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Time dependent behavior of ferroelectric materials undergoing changes in their material properties with electric field and temperature

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ABSTRACT

This paper presents a time dependent polarization constitutive model suitable for predicting nonlinear polarization and electro-mechanical strain responses of ferroelectric materials subject to various histories of electric fields. The constitutive model is derived based on a single integral form with nonlinear (electric field and temperature dependent) integrand. The total polarization consists of the time-dependent and residual components. The residual component of the polarization is due to polarization switching in the ferroelectric materials. We use an 'internal clock' concept to incorporate the effect of electric field on the rate of polarization. The corresponding strain response is determined through the use of third order piezoelectric constant and/or fourth order electrostrictive constant that vary with polarization stage. It is assumed that in absence of polarization, both piezoelectric and electrostrictive constants are zero. To incorporate the effect of temperature on the overall polarization behavior all material parameters in the constitutive model are allowed to change with the ambient temperature. We present numerical studies on the effect of time, temperature, and electric field on the response of ferroelectric material followed by verification of the constitutive model. Experimental data on lead zirconate titanate (PZT) materials available in the literature are used to verify the model.

1. Introduction

Ferroelectric materials[1] like lead zirconate titanate (PZT) have been used in energy conversion devices, structural health-monitoring systems, actuators, and sensors. Under these applications ferroelectric materials are often exposed to various external stimuli, such as mechanical, electrical, and thermal effects. Depending on the magnitude of- and duration of exposure to external stimuli and the boundary conditions, ferroelectric materials can exhibit nonlinear coupling between mechanical and nonmechanical effects in addition to the time-dependent effect.

In this study we focus on the application of ferroelectric ceramics as actuators where high electric fields at various rates are applied to induce desired deformations. Crawley and Anderson (1990) performed an experiment on a polarized PZT specimen. The specimen was under a stress-free condition and subjected to cyclic electric fields at several amplitudes and frequencies. The maximum amplitude applied was 85% of the coercive electric field in order to avoid polarization switching. The electric field (E_3) – in-plane strain (ε_{11}) responses were nonlinear. They also observed that the effect of creep and loading rate on the piezoelectric constant d_{311} were more significant at larger strains and lower frequencies. Polarized ferroelectric materials can experience depolarization when an electric field is applied in the opposite direction to the current poling direction. When a sufficiently large electric field is applied along the current poling direction, the polarized ferroelectric materials might fail due to arching or fracturing instead of experiencing polarization switching. A polarized ferroelectric material can also experience depolarization due to high compressive stresses applied parallel to its polarization axis and/or at temperature above its Curie temperature. The depolarized ferroelectric materials caused by a compressive stress cannot be repolarized by applying mechanical stresses.

There have been several experimental and theoretical studies on understanding polarization switching behavior in PZTs. Schmidt (1981), Armdt et al. (1984), Chan and Hagood (1994) and Fang and Li (1999) investigated electro-mechanical hysteresis responses of PLZT and PZT subject to cyclic electric fields, with amplitudes above the coercive electric field, applied in a quasi-static mode. Nonlinear behaviors were shown due to polarization switching. The effect of compressive stresses that are applied parallel to the poling axis on the electro-mechanical hysteresis behaviors of PZTs have been studied by Armdt et al. (1984), Hwang et al. (1995), Lynch (1996), Chen and Lynch (1998), Fang and Li (1999), Kamlah and Tsakmakis (1999), and Kamlah and Bohle (2001). It was shown that the compressive stresses accelerate depolarization in the ferroelectric ceramics. Experimental studies on PZT-based ceramics

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[1] There are different kinds of ferroelectric materials. In this manuscript, we limit our discussion to lead zirconate titanate (PZT).

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