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Crack instability of ferroelectric solids under alternative electric loading

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ABSTRACT

The low fracture toughness of the widely used piezoelectric and ferroelectric materials in technological applications raises a big concern about their durability and safety. Up to now, the mechanisms of electric-field induced fatigue crack growth in those materials are not fully understood. Here we report experimental observations that alternative electric loading at high frequency or large amplitude gives rise to dramatic temperature rise at the crack tip of a ferroelectric solid. The temperature rise subsequently lowers the energy barrier of materials for domain switch in the vicinity of the crack tip, increases the stress intensity factor and leads to unstable crack propagation finally. In contrast, at low frequency or small amplitude, crack tip temperature increases mildly and saturates quickly, no crack growth is observed. Together with our theoretical analysis on the non-linear heat transfer at the crack tip, we constructed a safe operating area curve with respect to the frequency and amplitude of the electric field, and validated the safety map by experiments. The revealed mechanisms about how electro-thermal-mechanical coupling influences fracture can be directly used to guide the design and safety assessment of piezoelectric and ferroelectric devices.

1. Introduction

Ferroelectric materials have been widely employed in sensors, transducers, actuators and ferroelectric memories (Eerenstein et al., 2006; Haertling, 1999; Scott, 2007) for their excellent piezoelectric property and intrinsic switchable spontaneous polarization. Depending on the application, the ferroelectric devices are always exposed to cyclic electric loading (Kuna, 2010). However, the low fracture toughness of ferroelectric materials makes it hard to resist the growth and coalescence of unavoidable initial cracks under alternative electric loading.

These cyclic electric loading induced crack propagation phenomenon was first observed by Cao and Evans (1994) and confirmed by Lynch et al. (1995). During the last decade, both the experimental and theoretical studies concerning the alternative electric load induced crack growth have been performed by several research groups, such as Lynch et al. (1995a, 1995b), Zhu and Yang (1998), Weitzing et al. (1999), Liu et al. (2002), Fang et al. (2004, 2005, 2007, 2008, 2011), Jeong and

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Beom (2004), Beom and Jeong (2005), Westram et al. (2007a, 2007b, 2009), Gehrig et al. (2008), Abdollahi and Arias (2012, 2013, 2014), Zhang et al. (2013), Jiang et al. (2014). Most of the published works concerned the insulating crack propagating in the direction perpendicular to the electric field under alternative electric loading with different field strength and frequency. It was widely accepted that there exists both electric field amplitude threshold and frequency threshold for the crack growth: (1) Amplitude threshold E_{th}. The field strength typically needs to exceed a certain level before crack propagation starts. Cao and Evans (1994) observed that the cyclic electric induced crack propagates for applied amplitudes $E \geq 1.1\ E_c$ (coercive field), while Zhu and Yang (1998) concluded that the certain level can be below the E_c based on the experimental tests of PZT-5 material. Fang et al. (2004) observed that the electric amplitude threshold E_{th} equals to 0.797 E_c. (2) Frequency threshold f_{th}. Fang and Liu (2013) also found that the crack growth is frequency-dependent, as was observed by Weitzing et al. (1999). They reported that until the applied frequency is lower than the threshold value f_{th}=341.53 Hz, obvious fatigue crack propagation can be observed. Up to now, it is difficult to grasp the phenomena in a theoretical manner for the variety of experimental conditions and results, and the mechanisms of electric-field induced fatigue crack growth are still not fully understood.

Furthermore, the thermal effect to fracture has been largely neglected since most piezoelectric or ferroelectric samples were immersed in oil during experiments to prevent possible electrical breakdown. In practices, however, most of the piezoelectric or ferroelectric devices are exposed to air. Given the thermal conductivity of ferroelectrics-air is one to two orders of magnitude smaller than that of ferroelectrics-oil, current experiments with ferroelectric samples immersed in oil differ significantly from their serving environment. Thermal effect could affect the piezoelectric behavior or even destroy the devices and their ancillary components, such as soldered connections and adhesively bonded joints (Härdtl, 1982; Jiehui et al., 1996; Lynch et al., 1995; Stewart and Cain, 2014; Uchino, 1998). This inconsistence would have great influence on the fracture mechanics of ferroelectric materials. More important, a connection between the electro-thermal-mechanical coupling at a crack tip (Livne et al., 2010) and the failure behaviors of the devices remains rarely explored, to our best knowledge.

In this paper, the mechanisms of self-heating induced crack instability of ferroelectric materials are researched systematically. We present experimental observations on how alternative electric loading at different frequency or amplitude would give rise to distinct temperature field at the crack tip and crack stability in Section 2. Further theoretical analysis and finite element analysis on the non-linear heat transfer problem at the crack tip shown in Section 3 sheds light on how electro-thermal-mechanical coupling influences fracture, which enables us to construct a fracture phase map for the design and safety assessment of piezoelectric and ferroelectric devices. We conclude in Section 4.

2. Experimental procedure

2.1. Materials and specimens

The material used for the experiment was the commercial PZT-5 (Pb[Zr,Ti]O_3) ceramic with Zr:Ti=0.52:0.48 manufactured by Hongsen Electronic Materials Co. Ltd., China. It has a tetragonal crystal structure at room temperature and an average rain size of 3 μm. The soft ferroelectric ceramics had a Curie temperature above θ_c=320 °C. The coercive electric field E_c is temperature-dependent and frequency-dependent. It equals to be about 0.8 kV/mm at the fixed frequency f=1 Hz and temperature θ=20 °C, which is defined as $E_{c0}=E_c$ (f=1 Hz, θ=20 °C). The saturation polarization P_s is also temperature and frequency dependent, it equals to be about 40.0 μC/cm^2 at the fixed frequency f=1 Hz and temperature θ=20 °C. Therefore we have $P_0=P_s$ (f=1 Hz, θ=20 °C). Rectangular samples with a central crack were used, as shown in Fig. 1.

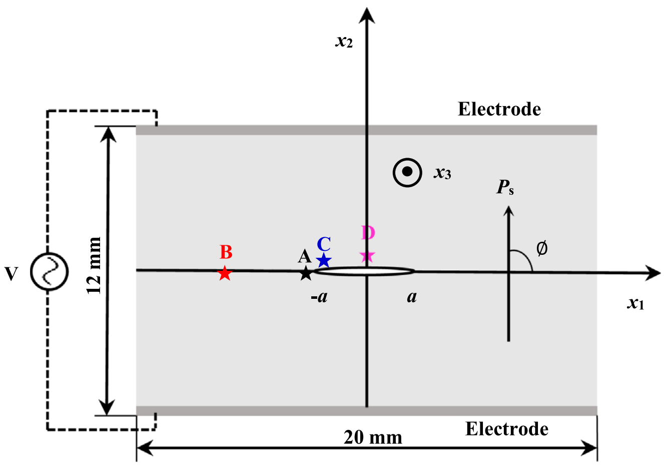

Fig. 1. Schematic illustration of a central crack in ferroelectric solids.