PVDF GAUGE PIEZOELECTRIC RESPONSE UNDER TWO-STAGE LIGHT GAS GUN IMPACT LOADING

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Abstract. Stress gauges based on ferroelectric polymer (PVDF) studies under very high pressure shock compression have shown that the piezoelectric response exhibits a precise reproducible behavior up to 25 GPa. Shock pressure profiles obtained with “in situ” PVDF gauges in porous H.E. (Formex) in a detonation regime have been achieved. Observations of a fast superpressure of a few nanoseconds followed by a pressure release have raised the question of the loading path dependence of the piezoelectric response of PVDF at high shock pressure levels. Consequently, studies of the piezoelectric behavior of PVDF gauges under impact loading using a two-stage light gas gun have been conducted recently. Symmetric impact as well as non symmetric impact and reverse impact techniques have been achieved. Strong viscoplastic behavior of some materials is observed. In typical experiments, the piezoelectric response of PVDF at shock equilibrium could be determined. These results show that the PVDF response appears independent of the loading path up to 30 GPa. Accurate measurements in situ H.E. are also reported with very low inductance PVDF gauges.

INTRODUCTION

Piezoelectric materials are widely used as stress gauges to provide nanosecond, time-resolved stress measurements of rapid impulsive stress pulses produced by impact, explosion or rapid deposition of radiation. In the earliest work the gauges used crystalline sensors made of either X-cut quartz or various cuts of lithium niobate with thicknesses of many millimeters. The wave transit times through such a sensor range from many tens of nanoseconds to a few microseconds. The upper response of the crystalline sensors is limited by either, or both, mechanical or electrical properties: dynamic yielding of the sensors or dielectric breakdown due to the large internal fields produced by the piezoelectric effect. Early work has shown that highly reproducible poled 25 µm polymer film PVDF (Poly(vinylidene fluoride)) can be reliably used in a wide range of precise stress and stress-rate measurements (1, 2). Reliable behavior under the various extreme shock conditions requires specific sample preparations according to the Bauer process (1, 2). The 25-micron thickness of such PVDF sensors allows to place the gauges unobtrusively in a variety of locations within samples. Their direct stress-derivative or stress-rate signals with a few nanosecond and higher operating stress limits offer capabilities not available with any other technique and move experimental capability to a new sensitivity. The behavior of PVDF studied over a wide range of pressures using high-pressure shock loading has yielded well-behaved reproducible data up to 25 GPa in inert materials. Two years ago (1) solutions using a new appropriate shielding were identified and were applied to shock measurements of polar materials. This shielding is achieved via a deposition of thin metallic layers sputtered on samples to be studied and then connected to the ground. It has also been shown that this shielding technique can be applied to shock pressure profile measurements “in situ” porous H.E. in a detonation...
regime. The measured shock pressure profiles with the PVDF gauge show a fast superpressure of a few nanoseconds followed by a pressure release down to a plateau level and then by a pressure decay. These observations raise naturally the question of the loading path dependence of the piezoelectric response of PVDF at such high shock pressure levels.

The present paper summarizes the recent studies of the piezoelectric behavior of PVDF gauges under impact loading using a two-stage light gas gun up to 35 GPa. Symmetric impact as well as non-symmetric impact and reverse impact techniques on PVDF gauges are presented. Accurate measurements in situ H.E. are also reported with very low inductance PVDF gauges.

**PVDF RESPONSE UNDER TWO-STAGE LIGHT GAS GUN IMPACT LOADING: EXPERIMENTS AND RESULTS**

The experimental measurements of the electrical response of a shock-compressed PVDF film are carried out on the ISL two-stage light gas gun facility. A range of impact velocities from 0.85 km/s to 3 km/s is achieved with a two-stage light gas gun which accelerates the projectile to a predetermined velocity. The planarity control and accuracy of velocities (0.5%) are comparable to those of our powder gun (1). In the impact experiment, symmetric impact as well as non-symmetric impact and reverse impact techniques (3) on PVDF gauges are used. PVDF gauges are placed on the impact surface of either Z-cut sapphire crystals, aluminum (Al 2024) or OFHC copper which serve as standard materials to define the stress (Fig. 1). The PVDF gauge response is determined by recording the short-circuited current during the time when the shock waves reverberate within the samples until the mechanical equilibrium is reached, corresponding to the longitudinal stress in the standard material. In the electrical measurement circuit a carbon resistance replaces the expensive current viewing resistor “CVR” (1). The electrical charge is determined by the numerical integration of the recorded current (2).

**Non Symmetric Impact Experiments**

In the non-symmetric impact experiments, 3 mm thick aluminum (Al 2024) or 2 mm thick copper samples were mounted on the projectile. The target consisted of a 10 mm thick electrically shielded Kel-F polymer. This electrical shielding was achieved via a deposition of thin metallic layers sputtered on polymer samples and then connected to the ground material (1). The PVDF gauge sandwiched between a 125 μm thick film and a 25 μm thick film of PFA –Teflon is bonded on the Kel-F target. The 125 μm thick layer faces the projectile. A typical record of the piezoelectric charge versus time obtained in such experiments is depicted in Fig. 2. As can be seen on the figure, the negative jump of the electrical charge, which corresponds to the early shock, is followed by a rapid decrease of the charge corresponding to a rapid relaxation to higher velocities. Then, the charge continues to decrease with a slope corresponding to a slow

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**Figure 1.** The piezoelectric response of the PVDF film is studied with the impact of materials with samples placed either on the impact surface or "in-situ".

**Figure 2.** The figure shows the electrical charge released from shock-compressed PVDF bonded on a Kel-F polymer. The Al impactor velocity is equal to 2958 m/s.
relaxation to higher velocities (2), until the release wave from the impactor comes. Looking at the Kel-F relaxation, we cannot attain in our experiment the stress equilibrium, and consequently the charge released cannot be correlated with the induced stress.

**Reverse Impact Technique**

The reverse impact configuration (3) consists of the inverse of the above-described experiment. Projectiles are made of Kel-F polymer. PVDF gauges are bonded on sapphire or Al or Cu targets (Fig. 1). In a first series of experiments, single crystals of Z-cut sapphire, which are elastic to stresses in excess of 12 GPa, were used as the target. The shielding of the Kel-F projectile was obtained via the sputtering of thin metallic layers (1500 Å) and then connected to the ground. In both cases, (Fig. 3), a plateau follows the early shock. In the case of the PVDF embedded between two pieces of 1 and 2 mm thick sapphire, the equilibrium is reached after 0.10 μs. For the test with the PVDF bonded between a 125 μm thick PFA-Teflon and a 3 mm thick sapphire, we can observe after 0.15 μs a small change in the charge. At a time of 0.52 μs, the change in the shape of the charge is due to the arrival of the released wave coming from the 3 mm thick sapphire backer. At this time, the leads of the PVDF gauge are destroyed. In both cases, the piezoelectric charge can be correlated with the induced stress. In a second series of experiments, shielded Kel-F projectiles impacted PVDF bonded on a Cu target. The PVDF gauge was sandwiced between two 125 μm thick films of PFA-Teflon. Figure 4 gives a typical record of the piezoelectric charge released. The equilibrium is reached after two compression steps. Even a small relaxation is observed, the charge can be correlated with the equilibrium-induced stress.

**Symmetric Impact Technique**

Impactor and sample materials are identical. One half of the velocity at impact is imparted to the sample. PVDF gauges between two 125 μm thick films of PFA-Teflon are bonded on the impact surface. Figure 5 shows the piezoelectric response of the PVDF gauge subjected to the impact of a Cu projectile at a velocity of 1588 m/s. The loading of the film proceeds as a series of reverberations with increasing stress until equilibrium is reached.

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**FIGURE 3.** The continuous curve corresponds to the test with PVDF bonded between a 125 μm thick PFA-Teflon and a 3 mm thick sapphire. The dotted curve corresponds to the test with PVDF bonded inside two pieces of 1 and 2 mm thick sapphire.

**FIGURE 4.** The figure shows the electrical charge released from shock-compressed PVDF bonded on a Cu target. The Kel-F impactor velocity is equal to 2561 m/s.

**FIGURE 5.** The electrical charge versus time is given for a Cu symmetric impact on PVDF. The projectile velocity is equal to 1588 m/s.
TABLE 1. Table of the valid results

<table>
<thead>
<tr>
<th>Type of experiment</th>
<th>Impact velocity (m/s)</th>
<th>Stress (GPa)</th>
<th>Charge (μC/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kel-F→Sa</td>
<td>1624</td>
<td>12.2</td>
<td>4.26</td>
</tr>
<tr>
<td>Kel-F→Sa</td>
<td>1850</td>
<td>14.7</td>
<td>4.79</td>
</tr>
<tr>
<td>Kel-F→Al</td>
<td>2695</td>
<td>17.8</td>
<td>4.89</td>
</tr>
<tr>
<td>Kel-F→Cu</td>
<td>2561</td>
<td>22.9</td>
<td>5.75</td>
</tr>
<tr>
<td>Cu→Cu</td>
<td>1357</td>
<td>30.0</td>
<td>6.16</td>
</tr>
<tr>
<td>Cu→Cu</td>
<td>1588</td>
<td>36.3</td>
<td>6.50</td>
</tr>
</tbody>
</table>

The charge is correlated with the equilibrium stress (for example, Figure 5 at 0.25 μs). Table 1 recapitulates the results obtained for reliable experiments.

Figure 6 shows the experimental and computed charges versus stress including these results. The observed charge versus stress data for these various loading paths show that the final charge seems to be independent of the loading path.

FIGURE 6. The electrical charge observed at various loading path pressures is shown for PVDF. The experimental and computed data are on the same curve.

SHOCK DETONATION PRESSURE PROFILES

Shock pressure profiles in situ porous H.E. in a detonation regime have been repeated (1). The overall features of H.E. studies under precise impact loading were described earlier (1). We have studied the influence of the value of load resistance on the charge released as well as on the pressure profile obtained. Figure 7 gives an example of detonation pressure profiles obtained with low-inductance 1 mm²-gauges “in situ” H.E. When the detonation wave propagates parallel to the PVDF gauge, the shock pressure profile shows a fast superpressure of a few nanoseconds followed by a pressure release down to a plateau level and then by a pressure decay (4). The changing resistance value of the CVR (between 0.4 and 1 ohm) does not affect significantly the shape of the profile. The values of the superpressure range between 15 and 20 GPa.

FIGURE 7. Zoom in a PVDF record of the detonation pressure “in situ” H.E. “Formex”.

CONCLUSIONS

Studies of the piezoelectric behavior of PVDF gauges under impact loading using a two-stage light gas gun have been presented. In spite of the difficulties encountered to obtain reliable measurements, the valid data obtained show the reproducible response of our ISL PVDF, independently of the loading path. PVDF in a low-inductance configuration can measure detonation waves of some specific porous H.E.

REFERENCES