DAMAGE, FRACTURE AND FATIGUE FOR THE PIEZOELECTRIC AND FERROELECTRIC MEDIUM

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ABSTRACT

Damage and dynamic fracture of the piezoelectric medium is an important branch of the fracture of smart materials and structures. Some new solutions for the damaged medium with micro-crack and micro-void are addressed and several solutions of dynamic fracture, wave scattering of crack weakened piezoelectric-medium under mode III and mode I for the response of electrical-mechanical impact are given**.** Two different boundary conditions of the surface for impermeable and perfect electric contact of crack surface are discussed.

Domain polarization switch near the tip of a flaw plays a critical role on the fracture and fatigue behavior of ferroelectric ceramics under electrical and/or mechanical loading. We will discuss three types of experiments, and propose the pertinent meso-mechanics models based on domain switching to explain the data.

1. DAMAGE ANALYSIS OF PIEZOELECTRIC PROPERTIES

Electromechanical coupling is known to be inherent in piezoelectric materials. They are used in actuators and transducers for a variety of applications..By way of Stroh's formula and the property on the root of multiplicit in piezoelectricity, the logarithmic singularity at a crack tip in homogeneous piezoelectric materials was investigated by Qin and Yu [1].Then a plane problem of a crack terminating at the interface between two piezoelectric solids was studied by using the concept of axial conjugate the technique of singular integral equations [1 , 2]. Further, the singular crack tip behavior for thermoelectroelastic problems was also studied. By application of Fourier transformations and extended Stroh's formula. Considering the above theoretical results, the formulation for estimating effective material parameters developed for thermopiezoelectric solids with microcracks or microvoids of various shapes deduced by Qin,Mai and Yu [3,4].These Models are capable to determinate the effective properties such as the conductivity,electrelastic modulu, thermal expansion and pyroelectric coefficients. Mori-Tanaka techniques give explicit estimates of the effective thermoelectroelastic moduli. Electromechanical coupling is known to be inherent in piezoelectric materials.

2. TRANSIENT RESPONSE UNDER MECHANICAL_ELECTRICAL IMPACT

mode III case

In applications, piezoelectric materials are often required to resist dynamic loads. The anti-plane problems of a finite length crack and a semi-infinite crack subjected to sudden electromechanical disturbances can be found in the papers of Chen and Yu [5,6,7]. It was shown that the dynamic stress intensity factor(SIF) depends not only on mechanical impact, but also on the electrical impact, piezoelectric constants and dielectric constants. The dynamic stress intensity factor (DSIF) and the dynamic energy release rate (DERR) are shown to depend on the ratio of crack length to strip width and the combination of loading parameters.

Mode I case

For Mode I, the results of transient response are shown in Wang and Yu [10] also depend on the boundary conditions and the loading parameter λ. Compared with Mode III, the boundary conditions tend to couple SIF and EDIF even if the loading is static. DEDIF exhibits a dynamic behavior owing to the more complicated coupling effect. For the crack driving force, the results also show that DERR (instead of DSIF) could shed information on crack extension. The dynamic electric displacement intensity factor (DEDIF) for Mode I exhibits the dynamic effect such that the electromechanical coupling effect tends to weaken the quasi-static approximation for electric fields.

In addition,a problem of propagated Yoffe-crack is solved by Chen and Yu[11],other solutions of propagated Griffith Crack can be found in the paper of Chen,Yu and Karihaloo[12].

3. SCATTERING OF INCIDENT WAVES BY A DEBONDED PIEZOELECTRIC INCLUSION

For the scattering of incident waves by a crack, the dynamic stress intensity factor and electric field intensity factor were given by Wang and Yu in [6] by application of the solutions of singular integral equations. Considered also is the scattering problem of SH waves by a debonded piezoelectric inclusion. Two types of material combinations are treated, namely, epoxy/piezoelectric and piezoelectric/piezoelectric. Near-field exhibits low frequency resonance behavior. Large sub-resonant peaks for the piezoelectric/piezoelectric far-field solution appear frequently in the high frequecy region[13,14].

4. CRACK TIP DOMAIN SWITCHING AND UNCONVENTIONAL DOMAIN PLATE ASSEMBLIES

Ferroelectric ceramics exhibit peculiar behaviors such as fracture and fatigue cracking near defects or electrodes under electric load. Reliability is a major concern that calls for a better understanding of their degradation mechanisms. Though the fracture of ferroelectrics appears as the outcome of the electrical loading, the crack extension itself is driven by stress concentration due to the incompatible switching strain. Recent work in [15] explored switch-toughening of ferroelectric ceramics. The intensive electric field near a crack tip stimulates local domain polarization switching. The switched domains generate incompatible strain under the constraint of un-switched material and consequently alter the stress distribution near the crack. To verify the theory by experiment, the specimens were poled to eliminate previous domain band structures. Cracks are introduced after poling. Lateral electric field was applied to cause field concentration near the crack tip. Domain switching occurs near the crack tip and its microscopy reveals banded structures [16], Fig. 1.

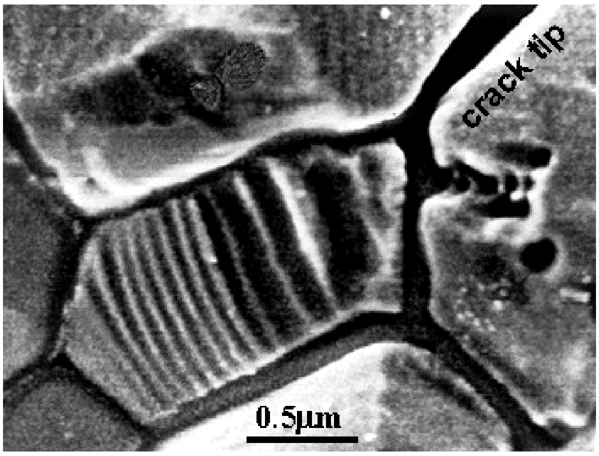

Fig. 1. SEM showing 90^{o} domain switching zone near a crack tip under lateral electric field

The observed band orientation indicates that the domain assembly near the crack tip is unconventional, caused by the highly localized crack tip electric field. An energetic and kinetic framework is proposed to quantify the parameters for the unconventional assembly and to take into account the embryos of domain structures. The elastic mismatch energy for a partially switched ferroelectric grain embedded in a polycrystalline ferroelectric matrix is formulated as a banded Eshelby inclusion. The domain wall energy is derived for unconventional domain structures via arrays of misfit dislocations, given a value of 0.023J/m^2 for Γ_{90}, the 90° domain wall energy. Micromechanics analysis quantifies various characteristics of unconventional domain band structures near a crack tip. The orientation of the domain wall is described by:

$$-\cos\phi\sin\phi x_1+\cos^2\phi x_2\pm\sqrt{\frac{1+\cos^4\phi}{2}}x_3=0\,. \qquad (1)$$

where $\phi = 70°$ is the measurable inclination angle. The volume fraction of the switched domain is:

$$V_{90} = \frac{C}{Y}\left(\frac{a}{c-a}\right)^2 P_s E_{\mathrm{app}} . \quad (2)$$

The constraining coefficient C is $15(1-\nu^2)/(7-5\nu)$ for a spherical grain constrained in all directions, and $16(1-\nu^2)/3$ for long cylindrical grains unconstrained along the cylinder axis. For the "soft" ferroelectric ceramics used in this test, the relevant physical constants are $Y = 33\mathrm{GPa}$, $\nu = 1/3$, $c/a = 1.013$, $E_c = 1.1\times10^6\,\mathrm{V/m}$ and $P_s = 0.3787\mathrm{C/m}^2$. The calculation gives $V_{90} = 0.249$ for fully constrained spherical grain and $V_{90} = 0.474$ for cylindrical grain unconstrained along its axis. They provide bounds for actual value of V_{90}, as assessed from Fig. 1 as $V_{90} \approx 0.35$. The thickness of the switching plates is given by:

$$t = \sqrt{\frac{\pi^3 \Gamma_{90} D}{1.8\left[\frac{P_s^{\,2}}{\varepsilon} + \frac{2(1-\nu)Y}{(1+\nu)(3-4\nu)}\frac{(c-a)^2}{a^2}\frac{1+2\cos^2\phi+5\cos^4\phi}{(1+\cos^2\phi)^2}\right]}} . \quad (3)$$

Substitution of above data, plus $\varepsilon = 1800\varepsilon_0 = 1.593\times10^{-8}\,\mathrm{F/m}$, into (3) gives a predicted domain wall spacing of $t = 0.2178\mu\mathrm{m}$, that is at the same order but larger than the measurement of Fig. 1.

5. FRACTURE TOUGHNESS OF POLED FERROELECTRICS

Experiments are conducted for SENB specimens of polycrystalline ferroelectrics when poled in longitudinal, vertical and through the thickness directions. Fracture toughness anisotropy is observed: the specimens poled along the longitudinal direction (normal to the crack front) has the least fracture toughness of $0.94\mathrm{MPa}\sqrt{\mathrm{m}}$; the ones poled along the vertical direction (parallel to the crack) has the intermediate fracture toughness of $1.08\mathrm{MPa}\sqrt{\mathrm{m}}$; and the ones poled out-of-plane has the highest fracture toughness of $1.24\mathrm{MPa}\sqrt{\mathrm{m}}$. The wakes of domain switching serve to raise the apparent fracture toughness. A model based on small scale domain switching is described in [17]. For a concrete calculation, we take the material parameters for PZT-5 furnished in the previous section. The toughening effect is given by:

$$K_{IC} \approx \frac{K_{intrinsic}}{1-5.277\Omega}. \tag{4}$$

Under a poling field of 2.5kV/mm, the calculations [15] indicated that $\Omega = 0.022$ for samples poled longitudinally and $\Omega = 0.044$ for samples poled along the height. The difference explains the fracture toughness anisotropy reported in the literatures. For the case of anti-plane poling, the dimensionless quantity Ω would be about 0.079 for PZT-5 if the specimen were composed of a mono-domain crystal directed in the thickness direction. The actual domain configuration under an anti-plane poling of strength 2.5kV/mm, however, would lead to rather even polarization distribution within a cone from -45 to 45 degrees with respect to the thickness direction. Then the Ω value should be scaled by a factor of $8/\pi^2$, and become 0.064.

An intrinsic fracture toughness of $0.83\text{MPa}\sqrt{\text{m}}$ is taken to fit three sets of experimental data. The present analysis predicts K_{ss} values of $0.939\text{MPa}\sqrt{\text{m}}$, $1.081\text{MPa}\sqrt{\text{m}}$ and $1.253\text{MPa}\sqrt{\text{m}}$ for the specimens poled in the longitudinal, height and thickness directions. The switching induced stress intensity factors for the ferroelectric specimens poled in different directions quantify our experimental data of Fang and Yang [18].

Vickers indents of single crystal ferroelectrics undergone in-plane or anti-plane poling are conducted, the theory of domain switching is able to explain the intrigue cracking patterns under different directions of poling, Fig. 2.

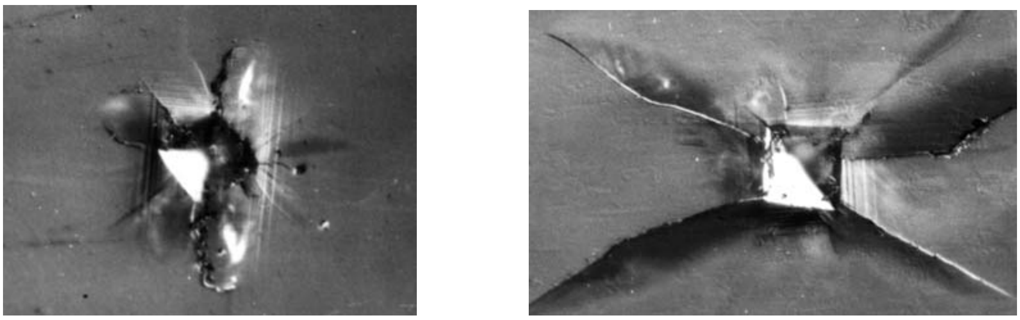

Fig. 2 Vickers indents for single crystal PLZT after anti-plane and vertical poling

6. FATIGUE CRACK GROWTH UNDER ALTERNATING ELECTRIC FIELD

The previous work by Cao and Evans reported fatigue crack growth in ferroelectrics by an alternate field whose amplitude is beyond the coercive value. By applying an alternate field with rectangular waveform, we observed [19] substantial fatigue crack growth even when the field amplitude is below the coercive field. Small scale switching model was proposed to link the fatigue crack growth to the unique domain switching sequence [20]. Our recent experiments indicate the important influence on the crack growth rates by the waveforms of the alternating field. For example, by changing the rectangular waveform to the sinusoidal waveform, the fatigue crack growth rate will reduce about two orders of magnitude. This finding may lead to many possibilities to suppress the fatigue growth rates by modulating the field wave patterns. The previous model [20] is modified to accommodate the case of arbitrary waveforms. Its prediction, without any fitting parameters, is compared with the electric fatigue cracking data.

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