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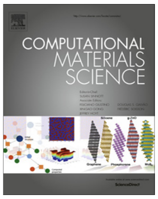

Ferroelectric creep associated with domain switching emission in the cracked ferroelectrics

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ABSTRACT

Investigations on the ferroelectric creep associated with domain switching emission near the tip of the mode I crack in ferroelectrics are conducted by birefringence experiment along with phase field simulation. Taking advantage of the birefringence technique, the evolution features of domain switching related to the spatial and temporal distribution of the remnant polarization are captured in the crack tip field. Moreover, phase field simulations are carried out to reveal the distribution of polarization and the evolution of domain switching in the cracked ferroelectrics. The domain switching emission is found to appear first in the crack tip zone and then spread to the surroundings in the ferroelectric specimen with time evolving. And the emission velocities of domain switching in the cracked ferroelectric samples are approximately calculated, which shows a clearly anisotropic feature. Results demonstrate a clear feature of ferroelectric creep occurs near the tip of crack where the total magnitude of polarization evolves with the time even under the applied constant electric loading. The key conclusion of the present paper is the intriguing feature of the ferroelectric creep associated with domain switching emission in the cracked ferroelectrics. The consistent features and conclusions can be obtained by both phase field simulation and birefringence experiment.

1. Introduction

Ferroelectric materials based on the intrinsic dielectric, piezoelectric and pyroelectric properties have found wide applications in smart structures (e.g., sensors and actuators). For the implement of the versatile applicability, ferroelectric materials are often required to work at relatively high electro-mechanical loadings. However, ferroelectric ceramics are mostly brittle and sensitive to cracks at all sizes and scales during production processes, ranging from micro domain structures to ferroelectric devices [1–3], which may lead to fracture and damage in materials and finally cause failure and malfunction in ferroelectric devices through the growth and propagation of cracks. Extensive research have been done on the fracture behaviors of ferroelectric materials in the past decades [4–10]. It is revealed that the fracture behavior of ferroelectric ceramics is very complicated due to different nonlinearities in the crack tip zone, such as domain switching or electrical yielding. Therefore, it is necessary to have a deep understanding of fracture behaviors in the cracked ferroelectrics subjected to electric or/and mechanical applied loading.

Currently, the physical phenomenon of domain switching in ferroelectric materials has been treated by both theoretical and experimental investigations [11–16]. However, there are few literatures reporting the real temporal and spatial evolution of domain switching in the cracked ferroelectrics, especially through experimental observation. Recently, birefringence method has provided a powerful tool to observe the spatial variation of the domain structures according to the unique electro-mechanical-optical properties in ferroelectric materials [17–22]. With this method, the spatial evolution of the polarization and domain switching can be captured by birefringence images. In the present paper, a standard birefringence experiment system is established for the cracked ferroelectrics, to observe the evolution pattern of domain switching near the tip of a stationary crack, where the temporal and spatial evolution of domain switching is practically investigated. Also, there have been a variety of numerical methods and models proposed for the domain structure evolution in the cracked ferroelectrics [23–36], among which the phase field method has become a significant approach in predicting the temporal evolution of domain structure and the mesoscopic behavior of materials [29–36]. Using polarization vector as the independent order parameter and taking the thermodynamic and kinetic information as input data [29,30], the domain switching evolution can be obtained by the numerical implementation of the time-dependent governing

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equations in the phase field model with given boundary and loading conditions. In this paper, two-dimensional phase field model is used to study the evolution laws of domain switching around the tip of a stationary crack in ferroelectric specimen. An efficient space discretization and implementation of the phase field simulation is developed by the finite element method (FEM), with appropriately setting of the kinetic coefficient in the governing equation, where the change of polarization is described on the basis of the minimization theory of Landau-type energy.

The main focus of this paper is to reveal the interesting features such as domain switching emission and ferroelectric creep by birefringence experiment and phase field simulation in the cracked ferroelectrics. It is important to conclude that the evolution of polarization presents the creep property in the cracked ferroelectrics. This new finding of ferroelectric creep is a very important concern in the applications of ferroelectrics which may occur even under a lower electric field, and this is rarely reported in the previous literature. The ferroelectric creep has a significant influence on the stability of the cracks in the ferroelectrics. The service life of the ferroelectric devices can be improved by control of the electric field for the polarization process and making use of the creep property properly.

The paper is organized as follows. Section 2 presents the fundamentals of the birefringence technique and the measurement system, and also gives an introduction to the theory of phase-field modeling. Section 3 gives a discussion and analysis on the results of interested in detail, including the description of the specimen and the simulation model, the evolution of polarization distribution, the domain switching emission, the emission velocity, and the ferroelectric creep. Finally, Section 4 gives a summary of the findings and conclusions obtained in this work.

2. Method and modeling

2.1. Birefringence measurement

Birefringence measurement is attributed to the piezoelectric effect or/ the unique electro-mechanical-optical properties of ferroelectric materials, the spatial variation of the internal electric field will lead to the spatial and temporal changes in the birefringence images. A standard system of birefringence measurement is shown in Fig. 1. Ferroelectric crystals are known as anisotropic materials and have intrinsic birefringence below the Curie temperature. Therefore, in a ferroelectric crystal with birefringence property, the light speed will change from c to c_i when the light enters a medium in accordance with the refractive law. Specifically, the refractive index, n, is determined by the ratio of light speeds, namely, $n = c/c_i$. Herein, the refractive index is determined by the polarized plane through which the light wave propagates. If the light wave propagates through the plane polarized in the 1–2 plane, then the refractive index is defined as n_1, and if the plane polarized in the 3–1 plane, the refractive index is n_3. The birefringence, defined as the difference of the refractive index, $\Delta n = |n_1 - n_3|$, will result in a relative phase difference δ, as the light wave propagates through the material, which is given by [17–22],

$$\delta = \frac{2\pi\tau}{\lambda}\Delta n \tag{1}$$

where τ and λ are the thickness of the specimens and the wavelength of the light, respectively.

Meanwhile, the birefringence, Δn, is known to be related to the remnant polarization and strain due to ferroelectric or piezoelectric properties, and the relations are generally described as follows [21],

$$\left(\frac{1}{\Delta n^2}\right)_{ij} = p_{ijkl}\varepsilon_{kl} + g_{ijmn}P_m P_n \tag{2}$$

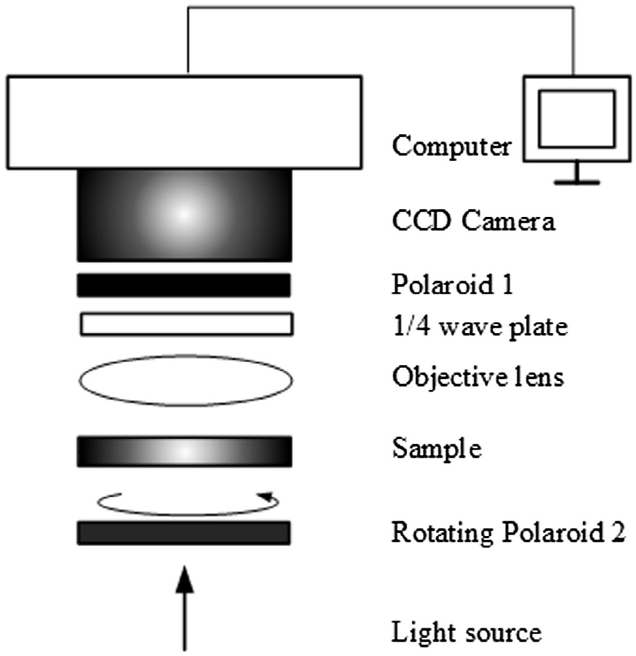

Fig. 1. Schematic for birefringence measurement system.

where ε_{kl} is the strain tensor, P_m is the material polarization induced by the applied voltage, and (p_{ijkl}, g_{ijmn}) are the elasto-optical and quadratic electro-optical coefficients, respectively.

It is noticed that the principle strain difference is almost zero at the very beginning of the birefringence experiment and increase little with the 300 s period of the test when the applied electric loading $E < 0.775E_c$ [20]. This indicates that the mechanical principle strain has a negligible contribution on the Δn. But meanwhile, the electric field intensities near the crack tip suddenly exceed the coercive field E_c and yield a large magnitude of polarization P. This indicates that the polarization has a large and major contribution on the Δn. Therefore, the change of the birefringence Δn is mainly corresponding to the remnant polarization and can be formulated by [21],

$$\Delta n = r^p (P_3^r)^2 \tag{3}$$

where r^p denotes the electro-optic coefficient related to the remnant polarization of ferroelectric materials.

Herein, we have the following relations between the relative phase difference δ and the remnant polarization P_3^r in the birefringence method, which is given by,

$$\delta = \frac{2\pi t}{\lambda} r^p (P_3^r)^2 \tag{4}$$

The relative phase difference δ, which defines the change induced by the birefringence in materials, can be related to the transmitted light intensity I by several experimental arrangements. For example, with the application of a charge-coupled device (CCD) camera, the intensity of transmitted light, I, can be measured according to the relations given by the following formula,

$$\begin{cases} I = \frac{1}{2}I_0\{1 + \sin\delta\sin 2(\varphi - \alpha)\}, \\ \varphi = \tan^{-1}(n_1/n_2). \end{cases} \tag{5}$$

where φ refers to the orientation angle of the optical indicatrix. I and I_0 define the transmitted light intensity under the conditions with and without any birefringence, respectively. In the present work, measurements of the birefringence properties are implemented by experiment method with an automated rotating