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Influences of imperfect interfaces on effective properties of multiferroic composites with coated inclusion

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ABSTRACT

In order to predict the effective properties of multiferroic composite materials, the effective material constants of multiferroic composites with the coated inclusion and imperfect interface are investigated. Based on the generalized self-consistent theory, the closed-form solutions of the effective material constants are derived. For the composites with piezomagnetic inclusion, piezoelectric coating and polymer matrix, numerical calculations are performed to present the influences of the imperfect interface cooperating with the coating on the effective material constants. From the results, it can be observed that the effective constants can be enhanced by the coating but reduced by the imperfect interface. Moreover, the coating has the shielding effects on the imperfect interface for the composite structures with its higher filling ratio.

1. Introductions

Due to the superior properties of the coupling among the mechanical, electric and magnetic fields, the recently emerging piezoelectric/piezomagnetic and multiferroic composites have been used as a class of new functional materials. Different from the previous traditional materials which do not simultaneously possess the coupling properties, composite materials with piezoelectric and piezomagnetic phases can exhibit a remarkable magnetoelectric coupling effect that cannot show in the single constituent [1–3]. By the conversion between electric and magnetic fields, these composites have various potential applications on intelligent materials, such as sensing, actuation and control, electromagnetics and information processing [4–7].

In recent years, the rapid development and wide application of multiferroic composites have stimulated the interests in some basic mechanics problems, such as micromechanics behaviors of multiferroic structures [8–11]. The major contributions to this subject and relevant problems are devoted to the systems with inclusions and inhomogeneities, as well as these systems with the coating layer by another material. Multiferroic system with the coated inclusion is the extension from the similar structure without the coating and behaves as the composite material with three-phases. With the introduction of the coating, some interesting phenomena can be observed and special applications can be achieved. One of them is to reduce the stress intensity between the inclusion and matrix and another one is to show the reinforcing property. Some recent works have been reported on the micromechanics characteristics of these composite structures with coating [12,13]. It is known that effective material properties of composites with inclusions are helpful for the design and analysis of the mechanical and physical behaviors. Then more attention should be drawn on these structures with the coating layer.

On the other hand, because of the micro defects, damage and weak bonding during the manufacture and application, different materials in composite structures cannot be bonded perfectly. Then the interface or transition with small thickness between the two neighboring materials can be found and the effective properties and mechanics performances of the composite systems will be significant changed. The importance of the imperfect interface on behaviors of piezoelectric or piezoelectric/piezomagnetic composites have be realized and received much attention, such as fracture behaviors [14,15], micromechanics characteristics [16–18] and elastic wave propagation [19–22]. Among the previous investigations, the spring-type model is widely accepted and extensively applied to characterize the imperfect interface. Such model assumes that the normal and tangential generalized stress components have a linear dependence on the corresponding generalized displacement jumps.

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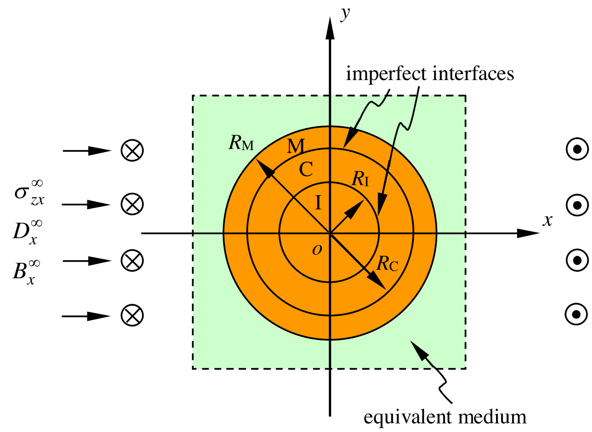

Fig. 1. Multiferroic composites with coated inclusion and imperfect interfaces.

Although a lot of investigations has been reported on the micromechanics analysis of piezoelectric/piezomagnetic and magnetoelectroelastic composite structures, a little attention has been paid on the performances of the multiferroic composite structures with the coating inclusion, especially for the systems with the imperfect interface. In this study, the influences of imperfect interface on effective material properties are investigated.

2. Basic equations

As shown in Fig. 1, the unbounded multiferroic composites with coated circular inclusions are considered. The remote mechanical, electric and magnetic loads are σ_{xz}^{∞}, D_x^{∞} and B_x^{∞}. The composites with the coated inclusions are considered and both circular interfaces (i.e. L_I and L_C) are assumed as imperfect. Based on the generalized self-constant method [23], the equivalent medium is considered around the matrix and the radiuses of the inclusion, coating materials, matrix are denoted by R_I, R_C and R_E, respectively.

From Fig. 1, the filling fractions of the inclusion and coating for the representative volume element (RVE) can be expressed as

$$n_I = R_I^2/R_M^2, \quad \mathrm{n}_C = (R_C^2 - R_I^2)/R_M^2, \tag{1a, b}$$

The material constants have the 6 mm symmetric properties, then the constitutive relation of the anti-plane deformation can be expressed as [24]

$$\sigma_{zx}^{(i)} = c_{44}^{(i)}\frac{\partial w^{(i)}}{\partial x} - e_{15}^{(i)}\frac{\partial \phi^{(i)}}{\partial x} - q_{15}^{(i)}\frac{\partial \phi^{(i)}}{\partial x}, \tag{2a}$$

$$\sigma_{zy}^{(i)} = c_{44}^{(i)}\frac{\partial w^{(i)}}{\partial y} - e_{15}^{(i)}\frac{\partial \phi^{(i)}}{\partial y} - q_{15}^{(i)}\frac{\partial \phi^{(i)}}{\partial y}, \tag{2b}$$

$$D_x^{(i)} = e_{15}^{(i)}\frac{\partial w^{(i)}}{\partial x} - \kappa_{11}^{(i)}\frac{\partial \phi^{(i)}}{\partial x} - \lambda_{11}^{(i)}\frac{\partial \phi^{(i)}}{\partial x}, \tag{2c}$$

$$D_y^{(i)} = e_{15}^{(i)}\frac{\partial w^{(i)}}{\partial y} - \kappa_{11}^{(i)}\frac{\partial \phi^{(i)}}{\partial y} - \lambda_{11}^{(i)}\frac{\partial \phi^{(i)}}{\partial y}, \tag{2d}$$

$$B_x^{(i)} = q_{15}^{(i)}\frac{\partial w^{(i)}}{\partial x} - \lambda_{11}^{(i)}\frac{\partial \phi^{(i)}}{\partial x} - \Gamma_{11}^{(i)}\frac{\partial \phi^{(i)}}{\partial x}, \tag{2e}$$

$$B_y^{(i)} = q_{15}^{(i)}\frac{\partial w^{(i)}}{\partial y} - \lambda_{11}^{(i)}\frac{\partial \phi^{(i)}}{\partial y} - \Gamma_{11}^{(i)}\frac{\partial \phi^{(i)}}{\partial y}, \tag{2f}$$

where i = I, C, M and E correspond to the inclusion, coating, matrix and equivalent medium, σ_{zx} and σ_{zy} are the elastic stresses, D_x and D_y are the electric displacements, B_x and B_y are the magnetic induction, w, ϕ and ϕ are the elastic displacement, electric and magnetic potentials, c_{44}, e_{15} and q_{15} are the elastic constant, piezoelectric and piezomagnetic coefficients, κ_{11}, λ_{11} and Γ_{11} are the dielectric, electromagnetic and magnetic coefficients, respectively.

For the anti-plane deformation of the multiferroic structures, we can have the following relations:

$$\frac{\partial \sigma_{zx}^{(i)}}{\partial x} + \frac{\partial \sigma_{zy}^{(i)}}{\partial y} = 0, \quad \frac{\partial D_x^{(i)}}{\partial x} + \frac{\partial D_y^{(i)}}{\partial y} = 0, \quad \frac{\partial B_x^{(i)}}{\partial x} + \frac{\partial B_y^{(i)}}{\partial y} = 0. \tag{3a–c}$$

Substituting Eqs. (2a)–(2f) into Eqs. (3a)–(3c), we can derive the governing equations as

$$\mathbf{M}^{(i)}\nabla^2(\mathbf{u}^{(i)}) = 0, \tag{4}$$