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Two bonded multiferroic ceramics half-planes with coupled interfacial imperfections: In-plane fracture and its dislocation-based physical mechanisms

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ABSTRACT

Essentially speaking, both crack and interfacial imperfection can be regarded as continuously distributed dislocations. Therefore, the fracture behavior of composites containing imperfect interfaces may be explained by the interactions of different distributed dislocations. The purpose of this paper is to make a try on such explanation. For this purpose, in-plane fracture analysis is performed on two bonded multiferroic half-planes with coupled interfacial imperfections by the methods of Fourier integral transform and Green's functions. Numerical results of the mechanical strain energy release rate are obtained by numerically solving the Cauchy singular integral equations of the crack problem. The effects of the three kinds of interfacial imperfections and their inter-couplings on the fracture behavior are discussed based on the variations of mechanical strain energy release rate versus the interface parameters, and the fracture behavior including shielding, anti-shielding, interference and anti-interference are revealed, respectively. Finally, the cracks and the imperfect interface are simulated as continuously distributed dislocations to construct two types of dislocation distribution models, which are then, for the first time, employed to explain the mechanisms of the fracture behavior.

1. Introduction

Due to their magneto-electric effect, multiferroic composites have wide application prospects in smart devices such as sensors, actuators, gyrators, filters, high-density memories and so on (Eerenstein et al., 2006; Bichurin et al., 2007; Nan et al., 2008). In order to increase the contact area between any two neighboring phases and thereby to improve the magneto-electric effect, multiferroic composites are generally fabricated as laminate structures that consist of alternate ferromagnetic and ferroelectric layers (Ryu et al., 2001; Zheng et al., 2004; Lin et al., 2005). The magneto-electric effect in them is induced by the mechanical interaction across the interfaces (Nan et al., 2008). Therefore, the interfaces are critical to the magneto-electric coupling performances of multiferroic composites.

Recently, there has been an upsurge in the investigation on layered multiferroic composites. In most existing papers, these composites are generally assumed to have perfectly bonded interfaces (Pang et al., 2014; Kuo, 2014; Li et al., 2013; Wang et al., 2009; Huang and Kuo, 1997) or contacting interfaces (Bisegna et al., 2002; Migorski et al., 2014, 2010). However, in the process of solid-state sintering, interfaces are regions rich of micro-defects, which are prone to nucleating and growing under harsh working circumstances. The nucleation and growth of micro-defects will inevitably give rise to mechanical, electrical and magnetic imperfections in the interfacial regions. Some researchers have paid attention to the imperfect interfaces in multiferroic composites in recent years. Yuan et al. (2014), Nie et al. (2012), Huang et al. (2009) and Fan et al. (2006) studied the wave propagation problems in piezoelectric/piezomagnetic composites with imperfect interfaces, respectively. Assuming that there are imperfect interfaces in piezoelectric fiber-matrix composites, Rodríguez-Ramos et al. (2013) surveyed the effect of interfacial imperfection on the effective properties, and Shodja et al. (2006) discussed its influence on the electro-mechanical response. In the latest work of Wang et al. (2014), the effective properties are obtained for an ellipsoidal particle reinforced piezoelectric composites with imperfect interfaces. A common feature of these papers is that only the mechanical imperfection was considered. Obviously, the electrical and

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magnetic imperfections on the interfaces will also affect the mechanical behavior, because of the magneto-electro-mechanical coupling performance of multiferroic composites. When mechanical, electrical and magnetic imperfections simultaneously exist on the interfaces, the composites will have more complex but meanwhile more interesting mechanical behavior. Therefore, it is necessary to consider the effects of these three kinds of coexistent interfacial imperfections in theoretical analyses.

When conducting theoretical studies on multiferroic composites that contain imperfect interfaces, one has to construct a reasonable model for the mechanical, electrical and magnetic imperfections at first. In this aspect, a convenient and widely applied method is to generalize the linear spring model (Benveniste, 1985) of the imperfect interfaces in traditional elastic composites to describe the three kinds of interfacial imperfections here. In the generalized linear spring model (Serpilli, 2014, 2015), it is supposed that the generalized stress is continuous across the interface, while the generalized displacement is discontinuous therein (Rizzoni et al., 2014). Further, the value of the former is assumed to be proportional to the jump of the latter (Zhou et al., 2010). Based on the generalized linear spring model, a series of analyses have been performed on piezoelectric/piezomagnetic composites to investigate their mechanical response such as the wave propagation (Otero et al., 2013; Zhou et al., 2012; Jin and Li, 2012; Sun et al., 2011; Li and Lee, 2010a), vibration (Bian et al., 2010), dislocation (Wang and Sudak, 2007; Jin and Fang, 2008; Fang et al., 2013) and fracture (Li and Lee, 2009).

Although the generalized linear spring model simultaneously considers the mechanical, electrical and magnetic imperfections in the interfacial regions, it neglects their inter-couplings. As is known, a prominent feature of the composites consisting of alternate ferroelectric and ferromagnetic layers is that inter-couplings generally exist among the deformation field, the electric field and the magnetic one. Due to this reason, it is naturally to conjecture that any one of the mechanical, electrical and magnetic imperfections cannot independently occur and/or grow in the interfacial regions. That is to say, these three kinds of interfacial imperfections will be inter-coupled together. Further, such inter-couplings may also affect the mechanical response of multiferroic composites. Obviously, the effects of such inter-couplings form an interesting subject that still needs studying. Up till now, this subject has been scarcely addressed. To our knowledge, Shi et al. have tackled the inter-coupling between the mechanical and electric imperfections when evaluating the effective modulus of a particulate piezoelectric composite with imperfect interfaces (Shi et al., 2014). Li et al. (2015a, 2015b, 2015c) proposed the interfacial imperfection coupling model and discussed the effects of coupled interfacial imperfections on the fracture behavior of layered multiferroic plates and cylinders.

In the present paper, in-plane fracture analysis is performed on two bonded multiferroic half-planes with coupled interfacial imperfections. Fourier integral transform and Cauchy singular integral equations are employed to analyze the crack problem. Numerical results of the mechanical strain energy release rate are obtained and the effects of the three kinds of interfacial imperfections and their inter-couplings are thereby revealed. Finally, some dislocation-based mechanisms are proposed to explain the fracture behavior.

2. Problem formulation

Fig. 1 shows the fracture model for two bonded multiferroic half planes with an intermediate interfacial region of thickness h. The upper half-plane is ferromagnetic ceramics, and the lower one is ferroelectric ceramics. There are two cracks, parallel to the interfacial region and each in a half plane. The horizontal space between the two crack centers is denoted by c, and the vertical distances of the two cracks off the lower interface are d_1 and d_2. A rectangular coordinate system is set up with the rightward x-axis along the lower interface and the upward z-axis normal to the interfacial region. For the convenience of description, subscripts/superscripts 1 and 2 are used to mark the quantities of the upper and lower half planes, respectively.

Assume that the bonded structure in Fig. 1 is polarized along the z-axis. Then, the deformation in the xoz plane is coupled with the in-plane electric/magnetic field, and the constitutive relations of the two half planes can be stated as (Li et al., 2013)

$$\left.\begin{aligned}\sigma_x^{(i)} &= c_{11}^{(i)}\frac{\partial u_i}{\partial x} + c_{13}^{(i)}\frac{\partial w_i}{\partial z} + \delta_{1i}h_{31}\frac{\partial \varphi_i}{\partial z} + \delta_{2i}e_{31}\frac{\partial \phi_i}{\partial z}\\ \sigma_z^{(i)} &= c_{13}^{(i)}\frac{\partial u_i}{\partial x} + c_{33}^{(i)}\frac{\partial w_i}{\partial z} + \delta_{1i}h_{33}\frac{\partial \varphi_i}{\partial z} + \delta_{2i}e_{33}\frac{\partial \phi_i}{\partial z}\\ \tau_{zx}^{(i)} &= c_{44}^{(i)}\left(\frac{\partial w_i}{\partial x} + \frac{\partial u_i}{\partial z}\right) + \delta_{1i}h_{15}\frac{\partial \varphi_i}{\partial x} + \delta_{2i}e_{15}\frac{\partial \phi_i}{\partial x}\end{aligned}\right\} \tag{1}$$

$$\left.\begin{aligned}B_x^{(i)} &= \delta_{1i}h_{15}\left(\frac{\partial w_i}{\partial x} + \frac{\partial u_i}{\partial z}\right) - \mu_{11}^{(i)}\frac{\partial \varphi_i}{\partial x}\\ B_z^{(i)} &= \delta_{1i}\left(h_{31}\frac{\partial u_i}{\partial x} + h_{33}\frac{\partial w_i}{\partial z}\right) - \mu_{33}^{(i)}\frac{\partial \varphi_i}{\partial z}\end{aligned}\right\} \tag{2}$$

$$\left.\begin{aligned}D_x^{(i)} &= \delta_{2i}e_{15}\left(\frac{\partial w_i}{\partial x} + \frac{\partial u_i}{\partial z}\right) - \varepsilon_{11}^{(i)}\frac{\partial \phi_i}{\partial x}\\ D_z^{(i)} &= \delta_{2i}\left(e_{31}\frac{\partial u_i}{\partial x} + e_{33}\frac{\partial w_i}{\partial z}\right) - \varepsilon_{33}^{(i)}\frac{\partial \phi_i}{\partial z}\end{aligned}\right\} \tag{3}$$

where $i = 1, 2$. δ_{1i} and δ_{2i} are the Kronecker symbol, which is 1 when its two subscripts are identical and 0 otherwise. u and w are the displacement components along the x-axis and z-axis. φ and ϕ are the magnetic potential and electric potential. σ_x, σ_z and τ_{zx} are the stress components. B_x and B_z are the magnetic induction components. D_x and D_z are the electric displacement components. c_{11}, c_{13}, c_{33} and c_{44} are elastic constants. μ_{11} and μ_{33} are magnetic permeabilities. ε_{11} and ε_{33} are dielectric coefficients. h_{15}, h_{31} and h_{33} are piezomagnetic coefficients. e_{15}, e_{31} and e_{33} are piezoelectric coefficients.

The governing equations of the two half planes have the form (Li et al., 2013)

$$\left.\begin{aligned}&c_{11}^{(1)}\frac{\partial^2 u_1}{\partial x^2} + c_{44}^{(1)}\frac{\partial^2 u_1}{\partial z^2} + \left[c_{13}^{(1)} + c_{44}^{(1)}\right]\frac{\partial^2 w_1}{\partial x \partial z} + (h_{31} + h_{15})\frac{\partial^2 \varphi_1}{\partial x \partial z} = 0\\ &c_{33}^{(1)}\frac{\partial^2 w_1}{\partial z^2} + c_{44}^{(1)}\frac{\partial^2 w_1}{\partial x^2} + \left[c_{13}^{(1)} + c_{44}^{(1)}\right]\frac{\partial^2 u_1}{\partial x \partial z} + h_{15}\frac{\partial^2 \varphi_1}{\partial x^2} + h_{33}\frac{\partial^2 \varphi_1}{\partial z^2} = 0\\ &h_{15}\frac{\partial^2 w_1}{\partial x^2} + h_{33}\frac{\partial^2 w_1}{\partial z^2} + (h_{15} + h_{31})\frac{\partial^2 u_1}{\partial x \partial z} - \mu_{11}^{(1)}\frac{\partial^2 \varphi_1}{\partial x^2} - \mu_{33}^{(1)}\frac{\partial^2 \varphi_1}{\partial z^2} = 0\\ &\varepsilon_{11}^{(1)}\frac{\partial^2 \phi_1}{\partial x^2} + \varepsilon_{33}^{(1)}\frac{\partial^2 \phi_1}{\partial z^2} = 0\end{aligned}\right\} \tag{4}$$