ICF100475OR

Fracture behavior of conductive cracks in PZT-4 piezoelectric ceramics

Tian-Hong Wang, Ran Fu and Tong-Yi Zhang*

Department of Mechanical Engineering
Hong Kong University of Science and Technology
Clear Water Bay, Kowloon, Hong Kong, China

ABSTRACT

The present work experimentally investigates the fracture behavior of conductive cracks in PZT-4 piezoelectric ceramics by using compact specimens under combined electrical and mechanical loading. Finite element calculations were conducted to obtain the energy release rate, the stress intensity factor and the intensity factor of electric field strength of the specimens. The results show that the critical energy release rate under purely either electric or mechanical load is a constant, independent of the ligament length. However, the critical energy release rate under combined electrical and mechanical loading depends on the weight of the electrical load in comparison with the mechanical load. We normalize the critical stress intensity factor by the critical stress intensity factor under purely mechanical loading and normalize the critical intensity factor of electric field strength by the critical intensity factor of electric field strength under purely electric loading. Then, a quadratic function describes the relationship between the normalized critical stress intensity factor and the normalized critical intensity factor of electric field strength, which can serve as a failure criterion of conductive cracks in piezoelectric ceramics.

KEYWORDS

piezoelectric ceramics, intensity factor, energy release rate, combined electrical and mechanical loading.

INTRODUCTION

Piezoelectric ceramics are one kind of smart materials widely used in high-tech industries, such as sonar transducers, electromechanical actuators, controlling devices and smart structures etc. due to their high piezoelectricity, permittivity and pyroelectricity as well as the merit of easy processing and low cost. However, piezoelectric ceramics are essentially brittle and susceptible to cracking at all scales from domains to devices. Therefore, the reliability and integrity of such devices and structures made of piezoelectric ceramics have recently attracted increasing interest from both academics and industrialists. There are voluminous theoretical studies on fracture of piezoelectric materials, and more and more increasing experimental results in the literature. Recently, Zhang *et al*. [1] gave an overview about the advances in fracture of piezoelectric ceramics, involving extensively theoretical and experimental studies.

* Corresponding author, E-mail: mezhangt@ust.hk

Internal electrodes are largely adopted in electronic and electromechanical devices made from piezoelectric ceramics. These embedded electrodes may naturally function as pre-conductive cracks or notches, which may lead to failure of these devices under combined electric and mechanical loads. However, only few experimental observations of conductive cracks in piezoelectric ceramics have been reported so far. Lynch *et al*. [2] carried out indentation fracture tests on electroded surfaces submerged in electrically conducting NaCl solution and in distilled water. In both cases, tree-like damage grew from the indented electrode under the cyclic electric field. Heyer *et al*. [3] studied the electromechanical fracture toughness of conductive cracks in PZT-PIC ceramics. They conducted four-point bending tests on pre-notched bars, in which the poling direction was toward the jig surface and the notch was filled with NaCl solution to make the crack conducting. Wide scattering results were obtained under a large applied electric field ($|K_E| > 50kv/m^{1/2}$, where K_E is the applied electric intensity factor). The critical stress intensity factor increased as the applied intensity factor of the electric field strength changed from $30kv/m^{1/2}$ to $-90kv/m^{1/2}$. When the applied electric intensity factor was relative small, within the range of $-15kv/m^{1/2}$ to $15kv/m^{1/2}$, they could explain the experimental data using a domain-switching-based model. Fu *et al*. [4] conducted fracture tests of conductive cracks in poled PZT-4 ceramics, in which only positive electric field was applied. They found that under purely electric loading, there existed a critical energy release rate that was named the electric fracture toughness. The electric fracture toughness is a material property, similar to the mechanical fracture toughness. Furthermore, the electric fracture toughness under positive electric loading is about 25 times higher than the mechanical fracture toughness [4]. The present work studies the fracture behavior of conductive cracks in poled PZT-4 ceramics under negative electric fields and combined electric and mechanical loads as well.

EXPERIMENTAL PROCEDURE

The material used in this study was poled lead zirconate titanate ceramics (PZT-4, Morgan Matroc). Pre-notched or cracked compact samples were adopted in the fracture tests under purely mechanical, purely electric and mixed mechanical and electric loads. All samples had the width *w*=10mm, height *h*=10mm and thickness *t*=3mm. A pre-notch or crack was cut in each sample with a 0.15mm thick diamond saw parallel to the poling direction, and further sharpened by a 0.12 mm diameter wire saw. After the cutting, the samples were cleaned ultrasonically in distilled water for 20 seconds. For conductive cracks, silver paint was filled into the notch (crack) to make it function as an electrode. Figure1 schematically shows the sample

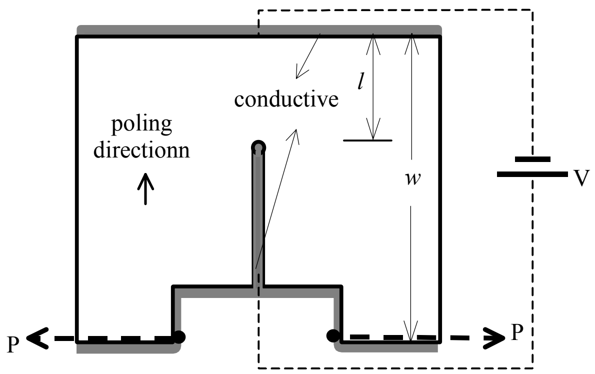

Fig.1 Depiction of the sample geometry and loading.

geometry and loading. The following three types of tests were conducted. 1) Purely mechanical loading (PM). On purpose, the ligament, *l*, varied from sample to sample and ranged from 2.5 to 4.5 mm. The tests were conducted on a mechanical testing machine (Miniature Materials Tester, Polymer Laboratories) at a crosshead rate 0.1mm/min under uniaxial tension. 2) Purely electric loading (PV). A static voltage was applied to a sample and manually increased until the sample was failed. Positive and negative electric fields, which were respectively parallel and anti-parallel to the poling direction, were applied in the tests. 3)

Mixed mechanical and electric loading. The fracture tests were carried out under a constant voltage (CV) or constant load (CM) mode on homemade loading apparatus. A constant voltage was applied first, then, the mechanical load was gradually increased until the sample fractured. In the CM mode, a constant mechanical load was applied first, following by the gradual increasing of the applied electric voltage until the sample fractured. In both modes, positive and negative electric fields were applied also. To avoid electric sparking, the samples were put into the silicone oil during tests under purely electric loading or covered by a thick layer of silicone grease under combined loading. All tests were implemented at room temperature. At least ten samples were tested under each loading condition in the CV or CM mode and 30 samples were tested in the PM or PV mode.

FINETE ELEMENT METHOD (FEM) FORMULATION

The energy release rate is equivalent to the contour-independent J-integral in the linear electro-mechanics [1, 5-8].

$$G = J = \int_{\Gamma} (hn_1 - \sigma_{ij} n_j u_{i,1} + D_i E_1 n_i) d\Gamma, \quad i, j = 1,2,3, \tag{1}$$

where $h = \sigma_{ij}\varepsilon_{ij}/2 - D_i E_i/2$ is the electric enthalpy per unit volume, Γ is an integration contour around the crack tip, and $\boldsymbol{n}$ is the unit out normal vector to the contour. In the finite element calculation of J-integral, we used the commercial software ABAQUS and the eight-node plane strain piezoelectric elements, and the material constants of the poled PZT-4 ceramics

Elastic constants ($10^{10}\ N/m^2$):
$c_{11} = 13.9,\ c_{12} = 7.78,\ c_{13} = 7.43,\ c_{33} = 11.3,\ c_{44} = 2.56$;
Piezoelectric constants (C/m^2):
$e_{31} = -6.89,\ e_{33} = 13.84,\ e_{15} = 13.44$;
Dielectric constants ($10^{-9} F/m$):
$\kappa_{11} = 6.00,\ \kappa_{33} = 5.47$

where the subscript "3" denotes the poling direction and *N*, *m*, *C* and *F* represent, respectively, Newton, Meter, Coulomb and Farad. The numerical results were fitted into the following formulas for the sample ligament, *l*, ranging from 2.5mm to 4.5mm.

$$G_I^M = \left[1.1783 - 9.8796s + 32.606s^2 - 49.125s^3 + 28.229s^4\right]P^2 \ \text{(N/m)} \tag{2}$$

for purely mechanical loading, and

$$G_I^E = \left[11.83 - 73.34s + 213.18s^2 - 306.53s^3 + 174.67s^4\right]V^2 \ \text{(N/m)} \tag{3}$$

for purely electric loading, where $s = l/w$ and *w*=10 mm is the sample width, *P* is the mechanical load in units of *N*, and *V* is the applied voltage in units of *kV*. The stress intensity factor and the intensity factor of electric field strength were derived from the J-integral under combined loading

$$K^{\sigma} = \frac{P}{t\sqrt{w}} f_1(s), \qquad K^E = \frac{V}{\sqrt{w}} f_2(s), \tag{4}$$

where *t* is the sample thickness, f_1 and f_2 are two dimensionless function of *s,* and given by

$$f_1(s) = (-2.861 + 15.076s - 26.612s^2 + 17.328s^3 - 1.603s^4) \times 10^2, \tag{5}$$

$$f_2(s) = 7.116 - 48.142s + 134.323s^2 - 160.043s^3 + 72.244s^4 . \tag{6}$$

Under mixed mechanical and electrical loading, the critical load and voltage at fracture were recorded to calculate the critical intensity factors with Eqs. (4-6).

RESULTS AND DISCUSSION

Fig. 2(a) shows the relationship of critical load versus ligament for purely mechanical loading, where a solid circle represents an experimental datum and hereafter the same symbol is used in the rest figures without notation. The mean of the energy release rate is $G_{IC}^M = 8.7 \pm 0.4 N/m$ (95% confidence). Using this mean and Eq. (2) we plot the load versus the ligament again, which is shown as the dot line in Fig. 2(a). On the other hand, a linear regression of the experimental data is shown as the solid line in Fig. 2(a). It can be seen the dotted line almost coincides with the solid one, indicating the existence of the mechanical fracture toughness in terms of the critical energy release rate. To be more straightforward, the calculated critical energy release rate versus the sample ligament is plotted in Fig. 2(b). It is clearly seen that the linear regression of the plot is very approximate to the horizontal line, indicating that the critical energy release rate is a material constant independent of the sample ligament. The mechanical fracture toughness can also be expressed in terms of the critical stress intensity factor, which is $K^{\sigma_0} = 0.934 \pm 0.06 MPa\sqrt{m}$ under purely mechanical loading. Fig. 2(c) shows that the failure probability of the PZT-4 ceramics under purely mechanical loading follows the Weibull distribution

$$F(G_I^M) = 1 - \exp\left[-\left(\frac{G_I^M}{9.0103} \right)^{9.6435} \right], \tag{7}$$

where F is the cumulative distribution function and G_I^M is in units of *N/m*. Under purely mechanical loading, the PZT-4 ceramics has a Weibull modulus of 9.6435, more or less the same as other engineering ceramics.

In the same way, Fig. 3(a) illustrates the critical voltage as a function of the ligament. The mean of the critical energy release rate is $G_{IC}^E = 223.7 \pm 17.0 N/m$ (95% confidence). As shown in Fig. 3(a), the dotted line of the theoretical prediction coincides the solid line of the linear regression of the experimental data, indicating the existence of the electrical fracture toughness. We also plot the critical energy release rate versus the sample ligament in Fig. 3(b). As expected, the linear regression of the plot is almost a horizontal line. This feature, in analogy with the mechanical case, indicates the existence of the electric fracture toughness under purely electric loading. The electric fracture toughness is a material property and has the value $G_{IC}^E = 223.7 \pm 17.0 N/m$ in terms of the critical energy release rate, which is about 25 times larger than $G_{IC}^M = 8.7 \pm 0.4 N/m$. This is because electrical discharge and domain switching may occur at the tip of the conductive crack, forming an electrically plastic zone. Actually, electric discharge was observed during the tests. This kind of electrical plastic deformation accompanies crack propagation and consumes energy, thus leading to the high electrical fracture toughness. The failure probability of the PZT-4 ceramics under purely electric loading, as shown in Fig. 3(c), follows the Weibull distribution of

$$F(G_I^E) = 1 - \exp\left[-\left(\frac{G_I^E - 130}{110.25} \right)^{2.331} \right] \text{ with } G_I^E \text{ in units of } N/m. \tag{8}$$

Comparing Eq. (8) with Eq. (7) indicates that a three parameter Weibull distribution has to be used to describe the failure probability under purely electrical loading, while a two parameter Weibull distribution is sufficient to describe the failure probability under purely mechanical loading. Equation (8) is valid only when G_I^E is larger than 130 *N/m*. When G_I^E is smaller than 130 *N/m*, no failure will occur under purely electrical loading. The PZT-4 ceramics under purely electric loading has a Weibull modulus of 2.331, as

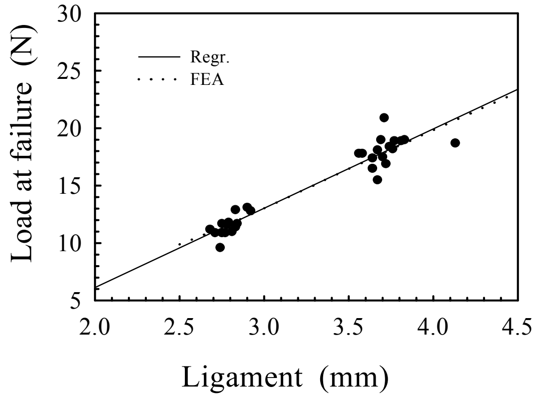

Fig.2(a) Critical force versus ligament under purely mechanical loading.

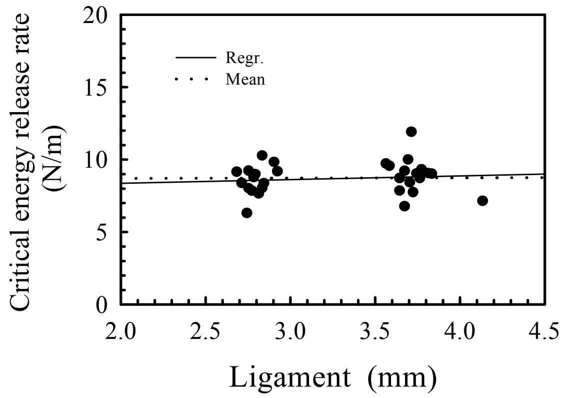

Fig.2(b) Critical energy release rate versus ligament under purely mechanical loading.

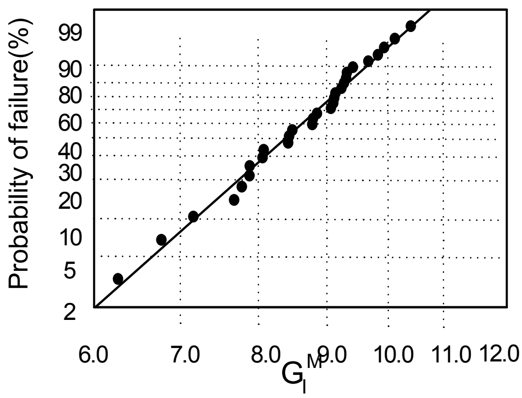

Fig.2(c) Weibull distribution of critical energy release rate under purely mechanical loading.

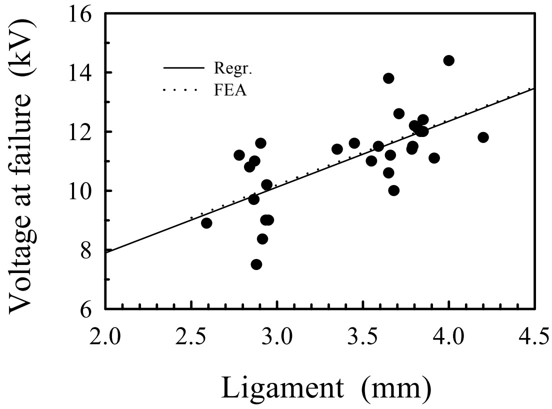

Fig.3(a) Critical voltage versus ligament under purely electric loading.

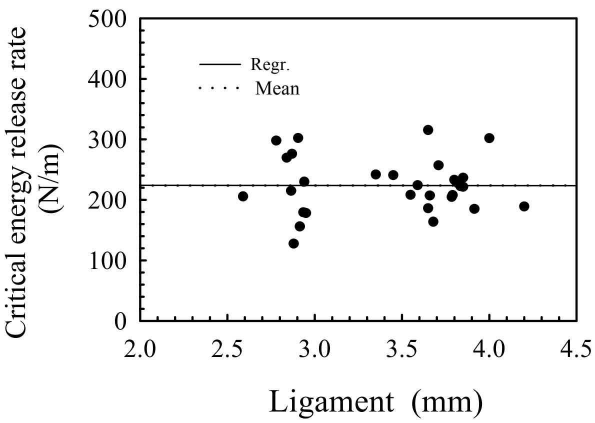

Fig.3(b) Critical energy release rate versus ligament under purely electric loading.

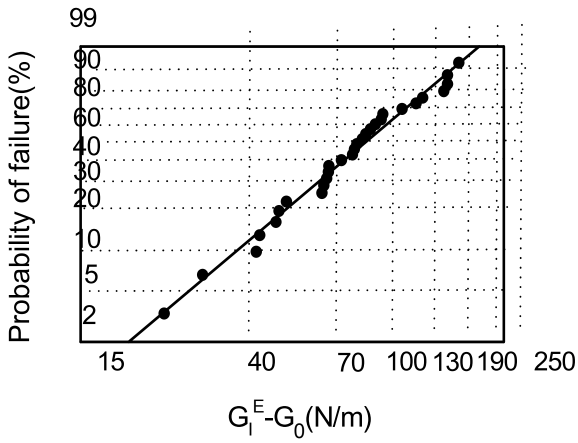

Fig.3 (c) Weibull distribution of critical energy release rate under purely electric loading.

shown in Eq. (8), which is much smaller than that under purely mechanical loading, indicating a larger variability of the electric fracture toughness.

Under combined electric and mechanical loading, we normalize the critical stress intensity factor by the critical stress intensity factor under purely mechanical loading and normalize the critical intensity factor of electric field strength by the critical intensity factor of electric field strength under purely electric loading. Figures 4(a) and 4(b) show the relationships of the normalized intensity factor of electric field strength versus the normalized stress intensity factor, respectively, for positive and negative electric loading. The experimental data can be approximately described by the equation

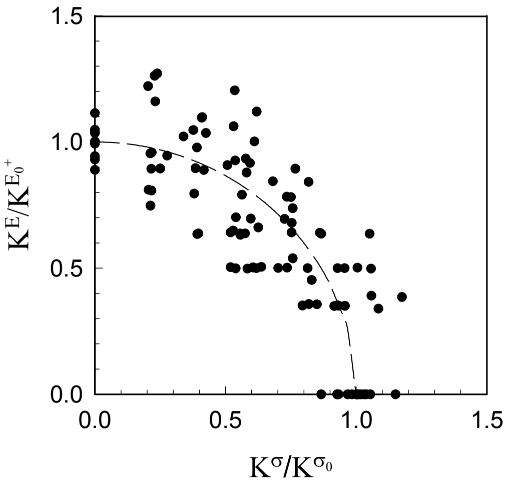

Fig.4(a) The normalized electric intensity factor versus the normalized stress intensity factor under positive electric fields.

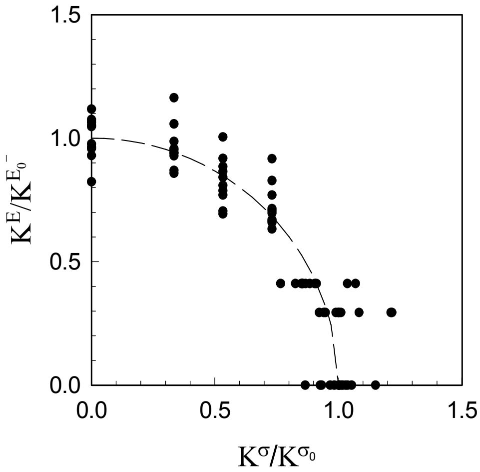

Fig.4(b) The normalized electric intensity factor versus the normalized stress intensity factor under negative electric fields.

$$\left(K^E / K^{E_0^\pm}\right)^2 + \left(K^\sigma / K^{\sigma_0}\right)^2 = 1, \quad (9)$$

which is shown as the dashed curve in Figs. 4(a) and 4(b). Equation (9) may serve as a failure criterion for poled PZT ceramics under combined electric and mechanical loading. A model to explain the experimental observations will be given in a separate paper [9].

CONCLUSIONS

This work experimentally investigates the fracture behavior of conductive cracks in PZT-4 piezoelectric ceramics. The results demonstrate the existence of the electric facture toughness under purely electrical loading. The failure probabilities of the PZT-4 ceramics are expressed in terms of three and two parameter Weibull distributions, respectively, for purely electrical and mechanical fracture toughnesses. An empirical criterion in terms of the normalized intensity factors of stress and electric field strength is proposed to describe the fracture behavior of poled PZT ceramics under combined electrical and mechanical loading.

ACKNOWLEDGEMENTS: The work was supported by the Research Grants Council of the Hong Kong Special Administrative Region, China.

REFENRENCES

1. Zhang, T.Y., Zhao, M.H. and Tong, P. (2001) Fracture of Piezoelectric Ceramics, *Advances in Applied Mechanics*, in press.
2. Lynch, C. S., Yang, W., Collier, L., Suo, Z., and McMeeking, R. M. (1995) *Ferroelectrics* **166**, 11.
3. Heyer, V., Schneider, G. A., Balker, H., Drescher, J., and Bahr, H. A. (1998) *Acta mater.* **46**, 6615.
4. Fu, R., Qian, C.F. and Zhang, T. Y., (2000) *Appl. Phys. Lett.* **76**, 126.
5. McMeeking, R. M. (1990) *Int. J. Engng, Sci.*, **28**, 605.
6. Suo, Z. (1993*) J. Mech. Phys. Solids*, **41**, 1155.
7. Zhang, T. Y., Qian, C. F. and Tong, P. (1998) *Int. J. Solids Structures*, **35**, 2121.
8. Cherepanov, G.P. (1979) Mechanics of Brittle Fracture, McGraw-Hill, New York.
9. Zhang, T. Y., Wang, T. H., Fu, R. and Zhao, M. H., unpublished work.