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Singularity of subsonic and transonic crack propagations along interfaces of magnetoelectroelastic bimaterials

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ABSTRACT

The unified method for addressing the propagation of subsonic and transonic cracks along the interfaces of anisotropic bimaterials in Shen and Nishioka (2000) is applied in this paper for the plain strain problem of subsonic and transonic crack propagation along the interfaces of anisotropic magnetoelectroelastic (MEE) bimaterials. Using a modified Eshelby–Stroh formalism and analytic continuation, the problem here leads to a Riemann–Hilbert problem. After solving the Riemann–Hilbert equation, near-tip asymptotic fields are obtained, which shows the properties of the subsonic and transonic crack propagation in an MEE bimaterial system. Finally, the numerical results related to different singularity powers of the crack-tip are presented and discussed for barium titanate-cobalt ferrite ($BaTiO_3$–$CoFe_2O_4$) composites. The effects of piezoelectricity and piezomagnetics are also examined.

1. Introduction

Magnetoelectroelastic (MEE) laminated composites are now being applied as the core components of multifunctional magnetoelectric (ME) energy conversion devices and surface acoustic wave (SAW) devices because of the effects of their unique magneto-electro-elastic coupling. However, these MEE materials are usually subjected to dynamic loading during their service life which results in interface cracking, one of the most commonly observed failure modes.

In contrast to static fractures (Feng, Su, Liu, & Li, 2010, 2012; Gao & Noda, 2004; Herrmann et al., 2010; Huang, Wang, & Mai, 2009; Li & Kardomateas, 2007; Ma, Feng, & Su, 2013, 2015 and 2016), dynamic cracks and their propagation along an interface are more realistic; for example, in transient response and moving crack problems. Zhong, Liu, and Li (2009) performed a fracture analysis of two limited permeable collinear cracks in a homogeneous MEE body subjected to impact loadings to examine the transient response of in-plane deformation. Chen (2009) established a dynamic contour integral for cracks in magneto-electro-thermo-elastic (METE) materials, and pointed out that the dynamic contour integral could be applied as a physically sound criterion for dynamic fracture analysis. Hu and Chen (2012) considered a pre-existing curving crack problem for an MEE strip under impact loadings and obtained the hoop stress intensity factor. Feng, Li, and Xu (2009) investigated the transient response of a crack on the interface between two MEE layers.

Another important topic in dynamic fracture mechanics is the moving crack problem (Yoffe, 1951). Some researchers have extended the moving crack model to the analysis of the fracture behaviors of MEE bimaterials (Chen, Wei, Liu, &

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Fang, 2012; Hu, Chen, & Fu, 2015; Zhong & Li, 2006), but only considered the anti-plane state. Among them, Zhong and Li (2006) studied a moving Yoffe crack of the interfaces between two types of MEE bimaterials based on the ME boundary conditions of a limited permeable crack-face. Chen et al. (2012) considered the problem of the propagation of a semi-infinite interfacial crack between piezoelectric and piezomagnetic solids. They observed that when determining the dynamic fracture parameters, the B-G waves play an important role for the considered combination of materials. Using the Fourier-transform method, Hu et al. (2015) investigated a moving ME permeable crack at the interfaces of MEE bimaterials by using the Dugdale model. They concluded that the generalized stresses are no longer singular at the crack tip. For in-plane fracture problems, Ma, Su, and Feng (2017) analyzed the fracture behavior of a moving interface crack with a contact zone between two dissimilar types of MEE materials. They examined the effect of the speed of the moving crack, poling direction, material volume fraction, load position and load ratio on the fracture parameters. However, their work is only limited to the subsonic regime.

A comprehensive review regarding steady-state and transient problems for uniform and non-uniform plane crack propagation in an homogeneous elastic solid can be found in Slepyan (2002), in which the speed-dependent crack-tip asymptotic fields were presented for different speed regions, including sub-Rayleigh, super-Rayleigh, transonic and supersonic regimes. Moreover, it was shown that, as a macrolevel crack growth criterion, the principle of maximum energy dissipation rate (Slepyan, 1993) could satisfactorily predict the propagation behavior of the dynamic cracks in brittle materials. On the other hand, investigations on transonic crack propagation in bimaterials can be traced back to Yang, Suo, and Shih (1991) and Liu, Lambros, and Rosakis (1993), and continued by other researchers, such as Huang, Liu, and Rosakis (1996), Lambros and Rosakis (1995), Yu and Yang (1995), and Nishioka and Yasin (1999). Yang et al. (1991) first proposed the theoretical possibility of transonic crack growth in elastic bimaterials. Liu et al. (1993) and Lambros and Rosakis (1995) observed that the speed of the crack-tip could be faster than the minimum shear wave speed of the poly(methyl methacrylate) (PMMA)/steel bimaterial system in their experimental investigation. Liu, Huang, and Rosakis (1995) pointed out that the near-tip field of transonic crack propagation at the interface of bimaterials is shear dominated and large scale contact could develop behind the crack tip for a certain velocity range. Yu and Yang (1995) and Huang et al. (1996) presented an asymptotic solution for a transonic crack at the isotropic bimaterial interface and demonstrated that a Mach wave emanates from the crack tip. Nishioka and Yasin (1999) performed simulations of the propagation of subsonic, transonic and supersonic cracks at the interfaces between isotropic bimaterials subjected to tension and shear dominated loadings, respectively. Their results showed that in the supersonic regime, the dynamic energy release rate is always equal to zero. Rosakis, Samudrala, Singh, and Shukla (1998) further confirmed the possibility of supersonic crack growth based on experiments. Samudrala and Rosakis (2003) studied the effects of loading and geometry on the subsonic/transonic transition of a crack at a bimaterial interface. They showed that the formation, size and evolution of the contact zone substantially differ based on the sign of the opening component of loading. Taking into account the effects of contact, Huang, Wang, Liu, and Rosakis (1998) and Wang, Huang, Rosakis, and Liu (1998) proposed near-tip solutions of a transonic crack at the interface between elastic/rigid and elastic/elastic bimaterials. On the other hand, Needleman and Rosakis (1999) and Hao, Liu, Klein, and Rosakis (2004), Xu and Needleman (1996) examined transonic crack growth of bimaterial debonding by using numerical simulation and also observed that compressive normal stresses along part of the interface could lead to the development of a large contact zone length. More recently, Barras, Kammer, Geubelle, and Molinari (2014) numerically investigated the in-plane propagation of bimaterial interfaces by considering the frictional contact with a spectral formulation of elastodynamic boundary integral equations.

However, all of these aforementioned works that concern interface crack propagation in a transonic regime are limited to isotropic bimaterial systems. Shen and Nishioka (2000) and Shen et al. (2000), respectively, considered the singularity of subsonic and transonic crack propagations along anisotropic elastic and piezoelectric bimaterials by using a unified method. They found that a Mach wave emanates from the crack tip and moves with the crack tip when the crack propagates in a transonic regime. Wu (2002) presented the crack-tip field of a supersonic crack at the interface of anisotropic bimaterials. However, to the best of the knowledge of the authors, the singularity of subsonic and transonic crack propagation along the interfaces of MEE bimaterials has not been reported yet. Therefore, in this paper, we discuss the asymptotic structure of the crack-tip field of a moving crack in the subsonic and transonic regimes at the interfaces of MEE bimaterials by referring to the unified method proposed by Shen and Nishioka (2000). Using modified Eshelby–Stroh formalism and analytic continuation, the problem here leads to a Riemann–Hilbert problem. After solving the Riemann–Hilbert equation, the near-tip asymptotic fields are obtained, which show the properties of the subsonic and transonic crack propagation in an MEE bimaterial system. Finally, the numerical results related to the singularity powers of the crack-tip are presented for barium titanate-cobalt ferrite ($BaTiO_3$–$CoFe_2O_4$) composites in order to show the fracture properties of the asymptotic fields.

2. Basic relations for MEE bimaterials with moving coordinate system

According to Huang and Kuo (1997), the dynamic constitutive equations for an MEE solid in a fixed coordinate system (X_1, X_2, X_3) can be written in the forms of:

$$\begin{cases} \sigma_{ij} = c_{ijkl}u_{k,l} - e_{lij}\varphi_{,l} - h_{lij}\phi_{,l} \\ D_i = e_{ikl}u_{k,l} + \alpha_{il}\varphi_{,l} + d_{il}\phi_{,l} \\ B_i = h_{ikl}u_{k,l} + d_{il}\varphi_{,l} + \mu_{il}\phi_{,l} \end{cases} \tag{1}$$