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CRACK GROWTH IN PIEZOELECTRIC CERAMICS BY CYCLIC ELECTRIC FIELDS

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ABSTRACT

Pre-existing cracks introduced by a Vickers diamond hardness indenter in BM 532 (Navy-Type VI) PZT increase in length under the action of low frequency cyclic electric fields applied normal to the crack. The cracks extend to a limiting length, of the order of the electrode separation, after relatively few cycles. At a common frequency of 1.46 Hz, the limiting size of the cracks increases progressively with increasing peak field in the range 0.9-1.8 x E_c. A distinct increase in crack length occurs at E = 2.0 x E_c and a further increase occurs at a frequency of 10 Hz.

INTRODUCTION

A form of electrically induced fatigue is known to occur in 58/42 lead zirconate-titanate (PZT) and 8/65/35 lead lanthanum zirconate-titanate (PLZT) (1,2). Low frequency cyclic electric fields with peak amplitudes less than the coercive field, E_c, cause cracks created by a Vickers diamond hardness indenter to grow in a direction normal to the applied field, while fields greater than E_c, cause more extensive crack growth at a rate that is independent of the crack length (1). At fields greater than E_c, the crack growth in unipolar cyclic fields is significantly greater than that in bipolar fields, indicating that the negative component of a bipolar cyclic field is ineffective for causing crack growth (2). Since undetected pores or agglomerates can act as potential crack initiators in piezoelectrics, the long term effect of cyclic electric fields is of great significance with the regard to the application of these materials in smart structures and systems. The growth of existing mechanically induced cracks in low cyclic electric fields 1-2 times greater than the coercive field has thus been investigated in a commercial grade of lead zirconate-titanate (BM 532, Navy Type-VI), which is extensively used in transducers, actuators, accelerometers, hydrophones, sonobouys and linear arrays. The preliminary findings of these experiments are presented in this paper.

EXPERIMENTAL METHODS

Powders of BM 532 were synthesized from component oxide powders at Sensor Technology Ltd., Collingwood, ON, by mixing, grinding and calcining. Sintered ceramics prepared from these powders were cut and ground to dimensions of 12.7 cm x 3 mm x 1.5 mm. As shown in Figure 1, the 3 mm (front and back) faces of the specimens were screen printed with silver paste to form electrodes for applying electric fields. These electrodes were also used to pole the specimens, using standard production procedures. The narrow 1.5 mm (top) face of each specimen was polished to a smooth finish with silicon carbide paper and then received a small indentation using a Vickers diamond indenter, with a load of 20 N, applied for a period of 10 sec. The diamond shaped indent was aligned, so that with one set of corners was parallel, and the other normal, to the electrodes. The applied load was sufficient to induce small cracks, 190-215 µm in length, that emanated from the corners of the indent. The crack oriented parallel to the electrodes (i.e. normal to an applied field) was used for the experimental work on the effect of cyclic electric fields.

To determine the coercive field, E_c, of the BM 532 ceramics used in these experiments, polarization vs. field hysteresis plots of selected specimens (before indentation) were measured using an SS05 polarization measurement system, which has been described previously (3). This apparatus was also used to apply cyclic electric fields of amplitude 0.9-2.0 x E_c, at frequencies of 1.46 and 10 Hz.

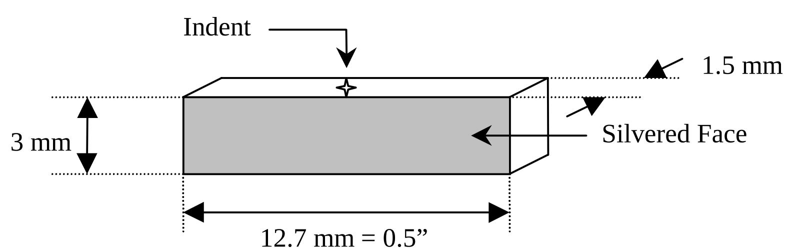

Fig. 1. Specimens used for crack growth studies in cyclic fields.

After the imposition of each electric field, the length of the crack aligned normal to the field was measured by mounting a Mitutoyo model ID-C112E displacement gage with 1 µm resolution on a microscope stage and monitoring the reading as the stage was translated to cause the projection of the cross-hair in the microscope objective to move from the left tip of the crack, past the indent, to the right tip of the crack. The accuracy of such a crack length measurement was estimated to be 50 µm.

RESULTS AND DISCUSSION

Polarization vs. Field Measurements

The polarization vs. electric field plot for the present specimens of BM 532 has a square hysteresis loop with remanent polarization greater that 90% of the saturation polarization and displays very sharp switching in the sign of polarization on passing through the coercive field. Similar plots obtained for several samples yielded an average value of 0.88 MV/m for the coercive field. All subsequent results are presented in terms of the normalized electric field E/E_c, using this value for the coercive field. Capacitances of the samples were also measured with this apparatus, but no significant trends were observed between the length of cracks induced by the electric fields and the changes in capacitance measured after the treatments.

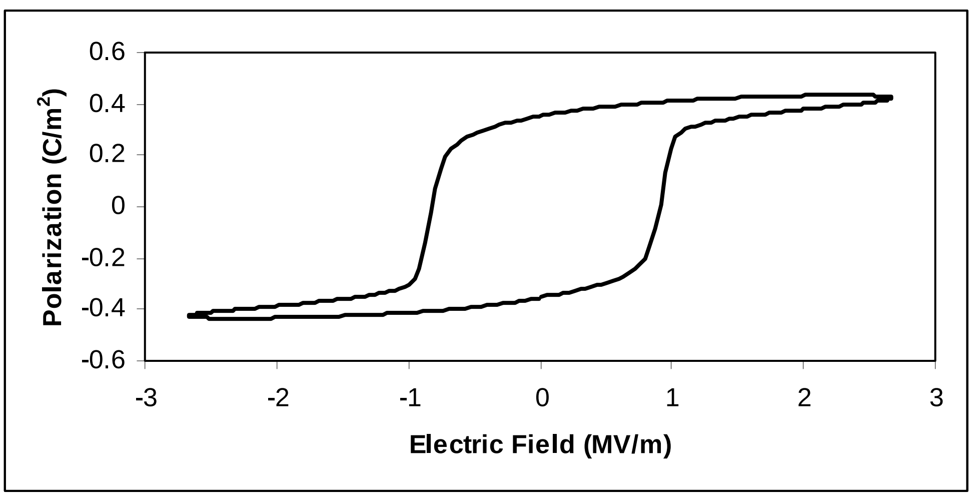

Fig. 2. Polarization vs. electric field hysteresis plot for BM 532.

Crack Growth in Cyclic Electric Fields

The crack growth observed after various numbers of cycles at different peak fields between 0.9 and 2.0 x E_c, is plotted in Figure 3. It is evident that the cracks grow to a common size after a relatively few cycles of the applied field and then show very little, or no, subsequent growth. This result is contrary to the previous finding of Cao and Evans (1), that crack growth at electric fields $E>E_c$ conform to steady state condition, in which the growth rate is independent of the crack length. It is consistent, however, with the findings Lynch et al. (2), who report that pre-cracks in PLZT grow rapidly to a length of the order of the separation between the two electrodes when exposed to cyclic fields of 1.2-2.0 x E_c. The limiting size of the cracks is a combined function of the specimen-electrode geometry and possible toughening within the material, for example, by the formation of microcracks oriented parallel to the applied field, which would blunt the tips of the growing crack aligned normal to the field (2). The results in Figure 3 also show that, for a field of 2.0 x E_c, the crack length at a frequency of 10 Hz is slightly greater than that observed at a frequency of 1.46 Hz, while others have reported that there is very little frequency dependence of crack growth in the range of 1.5-5.0 Hz (2).

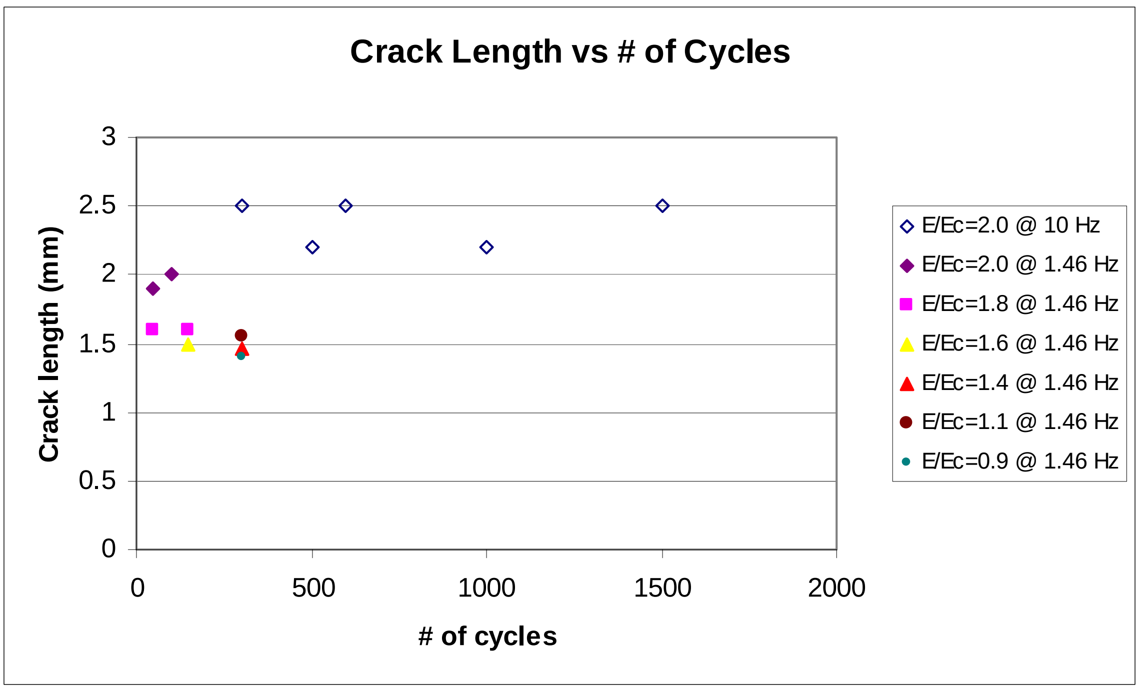

Fig. 3. Crack length vs. number of cycles, for E = 0.9-2.0 E_c.

The effect of peak field intensity on crack growth, at a common frequency of 1.46 Hz, is shown in Figure 4. A small, but progressive, increase in crack length is observed at increasing fields over the range from 0.9-1.8 x E_c, while a distinct increase in crack length occurs when the reduced field is increased to 2.0. This behaviour is analogous to the exponential increase in crack growth rate observed in PLZT at reduced fields between

2.0-3.0 (1). A possible explanation of this effect is that low electric fields simply extend the transgranular cracks induced by the initial mechanical loading, while higher fields transform these into intergranular cracks that are more easily propagated. A full investigation of the underlying crack propagation mechanism at different field intensities would require detailed micrographic studies, which are beyond the scope of the present work.

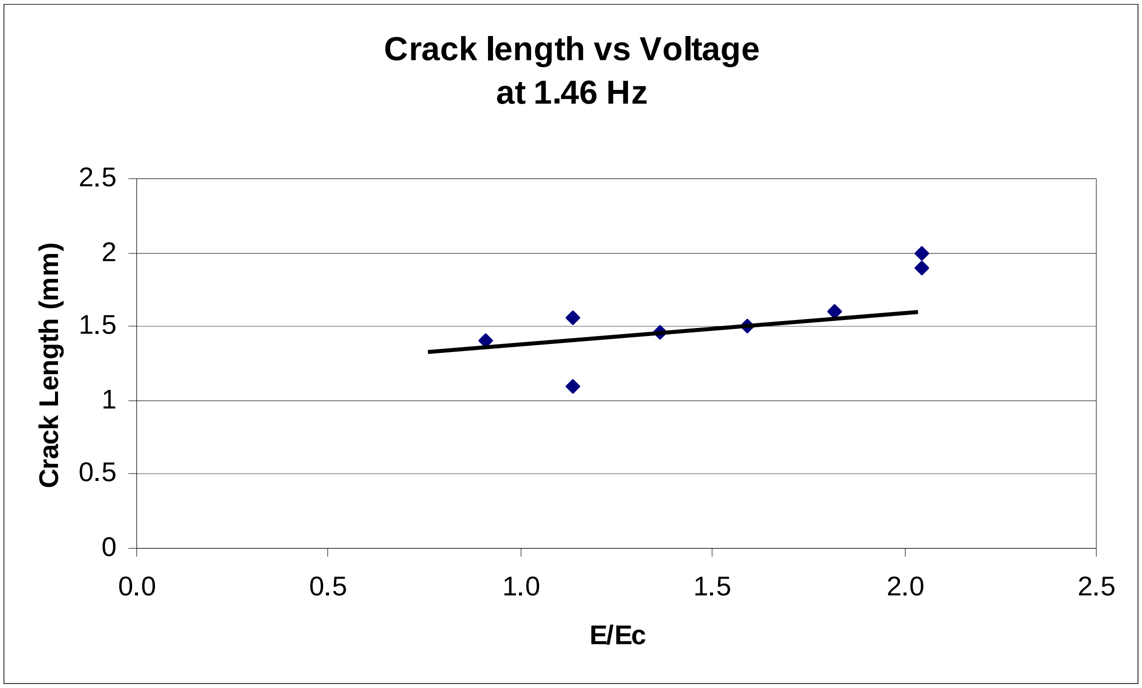

Fig. 4. Crack length vs. applied field at a frequency of 1.46 Hz.

These preliminary experiments on a commercial grade of PZT confirm that electric fields in excess of the coercive field can extend pre-existing cracks up to a length related to the electrode separation and also indicate that cyclic fields in excess of 2.0 x E_c can cause excessive crack growth which could result in accelerated electric breakdown. However, since the recommended maximum peak field is typically about one-half E_c, this potentially deleterious effect will not be experienced in normal practice. The results of continuing experiments on the growth of mechanically induced cracks in PZT materials in cyclic fields with peak intensities less than E_c will be presented in due course.

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