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Effects of electrical boundary conditions and poling approaches on the mechanical depolarization behavior of PZT ceramics

Fa-Xin Li, Dai-Ning Fang *

Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

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Abstract

In this investigation, the effects of electrical boundary conditions and poling approaches on the mechanical depolarization behavior of lead titanate zirconate ceramics are experimentally studied. Depolarization is more difficult to realize in open circuit than in short circuit, i.e., the material appears "harder" in open circuit. In short circuit, a ceramic poled with an impact electric loading at room temperature (with a negligible internal bias field) is easier to be mechanically depolarized than a ceramic poled at 120 °C with a gradually increasing electric loading (with an internal bias field of about 250 V/mm). While in open circuit, the case is completely the contrary. An analytical domain-switching model is proposed to explain the effects of electrical boundary conditions on the mechanical depolarization of ferroelectric ceramics.

Keywords: Ferroelectric ceramics; Electrical boundary; Internal bias field; Mechanical depolarization

1. Introduction

Due to their peculiar characteristics of electromechanical coupling, ferroelectric ceramics, especially lead titanate zirconate (PZT) have been widely used as actuators, sensors, transducers, etc. [1]. In these applications, they often have to be subjected to high stresses, which will lead to depolarization in the material and will hamper their performance. Experimental study on ferroelectric ceramics under high stress is essential for the reliability analysis of such smart materials and structures.

It has been well known that the linear properties of ferroelectric ceramics are strongly dependent on the electrical boundary conditions [2]. The early work of Berlincourt and Krueger [3] shows that these conditions also influence the nonlinear electromechanical behavior of ferroelectric ceramics. The nonlinear compressive behavior of ferroelectric ceramics in short circuit has been systematically investigated over the past few decades [4–8]. Cao and Evans [4] and Fan et al. [7] studied the compressive properties of soft and hard PZT ceramics. Schäufele and Härdtl [6] showed that there is a linear relationship between the coercive stress of ferroelectric ceramics and the electric field applied along the poling direction. The experimental results of Lynch [5], Fang and Li [8] and Li et al. [9] indicate that in the planes parallel to the compressive direction, non-180° domain switching is suppressed. The tensile response of ferroelectric ceramics has also been studied [10–12]. In contrast, few investigations have been concerned with the effects of electrical boundary conditions on the nonlinear electromechanical behavior of ferroelectric ceramics, except the work performed recently by Guillon et al. [12]. They studied the tensile behavior of PZT ceramics in short and open circuit conditions.

In this paper, the mechanical depolarization behavior of a soft PZT ceramic in short and open circuit is

* Corresponding author. Tel.: +86 10 627 72923; fax: +86 10 627 81824/83986.
E-mail address: fangdn@mail.tsinghua.edu.cn (D.-N. Fang).

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experimentally studied. Since the existence of an internal bias field in ferroelectric ceramics can stabilize the polarization and the internal bias field is significantly affected by the poling approaches [13,14], specimens poled by two approaches, i.e., poled at 120 °C with a gradually increasing electric field and poled at room temperature with an impact electric field, were used to experimentally study the effect of poling approach on the compressive electromechanical properties and mechanical depolarization behavior of ferroelectric ceramics. An analytical domain-switching model is proposed to explain the effect of electrical boundary conditions on the mechanical depolarization properties.

2. Experiment

2.1. Specimen

A soft PZT-5 ceramic was used in the experiment. Its properties, as provided by the manufacturer, are shown in Table 1. The specimen used in the compressive test was cut into $10 \times 10 \times 16\ mm^3$ bars with the $10 \times 10\ mm^2$ faces spread with silver electrodes. The corners of the specimen were slightly rounded to prevent cracking during testing.

Two poling approaches were applied to pole the ceramics: a traditional poling approach with field application at 120 °C and an impact poling approach at room temperature. For the traditional poling approach, the applied field magnitude was 1800 V/mm (the coercive field is about 830 V/mm) with the rising time of the loading curve usually longer than 30 s. The holding time was set to 10 min to stabilize the switched polarization. However, due to the internal bias field in PZT-5 ceramics, it is difficult to be fully poled at room temperature even if the field magnitude of above loading curve reaches 2500 V/mm. Accidentally, we found that an impact electric field with the magnitude of only 1200 V/mm is large enough to pole the ceramic fully at room temperature [14]. Thus, for the latter poling approach, an impact electric field also with the magnitude 1800 V/mm was employed at room temperature. Thanks to the excellent performance of the Treck 30/20 power supply, the rising time of the impact electric loading is no more than 1 ms [14]. At room temperature, a longer holding time (30 min) is necessary to stabilize the reversed polarization.

Table 1
Properties of PZT-5 ceramics provided by the manufacturer

Material constants		Value
Electromechanical coupling factors	K_{33}	0.70
	K_{31}	0.39
Piezoelectric constants (10^{-12} C/N)	d_{33}	450
	d_{31}	190
	d_{15}	750
Relative dielectric constants (measured at 1 kHz)	k_{33}^T/ε_0	1900–2200
	k_{11}^T/ε_0	1930–2230
Elastic constants (10^{-12} m^2/N)	s_{33}^E	17.6
	s_{11}^E	19.2

Due to the impurity doping, an internal bias field may build up in PZT ceramics after poling. The internal bias field in PZT ceramics has been systematically studied by measuring the *I–E* curves (electric current versus electric field) in prior work [15,16]. Recently, we found that a ceramic with an internal bias field will show non-symmetric hysteresis loops and butterfly loops (Fig. 1 in Ref. [14]). Furthermore, the symmetry of butterfly loops is even more sensitive to the internal bias field. Thus, in this paper, with the traditional Sawyer–Tower circuit and strain gauge [9], the butterfly loops were measured to investigate the internal bias field in PZT ceramics. Let E_1 and E_2 denote the electric field corresponding to the two tails (or valley floors) in the butterfly loop of the first circle, respectively (E_1 and E_2 can also be called the positive and negative coercive field, respectively); the internal bias field can then be expressed by $E_i = (E_1 + E_2)/2$. Compared with measuring the *I–E* curves, measuring the butterfly loops can give more information about domain switching (usually it can indicate whether non-180° domain switching occurs when compared with the ideal butterfly loops induced only by piezoelectricity). However, to measure strain with a strain gauge, bar shaped specimen should be used and the magnitude of the applied electric field is limited. To eliminate the effect of the aging process on the internal bias field, all the specimens were aged in air, and testing was conducted 4 days after poling.

Fig. 1 shows the butterfly loops of the PZT-5 specimens poled by means of the above two poling approaches. It can be deduced from Fig. 1 that E_i in the ceramics poled at 120 °C is about 250 V/mm, while E_i in the ceramics poled by an impact electric field at room temperature is almost negligible. The internal bias field in this soft PZT ceramic is thought to be caused by pyroelectricity-induced space charge concentration near the grain boundary defects or pores after poling [17], which will not be discussed here in detail.

2.2. Experimental setup

Fig. 2 shows the testing setup for compression loading in open circuit. A spherical hinge was used in this compressive setup to avoid any bias loading. Strain gauges were glued on the specimen to measure the strain along the compressive direction. A capacitive voltage divider is inserted in the circuit to measure the voltage on the specimen generated by the compression. The capacitor C_1 can resist high voltages up to 60 kV and its capacity is about one percent of the specimen (with