Sensors and Actuators A 209 (2014) 87–99

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Study on effective properties of 1-3-2 type magneto-electro-elastic composites

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ARTICLE INFO

Article history:
Received 22 July 2013
Received in revised form 6 January 2014
Accepted 7 January 2014
Available online 23 January 2014

Keywords:
1-3-2 type composites
Effective properties
Equivalent layered approach
Piezomagnetic constant

ABSTRACT

An analytical method based on parallel and series model (equivalent layered approach) is developed to study the performance of 1-3-2 magneto-electro-elastic (MEE) composite where fibers are active to electrical and magnetic fields. Although the matrix is passive to electrical and magnetic fields, the mechanical strain field in the matrix (elastic phase) couples the electric field of the piezoelectric phase to the magnetic field of the piezomagnetic phase. The combination of three-phase (electro-magneto-elastic) composite has ductility and enhanced properties. A parametric study is conducted to investigate the influence of the ceramic base and the piezomagnetic fiber volume fraction on the modified 1-3 composite. Although the fiber and matrix phases do not exhibit any magneto-electric coupling phenomena, the resulting MEE composite has an effective non-zero magneto-electric response. The proposed model is capable of predicting the effective properties of the composite subjected to magneto-electro-mechanical loading conditions. Simulated results based on the proposed model is compared well with the other models (Mori–Tanaka and finite element methods) from the literature [1]. It is observed that there is a significant influence on effective properties of the composite due to ceramic base volume fraction (V_2) of 1-3-2 type multiferroic composite. A simple phenomenological model is developed to predict the non-linear response of ferroelectric and magnetostrictive materials under high electro-magnetic loading conditions.

1. Introduction

Composite material consisting of a piezoelectric, piezomagnetic and shape memory phases has drawn significant interest in recent years due to the rapid development in adaptive material systems [2,3]. Smart composites have many advantages than individual/bulk smart materials such as, the possibility of weight or volume reduction, enhanced ductility, improved performance level and high coupling constant. Many theoretical and experimental studies were reported in the development of piezoelectric composites in the past three decades due to their high sensitivity, low acoustic impedance, a large range of mechanical properties, high strength and low density [4,5]. Multiferroics consist of ferroelectric, ferroelastic and ferromagnetic phases drawn more attentions due to their potential applications in multifunctional devices, ultrasonic imaging, acoustic devices, transducers and sensors [6–8]. The coupled interaction between magnetic and electrical domains could produce a new effect which is called megnetoelectric (ME) or magnetodielectric effect [9–12]. ME effects are characterized by the outcome of an electric polarization upon applying a magnetic field and/or the magnetization output upon applying an electric field to the magneto-electro-elastic (MEE) composite. This ME effect can be defined, when a magnetic field is applied to the composite, the ferromagnetic phase changes the shape magnetostrictively and the mechanical strain is passed along the polarization phase, resulting in dielectric polarization [13]. Soh and Liu [14] discussed about the different possible forms of the constitutive equations for the magneto-electro-elastic coupling and the thermodynamic potential corresponding to each form.

In the literature, several experimental investigations were reported related to magneto-electric (ME) effects on multiferroics. Ryu et al. [15] reported, the dependence on magnetostriction direction of Terfenol-D disk and the impact of applied magnetic field direction on PZT/Terfenol-D laminate composites. Mori and Wuttig [16] predicted the magnetic field induced magnetoelectric (ME) effect in the ferromagnetic/ferroelectric composite using Terfenol-D/polyvinylidene fluoride (PVDF). The enhanced magnetoelectric (ME) effect was reported by Srinivasan et al. [17] in zinc-substituted layered composites of ferrites and PZT. Experimental observation showed that the coupling effect is increased by 60% and the primary reason was due to low anisotropy and high permeability for the ferrites that results in favorable magneto-mechanical coupling. Shi

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0924-4247/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sna.2014.01.009

et al. [18] prepared a multifunctional composite with PZT, Terfenol-D and epoxy matrix. The study showed that ME effect strongly depends on the magnetostrictive behavior of the matrix and the volume fraction of PZT rods. In multiferroics, bonding process significantly influence the performance behaviour due to different shrinkage, thermal expansion mismatch, and/or chemical reactions [19]. Another attempt was made to understand the dependence of optimal orientation field on particle volume fraction with polyester resin under various orientation fields [20].

In order to better understand the magneto-electric effects, several studies were presented based on analytical and numerical models for magneto-electro-elastic (MEE) composites. An analytical expression for the effective properties of the composite were presented based on the Eshelby tensors which was used to identify the optimized fiber volume fraction for maximum magneto-electric coupling effect [21,22]. A micromechanics model was established to predict the effective properties of MEE composites with the mechanical and electro-magnetic continuity conditions across an interface of two dissimilar media [23]. Another attempt was made to calculate the effective behavior of magnetostrictive composite materials using micromechanics method wherein the effective magnetostriction of the particulate composites with cubic magnetostrictive crystallites were derived [24]. The impact of boundary conditions to the coupled ME effects and the variations of ME coefficients under mechanically clamped or free boundary conditions were reported by Shi et al. [25]. The orientation distribution and the alignment of second phase particles needed to be taken into account with appropriate texture coefficient in the effective properties prediction of MEE composites [26]. A three-phase cylindrical model was presented based on eigenstrain concept to reduce the complex multi-field coupling problem into 2D in-plane elasticity problem [27]. Recently, a micromechanical model was proposed to analyze the multiphysical fields on heterogeneous smart composites. The constitutive law was developed by considering complete coupled fields, different geometries and debonding process of the reinforcements [28].

Three-dimensional analytical model based on Mori–Tanaka theory was proposed for giant magnetostrictive composites [29]. Influence of interface and thermal residual stress (TRS) in the curing process were investigated. Simulated results showed that TRS has significant influence on the effective normal strains but little effect on the effective shear strains. A theoretical framework was developed to investigate the magnetoelectroelastic potential in a multi-coated elliptic fibrous composite which shows that the appropriate coating will enhance the ME coefficient with one order of magnitude compared to their non-coating counterpart [30]. An analytical model based on matrix formulation was proposed for analyzing the effective properties of functionally graded magneto-electro-thermo-elastic (METE) multilayer composites [31]. It was reported that the functional gradation affects significantly the magnitudes of these effective properties and the volume fractions at which these coefficients were maximized. In the numerical approach, a finite element based model was proposed to study the irregular fiber shape, allowing the existence of imperfections (local debonding and microcracks) and the fiber arrangements (regular and irregular distributions) [32]. A finite-strain homogenization framework and partial decoupling approximation was introduced to estimate the magneto-elastic properties of spheroidal-particles [33]. Kuo and Wang [34] showed the optimization of magneto-electricity with respect to the crystallographic orientations and the volume fraction for the piezoelectric–piezomagnetic composite. To study the influence of the different fiber distributions and the anisotropy induced by fiber arrays in MEE composite, the anti-plane magnetoelectroelastic coupling problem was formulated and the eigenfunction expansion-variational method (EEVM) was extended to solve such a problem [35].

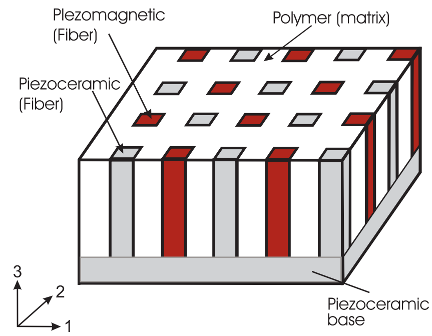

Fig. 1. Schematic of a 1-3-2 type multiferroic composite.

Monolithic piezoelectric materials show a linear response at low external fields. However, these materials exhibit pronounced nonlinear response under sufficiently higher electrical, mechanical and electromechanical loading conditions. In the literature, it was referred as the microstructural reorientation of domains, the so called domain switching, is the main factor for the non-linear response [36,37]. Similar to piezoelectric materials, the magnetostrictive materials are also show the non-linear response under complex loading condition [38,39]. Upon the application of high magnetic field, the rotation of domains in the magnetostrictive material renders a hysteretic effect in the performance behaviour [40]. Since MEE composite consists of both piezoelectric and magnetostrictive materials, it would interesting to study the non-linear effects under higher loading conditions. Hence, an attempt has been made to develop a simple phenomenological model for describing the macroscopic response of ferroelectric and magnetostrictive materials.

1-3 type multiferroic composites are generally manufactured by using dice-and-fill process [41]. The fabrication was done by poling the bulk PZT, then obtain the PZT array by making parallel & perpendicular cut and the removed portion in the bulk PZT will be filled with piezomagnetic and epoxy material. In this process, some amount of bulk PZT (referred to as ceramic base) will be left out as a layer in the bottom of multiferroic composite; see Fig. 1. This type of composites are referred as 1-3-2 or modified composites [42,43]. 1-3 type composites distort easily when heated or subjected to mechanical load. To overcome this limitation and to improve the stability of MEE composite, the modified 1-3 composites (1-3-2 type composites) are useful. Although, 1-3-2 type composite has similar characteristics as 1-3 type composite, it is necessary to study the effect of ceramic base volume fraction in overall MEE composite behavior. The authors are not aware of any published work in determination of effective magneto-electro-elastic properties of such 1-3-2 type composites. Hence, the overall objectives of the present study are:

1 to develop a micromechanics based analytical model for predicting the effective magneto-electro-elastic response of 1-3-2 MEE composites where both the fibers (piezoelectric and piezomagnetic) are active and transversely isotropic in nature,
2 to capture the fundamental elastic, dielectric, piezoelectric, piezomagnetic and magnetoelectric material constants of 1-3-2 type MEE composites by the developed model and compare the simulated results with the other proposed models for 1-3 type composites (no ceramic base ($V_2 = 0$) from the literature [1],
3 to study the influence of ceramic base volume fraction (V_2) on the variation of effective magneto-electric (ME) properties,
4 to perform a parametric study on effective behavior of MEE composite under the variations of matrix phase volume fraction and identity the impact of polymers in the MEE composites.