Effect of electric field, stress and environment on delayed fracture of a PZT-5 ferroelectric ceramic

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Abstract The combined effect of electric and mechanical loading on fracture of a PZT-5 ferroelectric ceramic in silicone oil has been investigated using a single edge notched specimen. The results show that the fracture toughness and the threshold stress intensity factor of delayed fracture in silicone oil, i.e. stress corrosion cracking, decrease linearly with the increasing applied electric field, either positive or negative. For the PZT-5 ferroelectric ceramics, delayed fracture in silicone oil under sustained positive or negative field can occur, and the threshold field for delayed fracture under sustained positive or negative field decreases linearly with applied stress intensity factor. The combined effect of electric and mechanical loading on delayed fracture in silicone oil includes field-enhancing delayed fracture under sustained load and stress-enhancing delayed fracture under sustained field.

Keywords: PZT-5 ferroelectric ceramics, fracture toughness, delayed fracture under sustained load, delayed fracture under sustained electric field.

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1 Introduction

Ferroelectric ceramics have become the preferred materials for a wide variety of electronic and mechanical devices due to their pronounced piezoelectric, dielectric and pyroelectric properties. Nonetheless, electrical and/or mechanical breakdown of the materials can cause device failure, and is therefore seriously considered in the design of ferroelectrics-based devices.

An applied electric field can influence evidently fracture toughness of ferroelectric ceramics. For example, Tobin and Pars indicated that crack propagation in Vickers’ indents of PZT-8 ceramics was promoted by a positive field and retarded by a negative field. Wang and Singh, however, observed an opposite phenomenon in Vickers’ indent of PZTEC-65 ceramics. Sun and Park showed that if the indentation load was low, the
results for PZT-4 ceramics were consistent with those of Tobin and Park\(^4\), however, if the indentation load was high, either negative or positive field facilitated crack propagation. Park and Sun\(^7\) indicated that positive field decreased but negative field increased the fracture toughness measured using compact-tension specimens of PZT-4 ceramics. Fu and Zhang\(^8,9\) showed that the applied electric field, either positive or negative, reduced the mean of the fracture toughness and the bending strength of PZT-841 ceramics measured using the compact-tension and three-point bending specimens, respectively.

Our papers\(^10,11\) indicated that delayed fracture, i.e. stress corrosion cracking (SCC), of PZT-5 ceramics in various environments, such as moist atmosphere, silicone oil, water, methanol and formamide, could occur under sustained load. On the other hand, we found that delayed fracture in silicone oil under a sustained field could occur\(^12\).

In operation of ferroelectrics-based devices, there may exist at the same time stress including internal stress, electric field and environment, such as moist atmosphere and oil. Therefore, the combined effect of electric and mechanical loading on delayed fracture in used environment of ferroelectric ceramics should be investigated. The first objective of this work is to investigate the effect of positive and negative fields on delayed fracture in silicone oil under sustained load, i.e. SCC, which is one kind of combined effect of electric and mechanical loading on delayed fracture in silicone oil. The second objective of this work is to study the effect of applied stress on field-induced delayed fracture in silicone oil under a sustained positive and negative fields, which is the other kind of combined effect of electric and mechanical loading on delayed fracture in silicone oil.

2 Experimental procedure

Soft lead zirconate titanate ceramics \((Zr_{1-x}Ti_x)O_3\) with a Zr/Ti ratio of 52/48 (PZT-5H) was used, which was pressured into a bulk in dimensions of 8 40 100 mm\(^3\), sintered at 1260°C for 1.5h. The coercive field of the ceramics was \(E_c=11\) kV/cm. The tensile specimens in dimensions of 0.9 8 40 mm\(^3\) were cut from the bulk with an average grain size of 2.5 \(\mu m\). Then two ends of the specimen were nickel electroplated and the distance between the cathode and anode was 25 mm, as shown in fig. 1(a). The specimens were poled along the longitudinal direction at 400°C, which is higher than the Curie point of 350°C, and the electric field of 2 kV/cm was applied continuously during cooling. After poling, \(d_{33}\) was 450 \(\times 10^{12}\) C/N, and an edge notch of 4 mm depth was cut by diamond cutting at the center of the specimen with a root radius of 0.15 mm. Two loading holes in a diameter of 2 mm were drilled using ultrasound method. All delayed fracture tests were carried out in silicone oil under a sustained load and/or a sustained electric field, as shown in fig. 1(b). The stress intensity factor for the single-edge notched specimen is given by\(^13\)

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K_I=\sigma f(a/w)\sqrt{\pi a},
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