Computational Materials Science 48 (2010) 759–767

Contents lists available at ScienceDirect

Computational Materials Science

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

An analytical model for predicting thermo-electro-mechanical response of 1–3 piezoelectric composites

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ARTICLE INFO

Article history:
Received 29 December 2009
Received in revised form 2 March 2010
Accepted 18 March 2010
Available online 13 April 2010

Keywords:
Piezoelectricity
Pyroelectricity
Effective properties
Composites

ABSTRACT

An analytical method based on parallel and series models is developed to evaluate the performance of 1–3 piezoelectric composite where both matrix and fiber phases are piezoelectrically active. A parametric study is conducted to investigate the influence of the volume fraction of ceramic on the smart composite and the performance of the 1–3 composite for underwater acoustics and biomedical imaging has been addressed. The present model is capable of predicting the effective properties of the composite subjected to thermo-electro-mechanical loading conditions. Simulated results are compared with experimentally measured data reported in literature (Taunaumang et al., 1994 [1]) and are found to be in reasonable agreement. The outcome of the present study demonstrates the influence of thermal effect on effective properties of the composite induces the polarization in the composite. Along the loading direction, there is a significant reduction in the effective pyroelectric coefficient of the piezocomposites, except near the monolithic ceramic fiber material.

1. Introduction

Systems that are "smart" and "intelligent" are thought to be the next generation systems that will enhance performance characteristics of different existing systems or serve newer purposes that human kind seeks. Piezoelectric materials have a property of converting mechanical energy into electrical energy (i.e., the direct effect) and vice-versa (i.e., converse effect). The unique electromechanical coupling behavior of this material serves as a key aspect to smart system applications such as sensors, actuators and transducers [2]. Despite the significant progress made in enhancing the coupling characteristics between the electrical and mechanical properties of monolithic piezoelectric materials, it generally exhibits limitations such as brittleness, difficulty to attach with curved structures and/or limited range of coupled properties [3]. As a consequence, piezocomposite approach has been developed where the brittle piezoelectric materials in the form of fibers are combined together with soft polymer matrix. The composites are manufactured as fibers in one dimension and the matrix in three dimensions with the mechanical continuity. This results in 1–3 piezoelectric composite structure that possess light weight, lower acoustic impedance, mechanical flexibility, high coupling factor, high stiffness and strength with desired material properties, and possibility of making undiced arrays by simply patterning the electrodes [4,5]. Hence, composite materials render better technological solutions in many scientific applications including medical diagnostic ultrasonic transducers, hydrophones for detecting low frequency underwater acoustic waves, micropositioning and accelerometer devices [6,7].

In order to better understand and explain the electromechanical properties of piezoelectric composites under different volume fractions, some experiments have been performed and reported in the literature; the reader is referred to the contributions by Furukawa et al. [8], Taunaumang et al. [1], Steinhausen et al. [9], Chan et al. [10] and references cited in these works. Research on the modeling of predicting the effective electromechanical response of composites can be classified into analytical and numerical approaches. Newnham et al. [11] developed a simple analytical model based on series and parallel connectivity for piezoelectric composites and pyroelectrics that interprets the structure–property relations. Based on a modified cubes model, Banno [12] developed an analytical formulation to characterize the coupled behavior of piezoelectric ceramics with closed pores (0–3 type) and open pores (1–3 type). Dunn and Taya [13] developed analytical models based on the dilute, self-consistent, Mori-Tanaka model (MT) and differential micromechanics theories to predict the effective electromechanical properties of piezoelectric composites. Kuo and Huang [14] developed a three-dimensional anisotropic inclusion method for determining the effective electroelastic properties of piezoelectric composites containing spatially oriented inclusions such as phase properties, orientation angles, volume fraction and shape. Another attempt

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doi:10.1016/j.commatsci.2010.03.027

has been made by Nan et al. [15] to study the effective properties of 1–3 type piezoelectric composites with various orientations of lead zirconate titanate rods/fibers aligned in an epoxy matrix using the Green's function technique. Odegard [16] proposed a model which is an extension of Mori-Tanaka and Self-consistent approaches for predicting mechanical properties of composites. Kar-Gupta and Venkatesh [17] presented an analytical model using the equivalent layer composite model where both the matrix and fiber phases are anisotropic in nature and piezoelectrically active. Recently, a micromechanics approach based on MT method was developed to provide a fundamental understanding of the influence of porosity in the polymer matrix on the performance of 1–3 piezoelectric composites [18].

Several numerical models based on finite elements have been reported in the literature to understand the constitutive behavior of piezoelectric composites; see, for instance [19–23]. Bennett and Hayward [19] used a finite element based model to study the effective behavior of 1–3 piezocomposite hydrophones for the thickness mode operation and also for the lateral pressures which is a typical loading for the hydrostatic environment. A finite element (FE) model with a unit-cell approach was suggested for 0–3 and 1–3 composites made of piezoceramic fibers embedded in a soft non-piezoelectric matrix [20]. This model was able to quantify the influence of microstructural parameters on the effective constants. A comprehensive finite element unit cell model was developed for studying composites with periodic hexagonal or square arrangements of continuous aligned fibers. In this work, a specific emphasis was placed on the formulation of the boundary conditions which gives rise to consistent behavior under arbitrary combination of mechanical and electrical loading conditions [21]. Kar-Gupta and Venkatesh [22] studied the fundamental insight on the effect of variations in the poling characteristics of the matrix and the fiber phase on the overall electromechanical behavior of 1–3 piezocomposite using a FE numerical tool. Recently, Berger et al. [23] developed a numerical homogenization technique using a unit cell model in connection with the FE method to predict the effective material properties of randomly distributed short fiber composites.

Piezoelectric composite with two piezoelectric phases (both ceramic and polymer phases are piezoelectrically active) can be used to fabricate novel ultrasonic transducers. In such transducers, the active ceramic phase is used for the transmission of signals and the piezopolymer matrix is used to receive the signals [1]. In addition, if both the phases are active then the piezoelectric coefficients are of opposite signs. It may be possible to pole the fiber and matrix phases in opposite directions, that will enhance the piezoelectric coupling effect which could be used for designing robust transducers. In the literature, few modeling aspects have been presented where both the matrix and the fiber phases could be piezoelectrically active; refer [13,15,17]. Furthermore, the research towards studies on effective thermo-electro-mechanical properties on 1–3 piezocomposite are very limited. In realistic applications, there will be a considerable impact on thermal effects and it is of cardial importance to study the effective properties of piezocomposite under such circumstances. Hence, the overall objectives of the present study is threefold:

(1) to develop an analytical model based on the approach proposed by Kar-Gupta and Venkatesh [17] to capture the effective thermo-electro-mechanical properties of 1–3 piezoelectric composites where both the fiber and matrix are piezoelectrically active,
(2) to compare the elastic, dielectric and piezoelectric material constants of 1–3 piezoelectric composites predicted by the developed model with the experimentally measured results [1] and other proposed models in the literature,
(3) to study the influence of volume fraction on the variation of effective pyroelectric properties.

The outline of the paper is as follows: the model formulation is discussed in Section 2 based on the constitutive behavior of piezoelectric composite, assumptions and validity of the model, effective parameter expressions of the 1–3 composite and performance characterstic formulation of 1–3 piezocomposite. Aspects of the related implementation, analytical treatment and results are included in Section 3. Finally, the paper is concluded with short summary in Section 4.

2. Model formulation

2.1. Constitutive behavior of piezoelectric composite

The constitutive equations for linear piezoelectric materials are

$$\begin{aligned} \sigma_{ij} &= C^E_{ijkl}\varepsilon_{kl} - e_{ijk}E_k - \beta_{ij}\theta \\ D_i &= e_{ikl}\varepsilon_{kl} + \kappa^{\varepsilon}_{ij}E_j + P_i\theta \end{aligned} \tag{1}$$

where σ_{ij}, ε_{ij}, E_i and D_i are the stress tensor, stain tensor, electric field vector and electric displacement vector, respectively. C_{ijkl}, e_{ijk}, κ_{ij}, β_{ij} and P_i are the elastic stiffness tensor, piezoelectric tensor, permittivity tensor, thermal coefficient tensor and pyroelectric vector, respectively. θ is the change in temperature. The superscripts E and ε indicate that the elasticity and permittivity constants are determined under conditions of zero or constant electric field and strain, respectively.

For convenience, we restate Eq. (1) as

$$\begin{aligned} \sigma_m &= C^E_{mn}\varepsilon_n - e_{mp}E_p - \beta_m\theta \\ D_q &= e_{qn}\varepsilon_n + \kappa^{\varepsilon}_{qp}E_p + P_q\theta \end{aligned} \tag{2}$$

where the subscript m and n are derived from ij and kl as follows: for ij or kl = 11, 22, 33, 23, 13, 12 (e.g., $C_{1122} = C_{11}$) and for p or q = 1, 2, 3. Stress tensor (m) and strain tensor (n) can be represented in the compact notation, given by 1, 2, 3, 4, 5, 6 (e.g., $\varepsilon_{11} = \varepsilon_1,\ 2\varepsilon_{12} = \varepsilon_6$). The 1–3 piezoelectric composite material can be treated as a piezoelectric ceramic that consists of an array of parallel piezoceramic fibers embedded in a polymer matrix, as shown in Fig. 1. Since the 1–3 composites are similar to piezoelectric ceramics (transversely isotropic properties), the constitutive equations can be written as

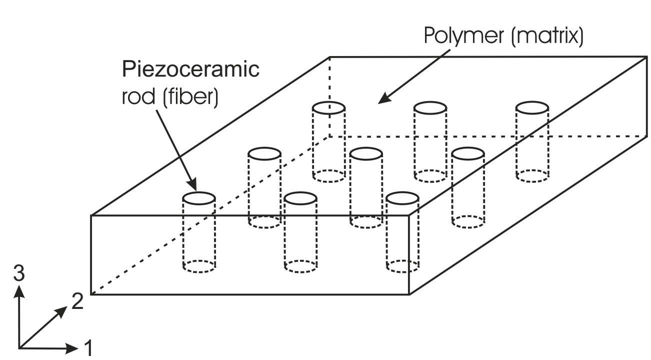

Fig. 1. Schematic of a 1–3 piezoelectric composite.