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Magneto-electro-elastic properties of multiferroic composites containing periodic distribution of general multi-coated inhomogeneities

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ABSTRACT

In this paper, a homogenization scheme with several desirable features is developed to determine the overall magneto-electro-elastic behavior of multiferroic composite materials containing periodic distribution of multi-inhomogeneities. The configuration of a typical inhomogeneity system is taken to be composed of an inner ellipsoidal particle surrounded by many coating layers of ellipsoidal shape. As such, the morphology of composite is sufficiently general, and then the developed methodology can be quite robust to handle a wide range of problems. Through the present analysis, we first adopt the equivalent inclusion principle in conjunction with a superposition procedure to decompose the multi-inhomogeneity system into a series of single-inclusion problems with position-dependent eigenstrain–electric–magnetic fields. The periodic microstructure will be accounted for through the Fourier series expansion of field quantities. The local form of consistency equations are then called upon, and integrated to give the expression for the average eigenfields. Finally, considering the relation between far-field loads and the local microscopic fields in the constituent phases the overall effective moduli of composite are obtained in terms of derived average eigenfields. The accuracy and generality of proposed theory is verified through consideration of several three-phase multiferroic composites with complex microstructures. In this process, the strong dependence of overall behavior of fibrous and particulate multiferroics on the microstructure parameters, such as the interface condition, thickness, eccentricity and material properties of core inhomogeneities and their coating layers is well demonstrated.

1. Introduction

In the recent years, multiferroic composites have attracted tremendous attention from the academic and industrial point of view due to the coupling effect among their elastic, electric and magnetic fields. As the most fascinating feature of these functional materials, they exhibit the magneto-electric coupling even though this effect is absent in their individual piezomagnetic and piezoelectric constituent phases. This characteristic results from the “product properties” of multiferroic composites (Van Suchtelen, 1972): an applied electric field generates a deformation in the piezoelectric phase, which in turn generates a deformation in the piezomagnetic phase, giving rise to the magnetization (Nan, Bichurin, Dong, Viehland, & Srinivasan, 2008). Noteworthy to mention that the magneto-electric effect of a multiferroic composite can be achieved

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even at room temperature, whereas similar coupling phenomena in single-phase magneto-electric materials is often observed only at very low temperature (Lawes & Srinivasan, 2011; Spaldin & Fiebig, 2005). Such a strong magneto-electric coupling behavior of multiferroic composites is a key factor for their broad potential applications in new multifunctional materials and devices, such as four-state memories, low-power systems, magnetically controlled opto-electric devices, and smart sensors. Inspired by these applications, numerous studies in the literature are concerned with the determination of overall properties of multiferroic composites, in particular, their magneto-electric coupling moduli. For instance, the mean field models have been employed by Huang (1998), Li (2000), Li and Dunn (1998) and Srinivas, Li, Zhou, and Soh (2006) to estimate the effective properties of multiferroic composites. Benveniste (1995) employed a formalism approach discovered by Milgrom and Shtrikman (1989) to obtain the exact relations for the effective moduli of a multiferroic with cylindrical fibers. Nan (1994) and Huang and Kuo (1997) adopted the Green's function approach to study the overall behavior of a fibrous multiferroic composite. In addition, a two-scale homogenization theory was employed by Aboudi (2001) to study the magneto-electro-elastic coupling and cross-property connections in a two-phase composite. Liu and Kuo (2012) developed the micromechanical approach of periodic E-inclusions to determine the effective properties of fibrous multiferroics. Moreover, the finite element method (FEM) was developed by Liu, Nan, Cai, and Lin (2004) and Lee, Boyd, and Lagoudas (2005) to address the multiferroic composites with general microstructures.

All foregoing investigations are based on the simplifying assumption of the two-phase models with an abrupt inhomogeneity-matrix interface. However, it is greatly known that the bond quality between inhomogeneities and surrounding matrix plays a significant role in overall response of composite materials. The consideration of three-phase models with interphase effect then seems to be inevitable for the appropriate treatment of a real multiferroic composite. It is notable that, often, a transition zone with weakened material properties undesirably forms between reinforcements and the host matrix, as a result of the chemical interactions during the manufacture process of composite material. In other situations, the reinforcing fillers can be intentionally coated by interphase layers to improve the bonding strength. The interphase layers may have constant properties or spatially varying properties (Hashemi, Spring, & Paulino, 2015; Kuo, 2011). Thanks to recent advances in coating technology, a single or multiple active coating layers also can be applied to inhomogeneites in order to achieve a better design flexibility and tailor the effective magneto-electro-elastic properties. In view of the physical contributions that can be made by the interphase layer, a number of theoretical investigations have paid special attention to this topic. For instance, Tong, Lo, Jiang, and Cheung (2008) adopted the generalized self-consistent method, while Camacho-Montes, Sabina, Bravo-Castillero, Guinovart-Díaz, and Rodríguez-Ramos (2009), Espinosa-Almeyda et al., (2011, 2014) and Guinovart-Díaz et al. (2013) employed the asymptotic homogenization method to calculate the effective magneto-electro-elastic properties of composites containing coated fibers. The classic Rayleigh's formulism was generalized by Kuo (2011) and Kuo and Pan (2011) to determine the overall behavior of composites with multicoated fibers under anti-plane shearing and in-plane electro-magnetic fields. Wang and Pan (2007) and Dinzart and Sabar (2011) applied the Mori–Tanaka model in conjunction with two different approaches, i.e. complex variable method and Green's function technique with interfacial operators, to determine the overall behavior of multiferroic composites with thinly coated inhomogeneities under anti-plane mechanical and in-plane electro-magnetic loadings. Yan, Jiang, and Song (2013) developed the eigenfunction expansion-variational method (originally formulated by Yan, Jiang, & Song, 2011) to address the anti-plane coupling problem of a three-phase multiferroic composite containing coated circular fibers with periodic distributions. In addition, Kuo and Peng (2013) and Wang, Su, Li, and Weng (2015) adopted a two-level recursive Mori-Tanaka model to assess the interphase effect on the magneto-electric coupling coefficients of multiferroic composites. All of these studies have demonstrated the significant impact of imperfect interface condition and/or the influence of active coating layer on the overall response of fibrous multiferroics.

This paper is intended to develop a homogenization scheme for determination of the effective magneto-electro-elastic properties of a periodic multiferroic composite with general multi-inhomogeneites. The newly proposed methodology is quite robust, so that it can be applied to a wide range of complex systems where the coating layers do not have to be thin, the shape and orientation of the core particle and coatings do not have to be identical, their centers do not have to coincide, their magneto-electro-elastic properties do not have to remain uniform, and the microstructure can be with the 2D elliptic or the 3D ellipsoidal inhomogeneity. In addition, the inter-phase interactions in each multi-coated particle and the long-range interactions between the periodically distributed particles can be fully accounted for. Present theory with such a desirable feature is achieved based on the theoretical framework of Shodja and Roumi (2005) in conjunction with the superposition procedure of Kargarnovin, Shodja, and Hashemi (2011) extended for the treatment of magneto-electro-elastic multi-coated inhomogeneities. The development starts from the local equivalent inclusion principle through the introduction of the position-dependent equivalent eigenstrain–electric–magnetic fields. Then with a Fourier series expansion and a superposition procedure, the volume-averaged equivalent eigenfields for each domain of multi-inclusion systems are obtained. This approach is very efficient regardless of the number of phases of the reinforcing particles, and yields accurate values of the eigenfields at any desired domain. The results for local fields over the constituent phases in turn are used to determine the effective magneto-electro-elastic properties of composite material. To demonstrate wide range of applicability of this scheme, we applied it to examine the properties of several multiferroic composites with different microstructures. The calculated results reflect the complex nature of interplay between the properties of core, matrix, and coating, as well as whether the coating is uniform, functionally graded, or eccentric. In the process of numerical studies, the accuracy of the developed methodology is also checked against other models (Kuo, 2011; Kuo & Peng, 2013; Yan et al., 2013), and good agreement is observed.