DYNAMIC ELECTROMECHANICAL BEHAVIOR OF PIEZOELECTRIC CERAMICS

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Summary This work focuses on high strain rate experiments 10^3 s^{-1} conducted on single crystal α-quartz, single crystal silicon carbide and aluminum nitride. The results exhibit nonsimilar stress-charge behavior during damage evolution. Specifically, when quartz is undergoing extensive and irreversible dynamic brittle fracture under a compressive stress impulse of up to 2 GPa, the effective piezoelectric stress coefficient (d) exhibits, on average, an approximate 15% increase from loading to unloading. The experimental results are examined in the framework of the theory of linear piezoelectricity and traditional continuum damage models in order to understand the role of increasing crack density on electroelastic properties.

INTRODUCTION

While a large amount of data is available on the properties and behavior of piezoelectric ceramics subjected to small strains and electric fields as used in conventional sensor and actuator applications, little data exists which contributes to a basic understanding of the behavior of piezoelectric ceramics when subjected to high-rate impulsive loading. This particular loading regime plays a critical role in defense applications, specifically for blast mitigation and ballistic protection since numerous armor ceramics such as silicon carbide and aluminum nitride exhibit piezoelectric properties. In addition, piezoelectric materials are also valued for their ability to be utilized as a single-shot, high-energy power supply (or switch) when pulverized. In these applications, the frequency response plays a crucial role and depends on both the mechanism of polarization [1], as well as the effect of damage on polarization.

Background

Piezoelectric materials exhibit an electrical polarization when subjected to mechanical stress, the direct effect, or a mechanical strain through the application of an electric field, the converse effect. The equivalence between the direct and converse effects can be validated by using thermodynamic arguments [3]. Due to the intrinsic electromechanical coupling, these materials have been extensively employed in technology as both sensor and actuators [4]. However, at the same time the brittle nature of piezoelectric ceramics make these materials particularly susceptible to damage. Consequently, an understanding of the electromechanical behavior in applications relevant to high-rate failure is necessary [5].

Polarization

On a microstructural level, piezoelectricity is a property that arises due to the anisotropy in the crystalline structure, or the uneven distribution of electrical charges inside the molecules that make up the crystalline structure. For example in α-quartz, the SiO_2 tetrahedra network contains oxygen atoms that are more negatively charged, and silicon more positively charged. In the absence of external strains, the crystal as a whole is electrically balanced and the charge distribution is symmetric. Hence the net electrical dipole moment is zero under ambient conditions. However, when an external stress is applied, the charges are displaced and the distribution is no longer symmetric, leading to a net polarization [6].

Experimental Procedure

Dynamic uniaxial compression experiments are conducted on a Kolsky bar (also called a Split-Hopkinson pressure bar) [2]. High-speed photography captures the fracture behavior in the sample during failure, and can consequently be used to determine the amount of damage in the specimen throughout the loading history. During loading, the electrical signal produced in the ceramic is passed from the vapor deposition surface to a steel platen, and then to fine gauge, low-noise wires via a solder joint that is further amplified by a Kistler 5010 charge amplifier.

RESULTS

In essence, the mechanical impulse (10^3 s^{-1}) and measured crack speeds (0.20 c_R) are much slower than the electromagnetic wave speed ($10^9 - 10^{12}$ s), and hence become the limiting time scale. This means that the volume average electromechanical response can only change as fast as the cracks can propagate and influence the coupled relations. In this context, this type of behavior is similar to a percolation problem where transport of the electrons become path restricted at a critical or threshold value. For this study, on average, the improved piezoelectric response occurs at a threshold level during unloading of approximately 60% damage, or roughly a when the specimen crack density is over half of the volume. In the case of quartz, the results have

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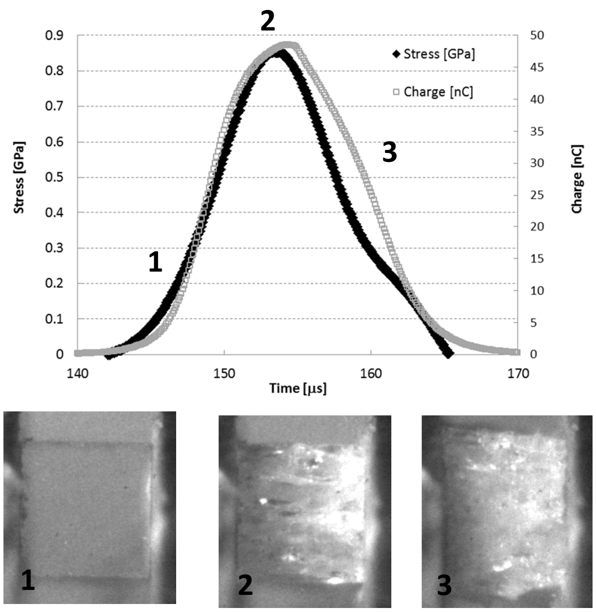

Figure 1. Example force and charge results for a 20 μs compressive impulse load on single crystal α-quartz specimen, and corresponding high-speed photography illustrating material damage.

shown that at this strain rate, regardless of the pulse durations examined (between 20–150 μs) an increase in the piezoelectric stress coefficient, d_{11}, of over 15% with increasing nominal damage is observed.

CONCLUSIONS

The dynamic electromechanical response of piezoelectric ceramics is complex. Due to the coupled electrical and mechanical response, as well as the numerous time and length scales being activated, a few observations on the resulting dynamic behavior have been made:

- Creation of free surfaces may influence charge transport.
- Macroscopic electrical response does not begin to change at the onset of damage.
- Stress singularities at a large and growing number of cracks may be considered a potential source of nonlinearities.
- Mechanical problem seems to dominate piezoelectric response given this type of impulsive loading.

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