planar loading with small detonator flyer plates, the PVDF signals appear to be reduced by about 15%. For highly nonplanar flyer impacts the PVDF signals are reduced by about 35%. In all stress environments, high quality, time-resolved current pulses are observed.

INTRODUCTION

Knowledge of the response of explosives and explosive devices is, in large part, based on measurements describing the detonation process or the resulting stress pulses produced by the explosive event. Although relatively crude measurements can be used to indicate that a detonation event has occurred, modeling of detonation processes and quantitative design of explosive devices requires time-resolved measurement. At present, most of the time-resolved observations are made with particle velocity measurements with the VISAR or electromagnetic particle velocity gauges, or stress measurements with the Manganin or other piezoresistant gauges[1].

Over the last few years, there has been considerable work in progress to study the features of the piezoelectric polymer film polyvinylidene fluoride (PVDF) under high pressure shock loading[2-4]. Although full characterization of the material is not complete, it is clear that if the material is prepared with careful attention to the mechanical processing (stretching) and to the electrical processing (electrical poling), that highly reproducible responses can be achieved to shock pressures of over 40 GPa. The range of pressure accessible for measurement, the unobtrusive nature of the thin film, the simplicity of the circuitry and the large signal levels from such PVDF gauges are highly desirable features for a gauge. In addition, if the output of the gauge is monitored in a "current mode," the measured current provides a measure of the stress-rate. Thus, a far more sensitive measure of details of the stress profile can be obtained with PVDF than heretofore possible.

Present interests in detonator performance require measurements over dimensions smaller than about 5 mm, thus a gauge for such a measurement must be no larger than about 1 mm. With a typical film thickness of 25 microns, two-dimensional electrical field fringing is expected to influence both the electrical poling process in gauge preparation and gauge measurements.

The purpose of the present study is to characterize the shock-compression response of a 1 mm x 1 mm

active area PVDF gauge that is subject to standardized gauge-preparation processes. The shock response is studied in both compressed-gas gun, controlled impact loading and in detonator loading configurations. In the present paper, a brief summary of standardization processes will be described, followed by a description of the controlled impact loading and the detonator-response measurements.

PVDF PIEZOELECTRIC POLYMER MATERIAL[5]

Although a chemical characterization of the present material as PVDF indicates a common basis for a starting material, it does not adequately describe electrical, mechanical and other physical properties. Both mechanical and electrical processing have a strong influence on the structure of PVDF. The piezoelectric and pyroelectric properties desired for most uses of the polymer derive from processing that produces a polar crystalline phase, designated the β phase. Well prepared film may have up to 50% crystalline material, but the composition of any film depends upon the mechanical processing which is accomplished with mechanical stretching. The largest concentrations of β-phase PVDF are achieved with biaxial stretching, which has been found to be essential to produce high quality film.

Once formed by the mechanical treatment, the β-phase crystallites must be aligned electrically to achieve a state of remanent ferroelectric polarization. As a typical ferroelectric, the treated film has physical properties controlled substantially by the remanent polarization which may typically vary from 2 to 9 $\mu C/cm^2$. Even in a high remanent-polarization state, it should be recognized that the film is heterogeneous, both mechanically and electrically due to the presence of both amorphous and β-phase material and internal fields due to heterogeneous distribution of polarization. At best, high quality PVDF film is substantially more complicated than piezoelectric crystals such as quartz[6] or lithium niobate[7] which have been used in the past for time-resolved measurements of shock-compression stress pulses.

In order to achieve a highly reproducible material, Francois Bauer of the Institut de Saint-Louis in France has developed a patented process[8-9] to electrically treat good mechanical-quality PVDF film to achieve a reproducible and internally uniform state of electrical polarization. As shock gauges are destroyed in use and must be studied over an extended period of time to characterize the response, such reproducible starting material must be in hand before a credible shock gauge can be developed. In a cooperative program with Bauer, our laboratory has worked to standardize a PVDF gauge sensing element and carry out its characterization under high pressure shock loading. As there is no unique set of properties for PVDF without specifying the processing, it is necessary to designate a particular grade of PVDF which follows the processing procedures recommended by Bauer.

STANDARDIZED PVDF GAUGE

The principal features of the standardized Bauer PVDF shock gauge are:

1. High quality, biaxially-stretched PVDF film.
2. Polymer film thickness of nominally 25 micron.
3. Sputtered gold-over-platinum strip electrodes and leads.
4. Remanent ferroelectric polarization of 9.2 $\mu C/cm^2$.
5. Quantitative specification of physical and electrical characteristics.
6. Bauer electrical poling process.

For the gauge elements of the present report, the film was formulated and biaxially-stretched by the Rhone Poulenc Company of Lyon, France, in a batch of material designated RPB by our working group. The electrode plating and electrical poling was carried out by the Metravib Company of Lyon, France at a laboratory in Saint-Louis, France. A batch of 100 gauges was produced with a remanent polarization of $9.15 \pm 0.15\ \mu C/cm^2$, $d_{33} = 20.2 \pm 1.4$ pC/N and relative dielectric constant 12.7 ± 0.7. Both controlled projectile impact and detonator response studies were carried out on this batch of gauges. Other batches of biaxially-stretched film from this supplier have been found to achieve the standardized polarization and other material constants within similar ranges.

COMPRESSED-GAS-GUN EXPERIMENTS

The experimental arrangement used to characterize the Bauer PVDF gauge elements is similar to that used previously for study of quartz[6] and lithium niobate[7] gauge crystals, in that standard materials are used for impactors and targets under planar low-tilt projectile impact configurations. Impact velocities are measured to an accuracy of less then 0.1%. A schematic drawing of the arrangement is shown in Figure l.

For the stress range from about 2 to 7 GPa, z-cut quartz crystals are used as impactors and targets for standards to establish the stress imposed on the PVDF. For the stress range of about 5 to 18 GPa, z-cut sapphire crystals are used for standards. These two crystalline materials remain elastic to stresses approaching 20 GPa. With the use of such high quality, single crystals, material properties are reproducibile within a few tenths of a percent and the release-wave behavior is not influenced by elastic-plastic response. For stresses less than 2 GPa, the polymer, Kel-F, is used as the standard. Although reproducibility of shock properites of such a polymer will not approach that achieved by quartz and sapphire, there is sufficient data in the literature to support an accurate stress calculation. Kel-F matches the shock impedance of PVDF to a good approximation. At stresses higher than 20 GPa, a tungsten carbide, Kennametal 68, is used for the standard. The properties of this material are under study.

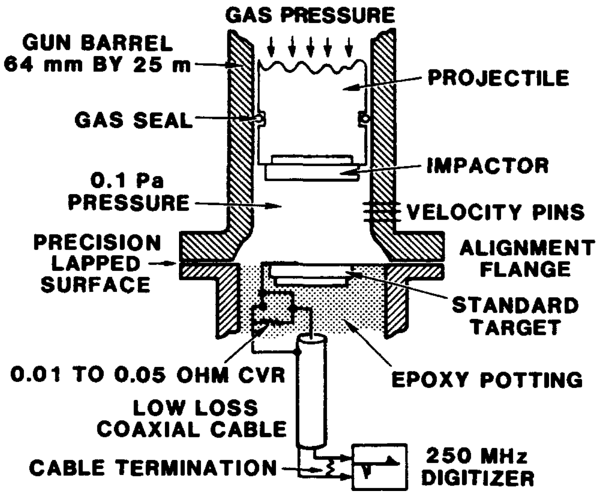

FIGURE 1. IMPACT LOADING CONFIGURATION.

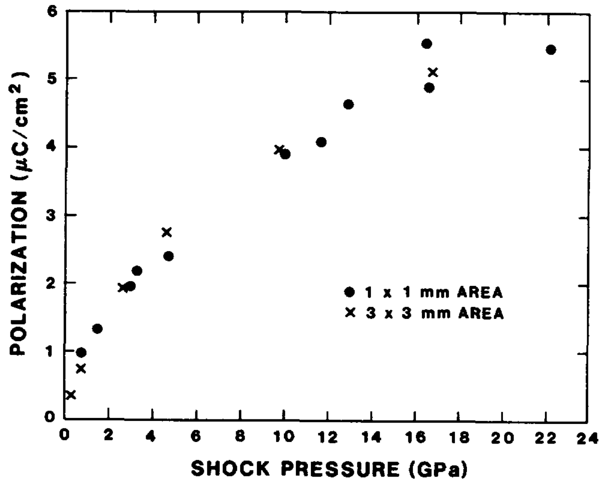

FIGURE 2. PVDF GAUGE CHARGE AS A FUNCTION OF STRESS.

To achieve well defined impact conditions, the gauge elements are bonded directly on the impact surfaces of the targets. For the tungsten carbide targets, a 12 micron thick film of PTFE (Teflon) is placed on either side of the PVDF film for electrical insulation because PTFE does not shock-polarize at the stress levels encountered. In this configuration, the gauge element is subjected to an initial stress determined by the shock impedances of the impactor and gauge element and subsequently "rings-up" to a final pressure determined by the shock impedances of the target and impactor. At low pressure, the transit time is typically 11 nsec, and at higher pressure the time is typically 5 nsec. Because the loading is rapid relative to the transit time, the loading in this configuration produces a lower temperature rise from shock-induced heating than in a direct shock to the peak pressure.

The electrical response of the PVDF elements is recorded on Le Croy 6880 digitizers with a digitizing rate of 0.742 nsec, a vertical resolution of 8 bits and a frequency response of 250 MHz. Other digitizers have been found to be inadequate to accurately record the very rapidly varying signals. Signals are transmitted from the gauge element to the digitizer through a length of about 13 metres of Andrews LDF-50, a low-loss coaxial cable (2.4 dB/100 ft at 1GHz).

The recorded current-versus-time pulses are integrated and processed in a special data-reduction program which has been compared to an another program developed independently by Bauer. Comparison of data processed by either program has been found to agree within a range of ±2 percent.

A summary of the experimental configurations and piezoelectric response data is shown in Table 1. The plot of shock-induced piezoelectric current observed at various peak shock pressures is shown in Figure 2 for 1 mm^2 active area gauges studied in this work. For comparison, earlier reported data on larger gauges (9 mm^2 active area) which are much less influenced by electrical field fringing are shown.

DETONATOR RESPONSE EXPERIMENTS

Two types of detonators were used in this series of experiments. Both devices use the explosive compound 2-(5-cyanotetrazalato) pentaamminecobalt (III) perchlorate (abbreviated CP[10]) which undergoes a deflagration-to-detonation transition (DDT[11]). The first device to be tested will be referred to as the Mod E test detonator. It was designed to meet the need for a relatively simple test device which could be used for studies of design parameters for the application of the explosive CP. The detonator consists of two pressings of energetic material in the igniter region and four in the output region for a nominal total mass of 130 milligrams. The second device to be tested will be referred to as the 4mm (the diameter of the flyer) system detonator. Six pressings of CP are used in this detonator, also. There are three pressings in the igniter region and three in the output region for a nominal total mass of 180 milligrams of CP.

EXPERIMENTAL ARRANGEMENTS

A fixture has been developed to precisely mount and align the PVDF gauge and the detonator. Figure 3 shows an exploded component view of the gauge assembly, the base plate and the alignment bridge. A 12 micron thick Teflon film is used to electrically isolate the gauge from the stainless-steel closure disk placed on the end of the detonator. A thin-film Hysol epoxy (2038 resin and 3404 hardener) is used to bond the Teflon film to the gauge and the gauge to the backing material.

TABLE 1. Piezoelectric Polymer (PVDF) Impact Response Measurements (1x1 mm active area)

Experiment Number	Configuration[a] Impactor-----> Target	Impact Velocity km/sec	Initial Stress[b] GPa	Peak Stress[c] GPa	Electrical Charge $\mu C/cm^2$
2259	Vac/Kel-F---> PVDF/Kel-F/Air 5.08/4.73 .025/3.12	0.292	0.70	0.70	0.961
2260	Vac/Kel-F---> PVDF/Kel-F/Air 5.08/4.74 .025/3.13	0.535	1.40	1.40	1.33
2233	Vac/ZSiO2---> PVDF/ZSiO2/Air 5.08/4.77 .025/3.19	0.320	1.27	2.79	1.96
2263	Vac/Kel-F---> PVDF/Kel-F/Air 5.08/4.75 .025/3.10	1.021	3.11	3.11	2.19
2239	Vac/ZSiO2---> PVDF/ZSiO2/Air 5.08/4.76 .025/3.18	0.503	2.14	4.47	2.41
2240	Vac/ZAl2O3--> PVDF/ZAl2O3/Air 5.08/4.75 .025/3.18	0.416	2.07	9.50	3.92
2241	Vac/ZAl2O3--> PVDF/ZAl2O3/Air 5.08/4.75 .025/3.18	0.485	2.48	11.1	4.09
2256	Vac/ZAl2O3--> PVDF/ZAl2O3/Air 5.08/1.57 .025/4.74	0.537	2.83	12.3	4.65
2251	Vac/ZAl2O3--> PVDF/ZAl203/Air 5.08/4.67 .025/3.18	0.683	3.80	15.7	5.53[d]
2242	Vac/ZAl2O3--> PVDF/ZAl203/Air 5.08/4.74 .025/3.18	0.690	3.87	15.8	4.90
2243	Vac/WC------> PTFE/PVDF/WC/Air 5.08/3.17 .012/.025/3.18	0.466	-.--	21.1[e]	5.47

[a]Impactor and target thicknesses are listed in millimeters.
[b]The initial stressis that produced by the impact of the impactor on the gauge whose Hugoniot is taken as corresponding to Kel-F.
[c]The peak stress is taken as that achieved by the direct impact of impactor and target. It is achieved by the reverberation of the initial shock between target and impactor.
[d]The active area of this gauge was not confirmed prior to use and may have been in error.
[e]Hugoniot properties of the WC (tungsten carbide, Kennametal 68, 15.0 Mg/m^3) are being refined at this time.

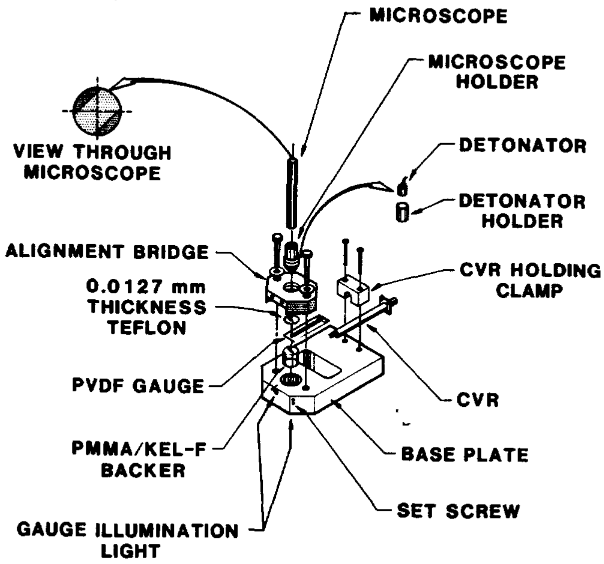

FIGURE 3. MOUNTING FIXTURE FOR DETONATOR AND PVDF GAUGE

The backing material (the flyer target material) is either of the two polmers, Kel-F or PMMA. These materials are chosen for their known shock-Hugoniot properties.

For assembly, the gauge is approximately centered on the backer, bonded to the backer and the assembly is cured at ambient temperature under pressure overnight. A microscope (2OX) and holder, mounted in an alignment bridge, are then used for precise alignment of the detonator and gauge active area. The insert shown in Figure 3 indicates the view seen through the microscope. After alignment the bolts holding the bridge to the base plate are firmly tightened. This procedure centers the detonator over the active area of the gauge to within .15 mm. A detonator with its holder then replaces the microscope/holder. The unit can be set in contact with the gauge for direct contact use or a Teflon spacer may be used to position the detonator for use in the flyer-plate mode. The holders are destroyed in each shot, but the assembly is designed for reuse of the bridge/base-plate unit.

It is important to observe that in this configuration the PVDF gauge surface is within 12 microns of the impact surface and that its sensing area is about one-quarter of the flyer diameter.

INSTRUMENTATION

The instrumentation used in these experiments is shown in the block diagram of Figure 4. The current pulse from the gauge is split at a current viewing resistor (CVR) with an N type tee so that a primary and secondary channel may be recorded. Each cable is terminated with its characteristic impedance of 50 Ohms. The vertical amplifier sensitivity of the primary channel is normally set to achieve good resolution with the secondary channel set less sensitively to assure recording of the signal without clipping.

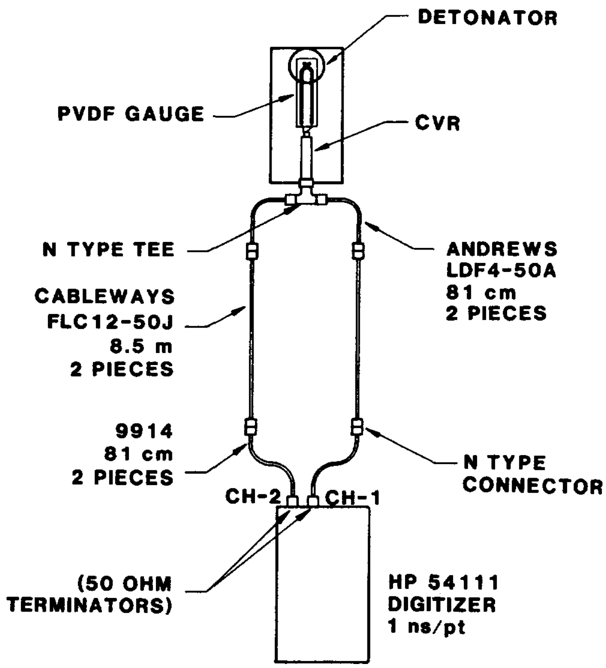

FIGURE 4. INSTRUMENTATION BLOCK DIAGRAM FOR DETONATOR TESTS.

Low-loss coaxial cables, such as Cableways FLC12-50J (1.37 dB/100 ft at 1 GHz), are used to prevent distortion of the several nanosecond duration current pulses. A Hewlett-Packard 54111 waveform digitizer was used to record the signal at 1 nanosecond/point sampling rate. This digitizer has a 6-bit vertical resolution and a 250 MHz frequency response. Control of the waveform digitizer as well as analysis of the data is done by a Hewlett-Packard desktop computer.

The experimental arrangement shown is conceptually simple with the electrical signal to noise ratio large and easy to record. Nevertheless, the signals are typically pulses whose durations and period are tens of nanoseconds wide signals, and details of the digitizer capabilities can influence the recording.

A typical current-time trace observed for the MOD E test detonator is shown in Figure 5. Note that the current pulse follows the stress-rate and is therefore a very sensitive indicator of the pulse. Upon integration, the stress-time pulse is obtained as shown in Figure 6.

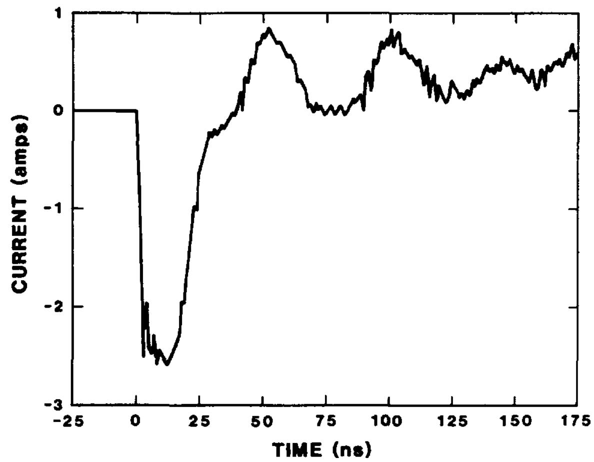

FIGURE 5. TYPICAL CURRENT VS. TIME WAVEFORM FOR MOD E TEST DETONATOR. EACH OF THE POSITIVE CURRENT PULSES REPRESENT A WAVE REVERBERATION THROUGH THE FLYER.

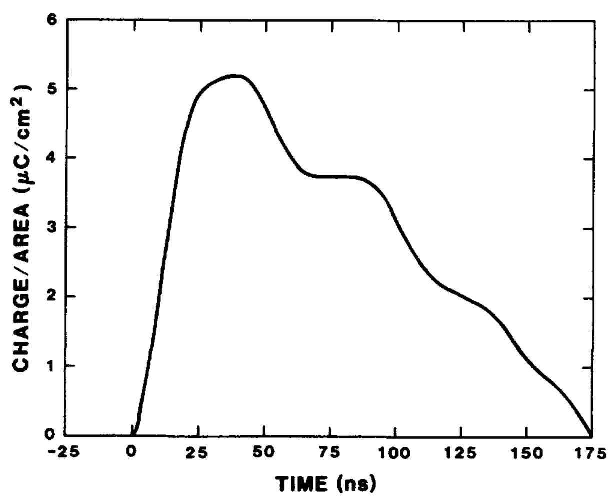

FIGURE 6. TYPICAL CHARGE/AREA VS. TIME WAVEFORM FOR MOD E TEST DETONATOR.

An important tool for our comparison experiments was the VISAR[13] (Velocity Interferometer System For Any Reflector). Both free surface and particle velocity measurements were done for comparison information. This measurement monitors a laser beam that is typically 100 microns in diameter reflected at a local surface to provide a time-resolved particle velocity profile.

MOD E TEST DETONATOR

The MOD E test detonators are single bridgewire units in which the CP explosive is pressed in a precisely controlled operation. They are positioned 1 mm (± .025 mm) above the gauge active area using a Teflon spacer. This distance corresponds to the flight distance at which the flyer velocity is evaluated with VISAR measurements. A 3.3 mm diameter by 127 micron thick stainless-steel closure disk is welded on the end of the detonator. This closure disk is the flyer propelled by the detonation. Five independent measurements of flyer velocity at 1 mm show a mean value of 2.52 km/sec with a variability of 3%. Errors in the flyer travel distance of 25 microns will produce an error in velocity of no more than 2.5%.

The averaged measured charge/unit area from the PVDF gauges for these four detonator flyer plate responses is found to be 5.2 $\mu C/cm^2$, with a variability of 0.1. The mean pressure computed from the charge measurements in the gas-gun responses is 18.8 GPa. The measured flyer velocity was used to compute a pressure assuming the gauge/Teflon cover to be impedance-matched to the Kel-F backer. This idealized, one-dimensional shock pressure of 22.4 GPa assumes steady, planar conditions within the measuring space. Thus, the PVDF gauge appears to indicate a pressure about 15% lower than the expected value under the loading conditions of this detonator.

4mm SYSTEM DETONATOR

The 4mm detonators are typical of those detonators produced in large scale production. They were tested in the flyer mode in the same manner as the previous detonators. Even though the configuration of the energetic material is the same in this device as in the MOD E test detonator, they were initiated asymmetrically by one of two bridgewires in the device. Because of this single-wire initiation, the flyer is strongly non-planar in flight and at impact. Measurements of the planarity by T. Warren[14] at the Pantex Plant of Mason & Hanger are summarized in Figure 7 and show the leading edge of the flyer impacts on a point near the outer edge of the PVDF gauge. The following surface of the flyer completes the impact about 25 nsec later. The planarity data of Figure 7 also show that the MOD E test detonator (label precision in Figure 7) and the dual-bridgewire ignited 4mm system detonator show significantly better planarity.

Seven VISAR flyer velocity measurements showed a mean flyer velocity of 2.49 km/sec with a variability of 4%. In the experiments on this detonator, transparent PMMA backers were used so that "in-material" particle velocity measurements could be carried out by VISAR simultaneously with PVDF gauge measurements. The VISAR particle velocity measurements were found to have a much larger spread (12%) than the variability in flyer velocity, and were found to be about 3% lower than that predicted from the idealized flyer impact conditions.

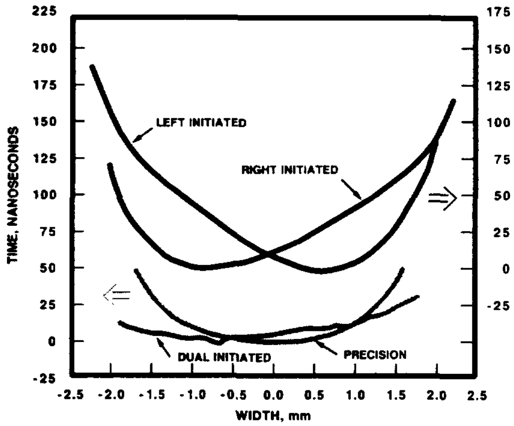

FIGURE 7. FLYER PLANARITY FOR THE MOD E TEST DETONATOR, THE SINGLE BRIDGE AND DUAL BRIDGE IGNITED 4mm SYSTEM DETONATOR

The average pressure measured by the PVDF gauge (using the PVDF gas-gun response data for conversion of charge/unit area to pressure) was found to be 10.4 GPa with a spread in value of about 10%. This value of average pressure under these high nonplanar conditions is about 35% lower than that predicted from the flyer-velocity measurements and that measured in the "in-material" VISAR particle velocity measurements. In every case, however, a well characterized, repeatable current pulse was observed with features corresponding to release waves in the flyer after impact.

CONCLUSIONS

In the present work the response of small diameter PVDF piezoelectric polymer gauges has been investigated under a wide range of impact conditions. They include ideal, precisely controlled impact conditions, less ideal but approximately planar, small diameter flyer impact conditions, and highly nonplanar small diameter flyer impacts. The present PVDF gauge response data thus provide the basis for an identification of problems to be encountered in a variety of device response environments.

In the compressed-gas gun response measurements, it has been established that the basic response properties of small size gauges prepared by the Bauer process are highly reproducible. Differences of about 2% observed under precise impact conditons are thought to be accounted for by ambiquities in the data recording and analysis as well as in materials response. These experiments show that the PVDF gauge will prove useful over a wide range of pressure and will therefore prove useful for a wide variety of measurement problems. Although these projectile impact data are obtained under precise conditions, it should be recognized that the peak pressures are obtained under "ring-up" conditions in which the rise time to peak pressure is typically 60 nsec. Thus, under a more rapidly rising pulse in which the peak pressure is obtained in a single shock, there may be differences in response due to a higher shock-induced temperature rise. This point requires further study.

The nearly planar detonator flyer-plate response measurements show a reduced output compared to idealized, one-dimensional pressure calculations. Even though this flyer is substantially more nonplanar than in the gun-impact studies, the 15% reduced outputs seem larger than can be accounted for by the nonplanar conditions. It remains to be seen whether direct shock measurements to similar pressure values can account for the observed differences.

The strongly non-planar, detonator flyer-plate response measurements show a very strong effect due to the three-dimensional nature of the loading, amounting to about a 35% reduction in signal. Whether this difference is due to a real difference in average pressure over the volume of the gauge or is due to an inherent reduced output in three-dimensional stress fields requires further study. When one considers that the measurement is made within 12 microns of the impact surface, it is remarkable that any type measurement is possible. Indeed, the presence of the reduced gauge output provides a direct measure of the strongly nonplanar impact conditions.

Because the gauge response is composed of such short duration current pulses, there is concern for the adequacy of digitizer responses. The LeCroy 6880 digitizer appears to have adequate vertical resolution with its 8-bit design, but the 6-bit resolution of the Hewlett-Packard digitizer may not be fully adequate for some of the narrower current pulses. Preliminary measurements in the gun-impact configuration suggest that gauge output of charge/area may be reduced with the Hewlett-Packard digitizer as much as 7%. Comparisons of the Le Croy digitizer measurements with independent measurements at our laboratories and in the laboratory of Francois Bauer show good agreement. This point requires further study.

It should be emphasized that the PVDF gauge provided sensitive, time-resolved measurements in all cases investigated. The measurement of the stress-rate provides a far more sensitive measurement of such stress pulses than available in any other shock-measurement technique. The unobtrusive nature of the gauge, its very large signal output, its wide pressure operating range, and its capability to measure stress-rate make it a far more useful gauge than previously developed piezoelectric gauges.

ACKNOWLEDGEMENTS

The authors are pleased to acknowledge the excellent technical assistance of Frank Horine, Mark Anderson, David Wackerbarth, Dan Sanchez and Mark Wing. Discussions with and encouragement from Francois Bauer, Reuben Weinmeister and Lloyd Bonzon were critical to the success of the present work. The authors are very appreciative of Truman Warren for permitting use of his flyer planarity measurements prior to publication.

REFERENCES

1. Chhabildas, L. C. and Graham, R. A. "Developments in Measurement Techniques for Shock-Loaded Solids, in Techniques and Theory of Stress Measurement for Shock Wave Applications, eds, Stout, R. B., Norwood, F. R. and Fourney, M. E., AMD Volume 83, American Society of Mechanical Engineers, NY, 1987, pp. 1-18.

2. Bauer, F., "Behavior of Ferroelectric Ceramics and PVF_2 Polymers Under Shock Loading," in Shock Waves in Condensed Matter-1981, eds, Nellis, W. J., Seaman, L., and Graham, R. A., American Institute of Physics, 1982, pp. 251-267.

3. Graham, R. A., Lee, L. M., Bauer, F., "Response of Bauer Piezoelectric Polymer Stress Gauges (PVDF) to Shock Loading," in Shock Waves in Condensed Matter 1987, eds. Schmidt, S. C., Holmes, N.C., Elsevier, 1988, pp. 619-622.

4. Graham, R. A., Bauer, F., Lee, L. M., and Reed, R. P., "Standardized Bauer Piezoelectric Polymer Shock Gauge," Shock Wave Compression of Condensed Matter, 1988, pp. 47-50.

5. Bauer F., "Properties and High Pressure Shock Loading Response of Poled Ferroelectric PVF_2 Polymer Gauges," in Stout, et al, loc cit

6. Graham, R. A. Neilson, F. W., and Benedick, W. B., "Piezoelectric Current from Shock-Loaded Quartz-A Submicrosecond Stress Gauge," Journal of Applied Phycis, Vol. 36, 1965, pp. 1775-1783.

7. Graham, R. A., "Second-and Third-Order Piezoelectric Stress Constants of Lithium Niobate as Determined by the Impact-Loading Technique," Journal of Applied Physics,Vol. 48, 1977, pp. 2153-2163.

8. Bauer, F., "Method and Device for Polarizing Ferroelectric Materials," U. S. Patent 4,611,260, 9 Sep 1986.

9. Bauer, F., "Device for Polarizing Ferroelectric Materials," U. S. Patent 4,684,337, 4 Aug 1987.

10. Stanton, P. L., Igel, E. A., Lee, L. M., Mohler, J. M., and West, G. T., "Characterization of the DDT Explosive, CP," Seventh Symposium (International) on Detonation, Annapolis, Maryland, June 1981, p. 865.

11. Bernecker, R.R. and Price, D., "Studies in the Transition from Deflagration to Detonation in Granular Explosives-III. Proposed Mechanisms for Transition and Comparison with Other Proposals in the Literature," Combust Flame 22, 1974, p. 161.

12. Fleming, W., Fronabarger, J.W. and Lieberman, M.L., "CP DDT Detonators: I. Design Sensitivity Study," Proceedings 12th Symposium on Explosives and Pyrotechnics, March 1984.

13. Barker, L. M. and Hollenback, R. E., "Laser Interferometer for Measuring High Velocities of Any Reflecting Surface," J Appl Physics, Vol.43 ,1972, p. 11.

14. Warren, T.W., written communication, Development Division, Mason & Hanger-Silas Mason Company, Inc., Tilt of detonator flyer plate, 5 January 1989.