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Effective properties of three-phase electro-magneto-elastic composites

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Abstract

Coupling between the electric field, magnetic field, and strain of composite materials is achieved when electro-elastic (piezoelectric) and magneto-elastic (piezomagnetic) particles are joined by an elastic matrix. Although the matrix is neither piezoelectric nor piezomagnetic, the strain field in the matrix couples the electric field of the piezoelectric phase to the magnetic field of the piezomagnetic phase. This three-phase electro-magneto-elastic composite should have greater ductility and formability than a two-phase composite in which the electric field and the magnetic field are coupled by directly bonding two brittle materials. A finite element analysis (FEA) and micromechanics based averaging of a representative volume element (RVE) are performed in this work to determine the effective dielectric, magnetic, mechanical, and coupled-field properties of an elastic matrix reinforced with piezoelectric and piezomagnetic fibers as functions of the phase volume fractions, the fiber arrangements in the RVE, and the fiber material properties with special emphasis on the poling directions of the piezoelectric and piezomagnetic fibers. The effective magneto-electric moduli of this three-phase composite are found to be less than the effective magneto-electric moduli of a two-phase piezoelectric/piezomagnetic composite, because the elastic matrix is not stiff enough to transfer significant strains between the piezomagnetic and piezoelectric fibers.

Keywords: Piezoelectric; Piezomagnetic; Magnetoelectric; Multifunctional material; Effective properties

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1. Introduction

Efforts are under way to develop composite materials with improved product properties [1], which are created by the interaction between the constituent phases. Those product properties, which are absent in constituent phases, are obtained by combining different active materials. An active material is a continuum whose mechanical constitutive response is coupled with a non-mechanical effect. Thermoelasticity, piezoelectricity, piezomagneticity, electrostriction, magnetostriction and hygroelasticity are a few examples of active phenomena [2]. A two-phase composite consisting of a thermoelastic phase and a piezoelectric phase can exhibit pyroelectricity even though neither of the phases is pyroelectric [3]. The composite consisting of a piezoelectric phase and a piezomagnetic phase exhibits a magneto-electric coupling effect that is absent in each of the phase. The magneto-electric coupling effect has recently attracted attention due to the extensive applications for broadband magnetic field probes, electronic packaging, acoustic devices, hydrophones, medical ultrasonic imaging, sensors, and actuators [4–8].

In 1974 Van Run et al. [9] reported that the magneto-electric effect obtained in a $BaTiO_3$ (piezoelectric phase)—$CoFe_2O_4$ (piezomagnetic phase) composite was two orders of magnitude larger than that of the single-phase magneto-electric material Co_2O_3. Bracke and Van Vliet [10] reported a broad band magneto-electric transducer with a flat frequency response using composite materials. Since then, much of the theoretical and experimental work for investigation into the magneto-electric coupling effect has been carried out in papers published by Harshe [11], Harshe et al. [12], Avellaneda and Harshe [13], Nan [1], Benveniste [14], Huang and Kuo [15], Li and Dunn [4], Wu and Huang [16], Huang et al. [17] and Aboudi [5]. They obtained expressions for the effective magneto-electric coefficient and showed numerical results with practical examples using $BaTiO_3$–$CoFe_2O_4$ two-phase composite.

Harshe et al. [12] treated the magneto-electric effect of piezoelectric–piezomagnetic two-phase composites in terms of a simple geometrical model by assuming the particles embedded in the matrix were small cubes. Then, they solved the fields in one cube for which the boundary value problem is tractable. This simple cubes model is lacking in theoretical rigor.

Nan [1] proposed a non-self-consistent (NSC) approach to calculate the effective properties of piezoelectric–piezomagnetic two-phase composites, consisting of aligned cylindrical fibers embedded in the matrix, based on a Green's function method and perturbation theory, which have been widely used to treat the general, linear-response properties of inhomogeneous media. However, Benveniste [14] derived exact connections between the effective moduli of piezoelectric–piezomagnetic two-phase composites, which were independent of the details of the microgeometry and of the particular choice of the averaging model, using the uniform field concept. The NSC approximation of Nan failed to satisfy the exact connections between different components of the effective moduli obtained by Benveniste.

Li and Dunn [4] developed a micromechanics approach to analyze the effective moduli for two-phase piezoelectric–piezomagnetic composites. They derived explicit expressions for the generalized Eshelby tensors and used the Mori–Tanaka method to obtain closed form expressions for the effective electro-magneto-elastic moduli of circular cylinder fibrous and laminated two-phase composites.

The Mori–Tanaka method was also employed by Wu and Huang [16] in order to obtain a closed form solution for effective moduli of piezoelectric–piezomagnetic two-phase composites