CRACK PROPAGATION IN PZT DCB SPECIMENS UNDER CYCLIC ELECTRIC LOADING

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ABSTRACT

Crack propagation in ferroelectric materials under cyclic electric and combined electro-mechanical loading has been studied by several research groups. In most experiments however, Vickers-indented surface cracks and not through-thickness cracks were used. We studied crack propagation under cyclic electric loading in a commercial, soft ferroelectric lead-zirconate-titanate material. The samples were 40mm x 5mm x 1.5mm in dimension, poled in the 5mm-direction with a through-thickness notch in the middle of the 5mm side. A cyclic electric field of variable maximum field strength was applied in the 5mm-direction. Crack propagation was observed in-situ by an optical microscope and recorded simultaneously on video. A crack is found to initiate in the first half cycle antiparallel to the poling direction once the electric field strength exceeds the coercive field strength of the material. In the subsequent cycles the crack propagates perpendicular to the electric field during each half cycle. The electric polarization was also measured so that a dielectric hysteresis could be observed during crack propagation. It was found that the crack does not propagate significantly before global domain switching takes place and stops growing after global domain switching has finished. During the first 10-20 cycles the crack propagates in a "steady-state" with a constant growth rate da/dN. The growth rate depends on the electric field strength. Further cycling leads to a slowing down of the crack with eventual arrest. Further experiments will include combined electrical and mechanical loading with static mechanical and cyclic electrical loads.

1 INTRODUCTION

Even though ferroelectric materials are nowadays widely used in sensor applications, transducers, memory devices and actuators [1, 2] there is still a concern about the degradation of their electromecanical properties due to electric fatigue. Cracks propagating in the devices under cyclic electric fields can lead to severe damage and failure. It is therefore crucial to gain thorough knowledge about this issue.

Several researchers in the past have studied crack growth in different PZT materials under cyclic electric loading and combined electro-mechanical loading [3-7]. However, most experiments were performed with Vickers-indented surface cracks and not through-thickness cracks. Cao and Evans [2] found that crack growth occurs mainly perpendicular to the applied electric field for $E > E_c$ (E_c being the coercive field) with eventual crack arrest. These results were confirmed by Lynch et al. [3]. They also found that the rate of crack growth per cycle, da/dN, depends on the strength of the applied electric field. In contrast, Zhu et al. observed crack growth for a field strength of 0.8 E_c [4]. In their opinion this is caused by domain switching in a confined switching zone close to the crack tip due to an intensified electric field in this region. Liu et al. studied through-thickness cracks and found a threshold of 0.797 E_C under which no crack propagation occurred [7]. They derived a phenomenological formula for the relation between field strength and rate of crack growth.

Some attempts have been made to find a theoretical description for fatigue crack growth under a cyclic electric field [8-10]. Zhu and Yang [8] used domain switching mechanisms ahead of the crack tip and at the crack faces as an explanation for this phenomenon and calculated a stress-intensity factor which varied cyclically with each polarisation reversal.

2 EXPERIMENTAL PROCEDURE

The material used was a commercial lead-zirconate-titanate (PZT) material (PIC 151, PICeramic). It is a soft ferroelectric material near the morphotropic phase boundary. The specimens were delivered as unpoled bars of 40mm × 5mm × 1.5mm in dimension. They were first polished on one side down to a 1µm finish. In order to reduce any residual stresses induced by polishing the specimens were annealed at 500°C for two hours. Electrodes of conductive silver were painted onto the 40mm × 1.5mm sides so that an electric field could be applied in the 5mm-direction. The specimens were then poled for 30 minutes at a field of two times E_c (E_c for this material is 1 kV/mm). A 1mm-long and 0.2mm-wide through-thickness notch was introduced into the middle of the 5mm-side by means of a wire saw.

The sample was mounted in a silicon oil bath on a x/y-stage below an optical microscope and covered with a thin glass plate. Electrical contacts were realized by two spring-like metal contacts at one end of the sample. A high voltage power supply driven by a frequency generator was used to apply a sinusoidal voltage of different amplitudes up to ± 10kV to the sample. In order to measure dielectric displacement during cycling, a Sawyer-Tower-circuit was used with a capacitance of 10 µF in series to the sample. Both the input voltage as well as the voltage measured at the second capacitance were fed into a computer via an AD-card and recorded during the experiment. Crack growth was observed in-situ through the microscope 200-times magnified and recorded simultaneously on video. A schematic of the setup is shown in Fig. 1.

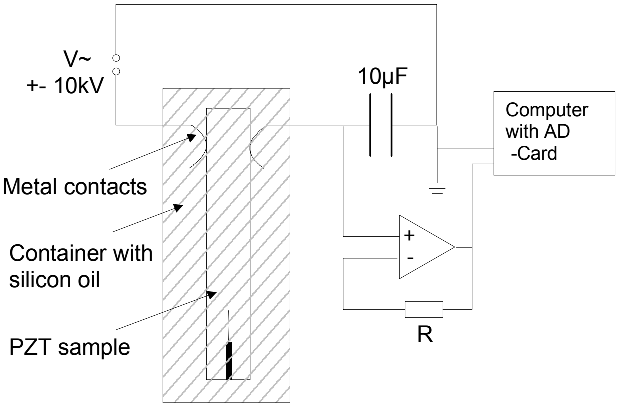

Fig. 1: Schematic of the experimental set-up

It was found that a crack is always initiated from the notch during the first half cycle antiparallel to the poling direction once the electric field exceeds ≈ 1.1 E_c. Therefore it was unnecessary to produce a precrack by mechanical means.

At first, a frequency of 0.01 Hz was used to cycle a specimen for five consecutive cycles with an amplitude of 1.5 E_c. Next a frequency of 1 Hz was used to cycle different specimens at seven different amplitudes varying between 0.9 and 1.9 E_c up to 60 cycles. Crack length was measured every ten cycles during a short pause in cycling.

3 RESULTS

In the lower part of Fig. 2 the complete dielectric hysteresis is displayed for the first cycle at 0.01 Hz. For the following cycles only those data points of dielectric displacement versus electric field have been added where crack growth occurred. In the upper part of Fig. 2 the increasing crack length is plotted versus electric field. As can be seen, the crack initiates when the electric field is negative with respect to the poling direction and exceeds the coercive field strength of the material. In the subsequent cycles the crack grows during each half-cycle, but only if the coercive field strength is reached.

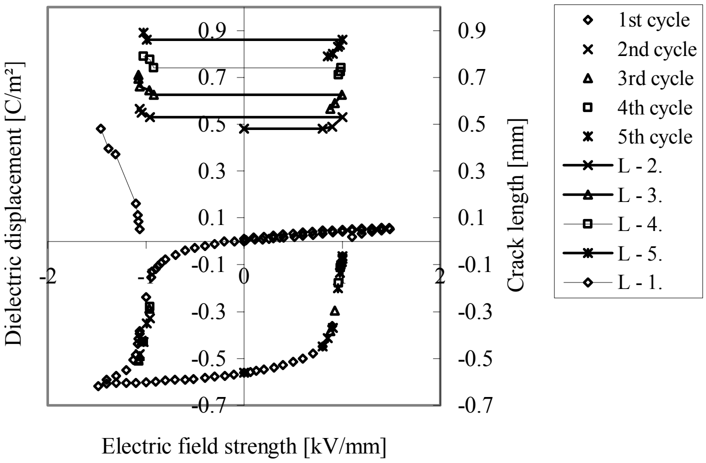

Figure 2: Dielectric displacement (left y-axis) and crack length (right y-axis) vs. electric field during the first five cycles for f=0.1Hz.

Next the field strength dependence of crack propagation was examined. Different specimens were cycled at 1 Hz up to 60 cycles at seven different field strengths, namely 0.9/1.1/1.2/1.3/1.5/1.7 and 1.9 E_c. The crack length was measured every ten cycles and is plotted vs. cycle number in Fig. 3. For 0.9 E_c no crack growth was observed even after 60 cycles. If switching takes place in a confined switching zone due to an intensified electric field close to the crack tip, it does not induce sufficient stress to cause crack growth. For 1.1 E_c there was minimal but visible crack growth. While the curve for 1.2 E_c still lies well below the one corresponding to 1.3 E_c and above the 1.1 E_c curve, the results for field strengths ≥ 1.3 E_c are inconsistent. A possible explanation is extensive crack branching that occurred in every sample after as little as 20 cycles. It results in very irregular crack growth, therefore the effect of the field strength is diminished to a large extent.

If only the first ten cycles are considered and the crack growth rate da/dN is plotted versus electric field strength [Fig. 4], an almost linear dependence can be observed up to 1.7 E_c. A further increase in field strength does not increase da/dN.

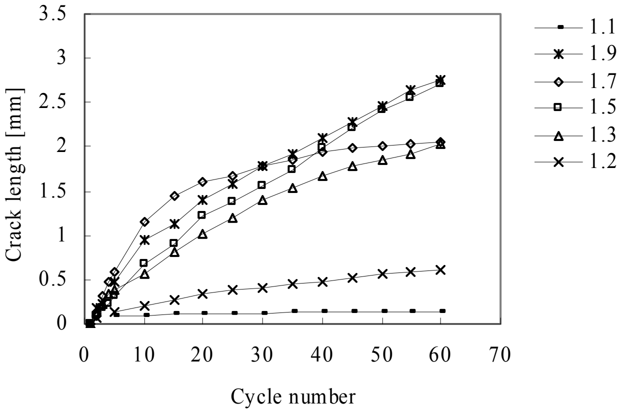

Figure 3: Crack length vs. cycle number up to 60 cycles for different electric field strengths (in kV/mm).

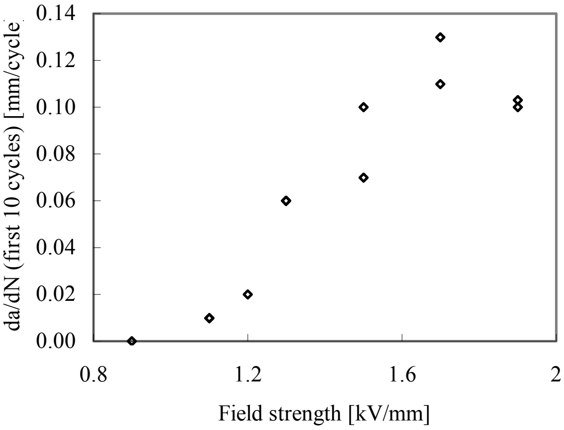

Figure 4: Crack growth rate da/dN during thefirst 10 cycles for different applied electric fields.

4 CONCLUSION

Crack growth was studied in DCB PZT specimens under cyclic electric loading of different amplitudes. In contrast to previous works no crack growth was observed at field strengths lower than the coercive field. For cases where switching occurs in a confined zone due to an intensified electric field close to the crack tip, it does not induce sufficient stress to cause crack growth.

Cycling at electric fields above E_C resulted in an increasing crack growth rate with increasing field strength, in agreement with previous results. The use of a very low frequency enabled us to determine the points in the dielectric hysteresis where crack growth takes place.

5 ACKNOWLEDGMENTS

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6 REFERENCES

1. Xu, Y., “Ferroelectric Materials and their Applications”, Elsevier Science Publishers B.V., Amsterdam, 1990
2. Cao, H., Evans, A. G., “Electric-field-induced fatigue crack growth in piezoelectrics”, J Am . Ceram. Soc. 77, 1783-86, 1994
3. Lynch, C. S., Yang, W., Collier, L., Suo, Z., McMeeking, R. M., “Electric Field Induced Cracking in Ferroelectric Ceramics”, Ferroelectrics 166, 11-30, 1995
4. Zhu, T., Fang, F., Yang, W., “Fatigue crack growth in ferroelectric ceramics below the coercive field”, J Mat Sci Let 18, 1025-27, 1999
5. Jiang, L. Z., Sun, C. T., “Crack growth behavior in piezoceramics under cyclic loads”, Ferroelectrics 233, 211-223, 1999
6. Weitzing, H., Schneider, G. A., Steffens, J., Hammer, M., Hoffmann, M. J., “Cyclic Fatigue Due to Electric Loading in Ferroelectric Ceramics” J. Europ. Ceram. Soc. 19, 1333-37, 1999
7. Liu, B., Fang, D., Hwang, K.-C., “Electric-field-induced fatigue crack growth in ferroelectric ceramics”, Materials Letters 54, 442-6, 2002
8. Zhu, T., Yang, W., “Fatigue crack growth in ferroelectrics driven by cyclic electric loading”, J. Mech. Phys. Solids 47, 81-97, 1999
9. Suo, Z., Kuo, C.-M., Barnett, D. M., Willis, J. R., “Fracture Mechanics for Piezoelectric Ceramics”, J. Mech. Phys. Solids 40, 739-765, 1992
10. Park, S.B., Sun, C. T., “Effect of electric field on fracture of piezoelectric ceramics”, Int J Frac 70, 203-216, 1995