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DYNAMIC ELECTROMECHANICAL CHARACTERIZATION OF THE FERROELECTRIC CERAMIC PZT 95/5

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Shock-induced depoling of the ferroelectric ceramic PZT 95/5 has been utilized in pulsed power applications for many years. Recently, new design and certification requirements have generated a strong interest in numerically simulating the operation of pulsed power devices. Because of a scarcity of relevant experimental data obtained within the past twenty years, we have initiated an extensive experimental study of the dynamic behavior of this material in support of simulation efforts. The experiments performed to date have been limited to examining the behavior of unpoled material. Samples of PZT 95/5 have been shocked to axial stresses from 0.5 to 5.0 GPa in planar impact experiments. Impact face conditions have been recorded using PVDF stress gauges, and transmitted wave profiles have been recorded either at window interfaces or at a free surface using laser interferometry (VISAR). The results significantly extend the stresses examined in prior studies of unpoled material, and ensure that a comprehensive experimental characterization of the mechanical behavior under shock loading is available for continuing development of PZT 95/5 material models.

INTRODUCTION

Many shock-activated pulsed power supplies have utilized a lead zirconate titanate ceramic having a Zr:Ti ratio of 95:5 and modified with 2% niobium, subsequently referred to as PZT 95/5. The nominal state of this material is ferroelectric (FE), but it is near an antiferroelectric (AFE) phase boundary. A remanent polarization can be produced by electrical poling, and the bound charge can be liberated into an external circuit by shock compression into the AFE phase. The poled ceramic has a complex dynamic behavior, with nonlinear coupling between mechanical and electrical variables. The electrical response of this material under shock loading was examined in some detail nearly twenty years ago (1) when pulsed power sources were under development. Interest in understanding the complex behavior of PZT 95/5 has been renewed recently due to new design and certification requirements. In particular, sufficient under-

standing of this behavior must be established so that these requirements can be addressed through numerical simulations. Because few relevant studies have been performed during the past twenty years, we have initiated an extensive experimental study to improve our understanding of PZT 95/5 and to provide well-characterized data for assessing material models under development.

The first phase of this study addresses the mechanical behavior of unpoled PZT 95/5. In an early study, Doran (2) examined a similar material using explosively driven shock waves. Using material at densities of 7.67-7.89 g/cm³, he found an obvious cusp in the Hugoniot curve at a pressure near 4 GPa, and a weaker cusp at a pressure near 0.2 GPa. He suggested that the strong cusp could be the Hugoniot elastic limit, and the weaker cusp the onset of the FE to AFE phase transition. Using planar-impact techniques, Dick and Vorthman (3) measured impact-face conditions and recorded

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transmitted wave profiles in unpoled material at densities from 7.29 to 7.37 g/cm³. They also measured electrical response and transmitted wave profiles in poled material. At a fixed peak stress of approximately 1.6 GPa, the transmitted wave profiles were strongly ramped with a weak two-wave structure. A more extensive study of shock wave propagation in unpoled material was performed some years later by Chhabildas (4). Using PZT 95/5 material at a density of 7.27-7.34 g/cm³, he recorded transmitted wave profiles under both uniaxial-strain and pressure-shear loading conditions at pressures from 0.9 to 4.6 GPa. Above 2.6 GPa a three-wave structure was observed due to the onset of pore compaction in the lower density material.

In the present study we have used unpoled PZT 95/5 samples having densities between 7.28 and 7.32 g/cm³. Planar impact conditions have generated axial stresses from 0.5 to 5.0 GPa, with particular conditions chosen primarily to cover ranges not addressed in previous studies.

EXPERIMENTAL CONFIGURATION

The general experimental configuration used in the present study is shown in Fig. 1. A 63.5-mm diameter, compressed-gas gun is used to conduct the planar-impact experiments. In most experiments a 3.2-mm thick, fused-silica impactor is

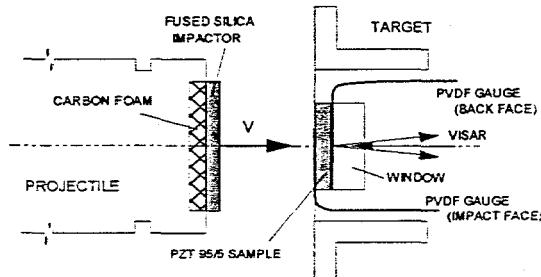


Figure 1. Experimental configuration used in the present study.

mounted on a layer of low-density (0.2 g/cm³) carbon foam to provide loading to a steady shock

condition followed after 1.1 μ s by a release wave. A PVDF gauge package consisting of the 0.025-mm PVDF film and a 0.025-mm film of insulating Teflon is bonded to the front surface of the PZT 95/5 sample at the impact surface. The rear surface of the PZT 95/5 sample is bonded to either a fused silica or sapphire window with a diffusively reflecting surface at the interface. Laser interferometry (VISAR) is used to obtain particle velocity histories at this interface. On one experiment a second PVDF gauge package was included at the window interface.

CHARACTERISTIC LOADING RECORDS

In one experiment a thick fused-silica impactor was used to produce sustained shock loading without release, and a second PVDF gauge was positioned at the window interface to obtain a transmitted wave profile for comparison with the VISAR records. The resulting profiles are shown in Fig. 2. The transmitted wave profiles show the characteristic three-wave structure observed by Chhabildas (4). The PVDF gauge at the impact surface showed a transient rise during the first two microseconds. As will be seen in a subsequent

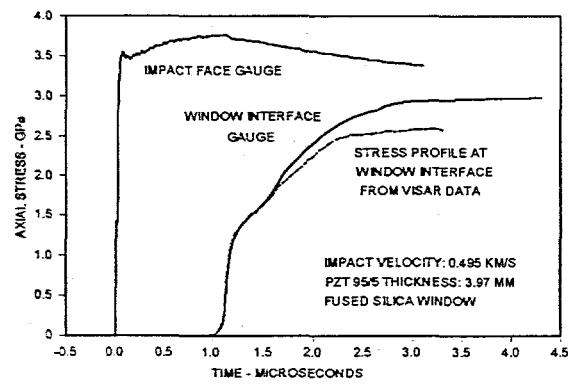


Figure 2. Combined data from a sustained-shock experiment.

figure, all of the impact gauge records showed a slow rise following impact. In the only previous study that examined impact conditions (3), a steady stress state was reported at 1.6 GPa levels. A possible explanation for the present observations is

an anomalous gauge response that has been observed in impact-face gauges having the same configuration of electrical leads as in the present experiments (5). In the VISAR profile shown in Fig. 2, particle velocity has been converted to stress using the fused silica Hugoniot curve (6). This profile shows good agreement with the PVDF gauge at the window interface for the first 0.7 μ s after wave arrival, then deviates progressively.

Figure 3 shows the charge histories obtained from PVDF gauges at the impact surface for three experiments with identical target and projectile assemblies but different impact velocities. The curves represent the time integral of the recorded current histories. In addition to the slow rise after impact, all of these records show a release to non-zero levels. Since the impact face stress releases to zero under these experimental conditions, the remanent charge levels indicate that charge has been added or lost. This suggests that the 0.025-mm layer of insulating Teflon between the gauge and the piezoelectric PZT 95/5 sample may not have been sufficient.

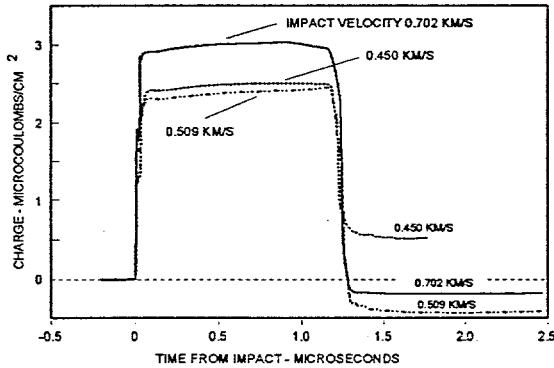


Figure 3. Charge histories from PVDF gauges at the impact face.

Figure 4 shows transmitted wave profiles recorded with VISAR at the window interface for the same three experiments as in Fig. 3. A small ramp at the start of each profile represents the behavior of the FE phase. The ramping behavior corresponds to compressibility increasing with increasing pressure. The front of this feature propagates at the longitudinal acoustic speed, which was found to be

4.16 ± 0.01 km/s in these samples. The corresponding transit time determined from the PVDF gauges shown in Fig. 2 was also 4.16 km/s. The low-amplitude ramp is followed by a fairly steep rise reflecting the transition to the AFE phase. The final wave feature represents relatively slow pore-compaction processes.

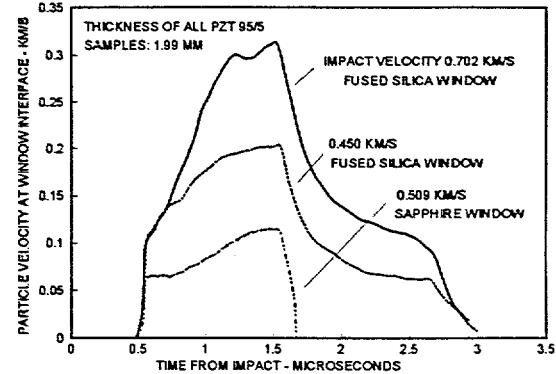


Figure 4. Particle velocity histories at the window interface.

Figure 5 shows the results of an approximate method that uses VISAR records to calculate the stress-strain paths followed by the PZT 95/5 samples during loading and unloading (7).

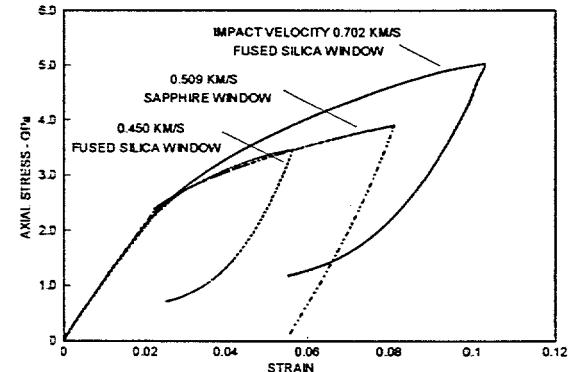


Figure 5. Approximate stress-strain loading and unloading paths calculated from the profiles shown in Fig. 4.

Although the assumptions required for this analysis (8) are not well met in this material, the curves in Fig. 5 are very consistent up to the onset of pore compaction at approximately 2.5 GPa. Well above this level the stress-strain path depends upon the

stress at impact. The strong deviation of the release paths from the loading paths results from several factors, including the irreversible pore compaction and differences in the reverse phase-transition kinetics.

HUGONIOT STATES

The approximate final states reached during loading (Fig. 5) can be plotted and compared with similar end states calculated by Chhabildas (4) and impact-face conditions measured by Dick and Vorthman (3). The comparison is quite good, as shown in Fig. 6. Also shown in this figure are the

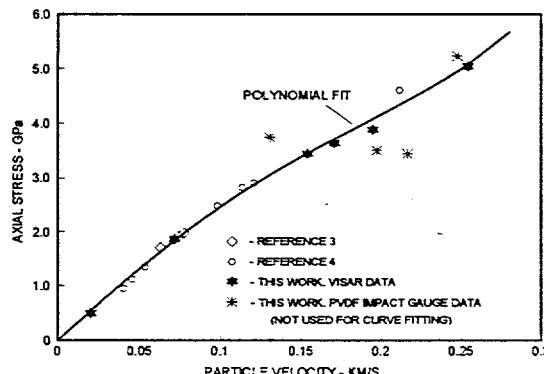


Figure 6. Hugoniot measurements and end states calculated from transmitted wave profiles.

initial impact states indicated by the PVDF gauges, which appear biased as could be expected (Fig. 3). The combined points (except for the PVDF gauge results) were fitted with a fourth-order polynomial using a least-squares routine. The coefficient values are: $C_1 = 26.86$, $C_2 = 5.271$, $C_3 = -363.8$, and $C_4 = 930.6$, where velocity is in km/s and axial stress is in GPa.

SUMMARY

The present work represents the first phase of extensive experimental characterizations of the dynamic electromechanical response of the ferroelectric ceramic PZT 95/5. The use of PVDF

gauges to record impact face conditions was limited by an apparent gain or loss in gauge charge, probably due to inadequate insulation. VISAR measurements of transmitted wave profiles were made for various impact conditions and sample thicknesses, showing the multi-wave loading structure and the release behavior. Approximate end states were calculated from these profiles. The current results confirm the material behavior described in previous studies and provide a continuous characterization of this behavior from 0.5 to 5.0 GPa.

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