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A study of mechanisms of domain switching in a ferroelectric material via loading rate effect

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Abstract

A method to characterize the strain–electric field butterfly behavior based on the underlying domain switching mechanism is first presented. The effect of loading rate on the different characteristics of the strain–electric field butterfly behavior is then studied. By comparing the changes in these characteristics under different loading rates, it is established that the loading rate dependence of the strain–electric field butterfly behavior is mainly due to two factors: (i) the dependence of the switching of individual domains on the magnitude and duration of the loading time; and (ii) the variation of the transition electric field with the loading rate. Finally, the stability of switched domains is investigated by unloading and reloading the electric field at several predetermined values in the loading cycle. Several interesting attributes of the domain switching behavior that may shed further light on understanding the underlying mechanism of domain switching is illustrated in the present study. The present study also demonstrates that the proposed method of characterizing the strain–electric butterfly behavior based on the underlying domain switching mechanism is very effective for studying ferroelectric behavior under different loading conditions.

Keywords: Electroceramics; Piezoelectricity; Ferroelastic; Domain switching mechanism; Rate effect

1. Introduction

The effect of loading rate on domain switching, and hence on nonlinear behavior, is of interest in many applications. The stress and electric field concentration near defects in ferroelectric material can produce domain switching in the vicinity of these defects, and understanding the effect of loading rate is critical in predicting the performance and durability of such materials [1]. In certain applications, such as high-field energy absorption at 1 Hz for damping, where large electric/mechanical cyclic loads are applied, it is important to understand the effect of loading rate on strain buildup [2].

Microstructural in situ observation studies have shown that domain switching is not an instantaneous process, even in single crystals [3]. Domain switching involves nucleation, and occurs at different locations inside a domain, with outward growth sweeping through the whole domain. Hence the strain developed under the application of an electric field depends both on the magnitude of the electric field and its duration. Because of the dependence of strain on the duration of applied electric field apart from its magnitude, the strain–electric field butterfly behavior varies with the loading rate.

Most studies on the loading rate dependent behavior of ferroelectric materials are either based on analytical or computational models [4–14]. Several approaches have been used to introduce rate dependency in these models. Soukhojak and Chiang [4] extended rheological models for predicting loading rate effects on nonlinear behavior. Rate dependent models were also developed based on micromechanical principles [5–7]. Another approach used in model-

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ing is based on using free energy to obtain mesoscopic scale local average properties and then using stochastic homogenization techniques [8,9]. Huber and Fleck [10] developed rate-dependent models using a crystal plasticity model with viscoplastic behavior. Wieland and Lynch [12] have provided a detailed literature review of the modeling studies on the rate dependent behavior of ferroelectric materials.

Only a few experimental studies have reported the rate-dependent behavior of nonlinear ferroelectric materials under cyclic loading [15–22]. Viehland and Chen [15] obtained the hysteresis and butterfly behavior under different frequencies and amplitudes of cyclic electric field. The frequency dependence on polarization behavior and strain behavior was also reported by Zhou et al. [16] for soft PZT ceramics. The dependence of piezoelectric properties of $SrBi_4Ti_4O_{15}$ material on loading frequency has also been obtained for frequencies ranging from 0.01 to 100 Hz [17]. All these studies have demonstrated that the coercive electric field increases with an increase in the loading rate/frequency of the loading cycle. The term loading rate dependent behavior may be more appropriate from the domain switching perspective than the widely used term frequency dependent behavior. Using frequency as a parameter to study the rate dependency may give misleading results if the study involves variation in the amplitude of the loading cycle. Holding the electric field at different values for several minutes during cyclic electric field loading has been shown to affect significantly the polarization–field hysteresis behavior and strain–electric field butterfly behavior [18–20]. This creep type of behavior has also been reported under mechanical loading [21,22].

The objective of the present study is to investigate the loading rate effect on domain switching and on different characteristics of the strain–electric field butterfly behavior during polarization reversal. In view of this, the mechanism of domain switching during polarization reversal, reported in an earlier article [23], is revisited. Then, the significance of certain characteristics in defining the strain–electric field behavior is identified. The loading rate effect on these characteristics was studied under constant and varying loading rates. The stability of switched domains during the first and second set of non-180° domain switchings was also studied.

2. Materials and methods

Experiments were conducted on commercially supplied PZT-5H soft piezoceramic material that was poled and electroplated by the manufacturer (APC International Ltd.). The material composition is at the morphotropic phase boundary with a zirconate:titanate ratio of 0.52:0.48, which at room temperature has approximately 80% tetragonal structure and 20% rhombohedral structure (based on information provided by the vendor). The material was supplied in the form of cubes 10 mm × 10 mm × 10 mm. The electric field was generated using a Gamma high-voltage DC power supply. To prevent arcing, the whole assembly was immersed in silicone oil inside a Plexiglas container. A layer of M-coat C silicon rubber was also applied on the strain gages to prevent arcing. A very thin coat of insulating paint was applied on all the four edges of both electrodes as additional protection.

3. Results and discussion

3.1. Mechanism of domain switching

An unpoled piezoelectric material has zero average polarization in any direction due to the random distribution of the polarization direction of its individual domains. On poling under a large electric field, many of these domains switch their polarization to a direction closer to the direction of the electric field, developing a net (average) polarization in the electric field direction. A large electric field applied opposite to the poling direction of the material causes the individual domains to switch their polarization towards a direction closer to the direction of the electric field, resulting in the reversal of the average polarization. In the case of a cyclic electric field with large amplitude, the average polarization keeps reversing its direction towards the positive direction of the electric field, resulting in the well known polarization–electric field hysteresis behavior and strain–electric field butterfly behavior.

A typical strain–electric field butterfly behavior of an unpoled ferroelectric material under a cyclic electric field is shown in Fig. 1. Theoretically, application of an electric field opposite to the average polarization direction can produce either 180° domain switchings or non-180° domain switchings (71°, 90° and 109° domain switchings) of individual domains. In addition to the change in the spontaneous polarization direction, the non-180° domain switchings are associated with spontaneous strain change, requiring more energy. Hence, from the energy point of view, non-180° domain switchings should be relatively harder to achieve [23]. However, the considerable strain development in the strain–electric field butterfly behavior can only be explained by the involvement of a significant amount of

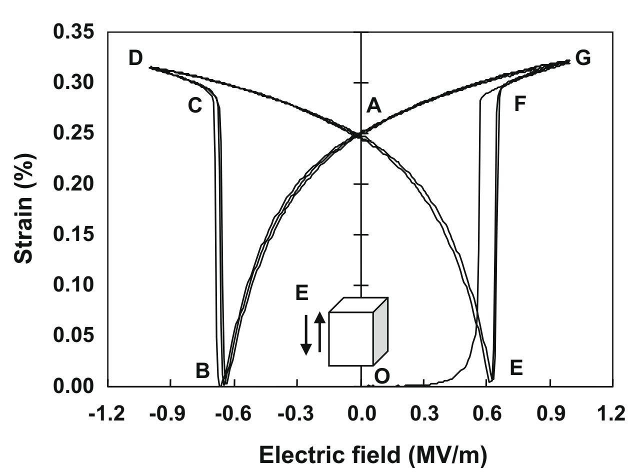

Fig. 1. Strain–electric field butterfly behavior under cyclic loading.