Mechanics of Materials 102 (2016) 74–89

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

Research paper

Time-dependent and energy dissipation effects on the electro-mechanical response of PZTs

Kamran A. Khan[a], Anastasia H. Muliana[b,*], Hassene Ben Atitallah[c], Zoubeida Ounaies[c]

[a] Department of Aerospace Engineering, Khalifa University of Science, Technology and Research (KUSTAR), Abu Dhabi, UAE
[b] Department of Mechanical Engineering, Texas A&M University, TX, USA
[c] Department of Mechanical and Nuclear Engineering, the Pennsylvania State University, PA, USA

ARTICLE INFO

Article history:
Received 24 March 2016
Revised 29 July 2016
Available online 4 August 2016

Keywords:
Piezoelectric
Electro-mechanical
Time-dependent
Dissipation
Heat generation
PZT
AFC

ABSTRACT

In this study, we formulate a constitutive model for coupled thermo-electro-mechanical behavior of piezoelectric ceramics, i.e. lead zirconate titanate (PZT) that takes into account time-dependent behavior and heat generation due to energy dissipation from the electro-mechanical response. Experimental studies show that PZTs dissipate energy when subjected to cyclic electric fields. The dissipated energy is, in some part, converted into heat and raises the temperature of the PZTs. The hysteretic dielectric and strain responses are also dependent on the amplitude and frequency of the applied electric field. The aim of this study is to investigate the energy dissipation and time-dependent effects on the electro-mechanical responses of polarized PZTs. The thermodynamics of irreversible processes for modeling dissipative material responses is adopted to incorporate the time-dependent electromechanical coupling effect. A Gibbs free energy is defined in order to account for the different time-dependent and dissipation behaviors in piezoelectric materials under combined electro-mechanical stimuli. Experimental data on polarized PZTs and PZT based composites at applied electric field magnitudes lower than the coercive electric field, are used to examine the model. The constitutive equations along with the energy equations are solved numerically and used to predict the creep, hysteretic and heat generation responses of PZTs and composites at different frequencies and cyclic electric fields.

1. Introduction

Ferroelectric ceramics like PZTs have been widely used in actuators, sensors, energy harvesting devices, vibration suppression, structural health monitoring systems (Lines and Glass, 1977). During their service, ferroelectric materials are often exposed to various external stimuli such as electrical, mechanical and thermal stimuli and can exhibit a strong coupling between mechanical and other effects, which depend on the magnitude and rate of the external stimuli (Uchino, 2010). Ferroelectric ceramics also show rate-dependent (or frequency-dependent) hysteretic electro-mechanical response and dissipate energy under cyclic electric field (Ben Atitallah et al., 2016; Pritchard et al., 2004). The energy dissipation causes temperature increase and can alter the electromechanical properties of ferroelectric materials, and thus affecting their performance. In order to better predict life performance of ferroelectric materials, it is necessary to understand their time-dependent hysteretic responses and dissipation mechanisms under different external stimuli. In this study, we focus on understanding the linear hysteresis response of polarized ferroelectric materials under electrical loading (below coercive field to avoid polarization switching) at off-resonant frequencies and investigate the amount of heat generation.

Several experimental and theoretical studies have been conducted to understand hysteretic and time dependent response of PZTs. Most of these studies have been done on polarization switching behavior (e.g. Schmidt, (1981), Li and Weng, (1999), Muliana, (2011). Hysteretic responses are also seen in polarized ferroelectric materials under relatively low electric amplitude (minor loops[1]) in which polarization switching does not occur (Ben Atitallah et al., 2010). When subjected to cyclic electric fields, the piezoelectric ceramics show hysteretic responses, which strongly depend on the amplitude and frequency of electric field, existence of stresses, and ambient temperatures (Fett and Thun, 1998), (Liu, 2011). Zhou and Kamlah (2006) investigated the time dependent effects of a

* Corresponding author.
E-mail addresses: kamran.khan@kustar.ac.ae (K.A. Khan), amuliana@tamu.edu (A.H. Muliana).

[1] In minor loops, the hysteretic strain shows an ellipsoidal shape or distorted ellipsoidal shape, while when polarization switching occurs butterfly hysteretic strain is seen.

http://dx.doi.org/10.1016/j.mechmat.2016.08.001
0167-6636/

commercial soft piezoelectric ceramics under constant electric field, cyclic electric field and stresses at room temperature. The time dependent hysteretic effects were found to be significant at higher stresses and at electric field near the coercive electric field.

Heat generation is one of the major issues in piezoelectrics when subjected to cyclic electric fields. Several systematic studies were conducted to analyze the loss mechanisms in piezoelectric materials for high power density applications (Uchino and Hirose, 2001). Heat generation in various PZT based actuators were studied under a small electric field applied at resonant frequency (Zheng et al., 1996) and under a large electric field applied at off-resonance frequency (Tashiro et al., 1997). The heat generation at resonance frequency was attributed mainly to the mechanical loss while polarization – electric field hysteresis loss were the main reason for heat generation at off-resonance electrical loadings (Uchino, 2010). Further discussion on dielectric behaviors of piezoelectric material can be found in Ye, (2008). Recently, Ben Atitallah et al. (2016) studied the hysteretic response of PZT fiber and active fiber composites (AFC) at several frequencies and different electric field magnitudes. At relatively low electric field magnitude the responses were linear. For the electric field loading around 10 min, they observed substantial temperature rise in the sample. However, the systematic temperature changes in the material were not recorded during the tests. The present study investigates the temperature changes due to cyclic electric field. We hypothesize that this temperature increase is due to the dissipation of energy and can cause changes in the response of the ferroelectrics ceramics. Our aim is to develop a constitutive model for time-dependent electro-mechanical responses of piezoelectric ceramics, such as PZTs, incorporating the heat generation due to dissipation of energy.

Piezoelectric ceramics, such as PZT, are brittle, can only undergo relatively small strains, and experience time-dependent behaviors when subjected to electro-mechanical stimuli. Understanding coupled electro-thermo-mechanical response in PZT that takes into accounts the dissipation of energy is currently limited. Chen (2009) derived a thermo-electro-viscoelastic constitutive equation based on time-integral model that incorporates heat generation due to the dissipation of energy and damage. The theoretical formulation was presented for general large deformation responses without showing any application of the model. In this paper, we adopt the thermodynamics of irreversible processes (TIP) and modify the approach used for viscoelastic responses (Schapery, 1997; Khan and Muliana, 2012), in order to model the thermo-electro-mechanical responses of piezoelectric materials. A Gibbs free energy is defined to obtain the constitutive relations and energy equation capable of incorporating temperature evolution in the materials with time-dependent electro-thermo-mechanical responses. The model is currently restricted to linear time-dependent responses.

This paper is organized as follows. Section 2 describes the formulation of a coupled electro-thermo-mechanical model. Generalized constitutive relations and energy equation in terms of dissipation potentials are obtained from the energy balance and the entropy production inequality. A Gibbs free energy function is proposed to account for different dissipation effect under combined electro-mechanical stimuli. Specific forms of the constitutive equations, the evolution equation for each dissipation mechanism, and energy equations are presented. Section 3 presents experimental tests on PZT5A fibers and active fiber composite (AFC) under cyclic electric field. Section 4 describes the characterization of the material parameters required in this formulation. Verification and prediction of constitutive model responses are also presented. Finally, Section 5 is dedicated to concluding remarks.

2. Formulation of coupled time-dependent thermo-electro-mechanical responses

This section presents formulations of the constitutive and energy equations derived from TIP.

For the coupled thermo-electro-mechanical responses, various dissipation effects from electro-mechanical stimuli occur, which results in a temperature increase and subsequent alteration of material properties. Following TIP, in a system that has energy dissipation from different external stimuli, the free energy can be expressed as a function of the observable variables (stress σ_i, strain ε_i, electric field E_i, electric displacement D_i) and other possible internal state variables (ISVs), which account for time-dependent behaviors. A linearized strain measure is considered. It is noted that Voigt notation is used for the second order tensors, i.e., the six components of strain are $\{\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4, \varepsilon_5, \varepsilon_6\}$ and similar notation is used for the corresponding stress $\{\sigma_1, \sigma_2, \sigma_3, \sigma_4, \sigma_5, \sigma_6\}$.

2.1. Free energy

Following Schapery (1997) approach, we consider the following form of Gibbs free energy in terms of stresses, electric field, ISVs (ξ_m, $\xi_m{}'$, χ_m, $\chi_m{}'$)and temperature T, i.e.

$$\begin{aligned} G(\sigma_i, E_i, \xi_m, \xi'_m, \chi_m, \chi'_m, T) = G_0 - A_m\xi_m + \frac{1}{2}B_{mn}\xi_m\xi_n \\ - P_m\chi_m + \frac{1}{2}Q_{mn}\chi_m\chi_n - C_m\xi'_m \\ + \frac{1}{2}D_{mn}\xi'_m\xi'_n - R_m\chi'_m \\ + \frac{1}{2}S_{mn}\chi'_m\chi'_n + H.O.T \end{aligned} \tag{1}$$

where G_0 is the thermo-electro-elastic Gibbs free energy, A_m, P_m, C_m, R_m, B_{mn} Q_{mn} D_{mn} and S_{mn} may also be a function of σ_i, E_i and T. The appropriate functionality in these expressions will be explained when we derive the evolution equation for each internal state variable. In obtaining expressions for the strain and electric displacement we assume that B_{mn}, Q_{mn}, D_{mn} and S_{mn} are not a function of σ_i and E_i, but can be a function of temperature, and thus the second order terms of the ISVs are dropped from the strain and electric displacement, resulting in linear relations. Using the time derivative of the Gibbs free energy and imposing the first and second laws of thermodynamics, the following constitutive relations for the strain, electric displacement and entropy per unit volume are determined from $\varepsilon_i = -\frac{\partial G}{\partial \sigma_i}$, $D_i = -\frac{\partial G}{\partial E_i}$ and $\eta = -\frac{\partial G}{\partial T}$, respectively, and the condition for the entropy production rate is:

$$T\dot{\gamma} \equiv -\frac{\partial G}{\partial \xi_m}\dot{\xi}_m - \frac{\partial G}{\partial \xi'_m}\dot{\xi}'_m - \frac{\partial G}{\partial \chi_m}\dot{\chi}_m - \frac{\partial G}{\partial \chi'_m}\dot{\chi}'_m - \frac{q_i T_{,i}}{T} \geq 0 \tag{2}$$

Following Truesdell and Noll (2013) we can split the entropy production into the internal entropy production (γ_{int}) and the entropy production from conduction (γ_{cond}): $T\dot{\gamma} \equiv T\dot{\gamma}_{\text{int}} + T\dot{\gamma}_{cond}$. In our study, the internal entropy production is associated with the volumetric heat generation rate $\dot{w}^t_{dis} \equiv T\dot{\gamma}_{\text{int}}$ due to multiple dissipation behaviors.

The linearized time-dependent strain and electric displacement are then obtained from the following equations:

$$\varepsilon_i = -\frac{\partial G}{\partial \sigma_i} = -\frac{\partial G_0}{\partial \sigma_i} + \frac{\partial A_m}{\partial \sigma_i}\xi_m + \frac{\partial C_m}{\partial \sigma_i}\xi'_m \tag{3}$$

$$D_i = -\frac{\partial G}{\partial E_i} = -\frac{\partial G_0}{\partial E_i} + \frac{\partial P_m}{\partial E_i}\chi_m + \frac{\partial R_m}{\partial E_i}\chi'_m \tag{4}$$

so that,

$$\varepsilon_i = -\frac{\partial G_0}{\partial \sigma_i} + d\varepsilon_i \quad \text{where} \quad d\varepsilon_i = \frac{\partial A_m}{\partial \sigma_i}\xi_m + \frac{\partial C_m}{\partial \sigma_i}\xi'_m \tag{5}$$