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Effect of interface stress on the fracture behavior of a nanoscale linear inclusion along the interface of bimaterials

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ABSTRACT

This paper investigates the influence of residual interface tension on the fracture behavior of a nanoscale linear interface inclusion in a bimaterial matrix. Solutions to the inclusion opening displacement and the energy release rate are obtained. The results show that the interface effect on the inclusion deformation and inclusion tip field are prominent at nanoscale. Especially, the residual interface stress has a dramatic influence on the energy release rate. It is also found that the importance of the interface effect depends on the size of the inclusion, the shear modulus ratios of the bimaterial. The inclusion opening displacement and the energy release rate can be reduced considerably by decreasing the inclusion length at nanoscale.

1. Introduction

Due to the unique mechanical and physical properties, nanostructured materials have found wide applications in constructing nanodevices, such as chemical and biological nanosensors (Zhang et al., 2013), nanoresonators (André, 2010; Beil et al., 2006) and nanogenerators (Liu et al., 2008; Yang et al., 2009). However, nanomaterials have different properties from their bulk materials. It is because that when the characteristic sizes of materials shrink to microns or nanometers, the surface/interface area-to-volume ratio becomes huge and surface/interface stresses may play a crucial role in the behavior of such materials. Thus considering the influence of surface and interface stresses on mechanical behaviors of nanoscale materials containing nanoscale objects is essential for the performance prediction and design of nanodevices.

In order to analyze the surface and interface effects, Gurtin and his co-workers (Gurtin et al., 1998; Gurtin and Murdoch, 1975; Guitin and Murdoch, 1978) proposed a mathematical theory. They treated the interface region as a two-dimensional membrane in a three-dimensional continuum. This model has been adopted by many scholars to study the subjects of the interface effect on nanoscale composites. Yang (2004) investigated the surface effect on the effective elastic properties by using an incomplete Gurtin–Murdoch model. Moreover, they leading to an erroneous conclusion that the effective properties of material depend upon the applied strains which is noted by Mogilevskaya et al.(2010) and Mi and Kouris (2013a). In the work of Mogilevskaya et al. (2010), they studied the problem of unidirectional nano-scale fiber-reinforced composites, and gave the transverse overall behavior of unidirectional affected by the surface elasticity and surface tension. Based on the complete form of Gurtin Murdoch model, Mogilevskaya et al. (2008) investigated surface effect on the multiple interacting circular nano-inhomogeneities. Incorporating surface tension and surface stiffness effects, Kushch et al. (2011) solved the problem of multiple interacting spherical inhomogeneities with the Gurtin–Murdoch interface model. Many experiments have verified the valid of the continuum mechanics solutions for plates as thin as three atomic monolayers, and atomistic methods and classical elasticity show similar results for small strains (Duan et al., 2005a; Stoleru et al., 2002). It also should be mentioned that the model proposed by Dingreville and Qu (2008) which introduced the concept of transverse interfacial excess strain and fully reflected the elastic behavior of a coherent interface. They derived complementary Shuttleworth equation and pointed that the well-known Shuttleworth relationship is valid only when the transverse interfacial excess stress along the interface is ignored. In fact, when the transverse stress is considered, the interface can be treated as a 3D mathematical object, i.e. a "layer" with the intrinsic "width".

Since the great development of nano-structures made from layered materials, how to deal with the problem of nano-scale inhomogeneities in such materials becomes a hot issue. Some researchers concentrated on the problems of nano-inhomogeneities or cavities embedded in an infinite or semi-infinite matrix. In particular, the surface and interface effect on the elastic properties of nanoparticles, wires, and films were investigated by Dingreville et al. (2005) and Mi and Kouris (2012) developed a solution

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methodology to perform the interface effect for embedded nanoparticles; the effective bulk modulus of nanocomposites containing inclusions were obtained by Yang (2006) and Duan et al. (2005b); the elastic deformation near nanosized spherical and elliptical inhomogeneities were analyzed by Sharma et al. (2003) and Wang and Wang (2006), etc. To evaluate the deformation of embedded nano-inhomogeneities or cavity, some researchers focused on the mechanical behaviors of such materials. He and Li (2006) studied surface effect on stress concentration near a spherical void in an infinite elastic solid. Sharma and Wheeler (2007) studied the ellipsoidal nanoinclusions and give an approximate solution for the relaxed elastic state. Avazmohammadi et al. (2009) investigated the interface effect on the elastic deformation of an elastic half-plane embedded an elastic inclusion. By applying the complex variable method, Luo and Wang (2009) considered the elastic field of an elliptic nano inhomogeneity embedded in an infinite matrix under anti-plane and their semi-analytic method is proved to be effective and accurate. In addition, the problem of nano composites containing nanoscale inclusions/inhomogenities or cavities have also been studied (Chen et al., 2007; Duan et al., 2007; Mi and Kouris, 2013b; Sun et al., 2004; Zhang and Wang, 2007). For bimaterials, Jammes et al. (2009) investigated the multiple circular nano-inhomogeneities in one of two joined isotropic elastic half-planes.

Although interface effects on the mechanical properties of nanomaterials embedded inclusions/inhomogenities have been extensively studied, it must be pointed out that most previous studies predicted the influence of the interfacial tension on the effective elastic modulus of the bulk materials (Dingreville et al., 2005; Duan et al., 2005b), the elastic field and stress concentration of elliptical holes, spherical voids, cavity, and inclusions/inhomogeneities (Avazmohammadi et al., 2009; Chen et al., 2007; Duan et al., 2007; He and Li, 2006; Jammes et al., 2009; Luo and Wang, 2009; Sharma and Wheeler, 2007; Sun et al., 2004; Sharma et al., 2003; Wang and Wang, 2006; Zhang and Wang, 2007). As a parameter to measure the fracture behavior of the materials, the inclusion tip field intensity factor and the energy release rate are essential for evaluating the reliability and estimating the residual life of the structures. For the future applications of fracture in micro/nanoscale material, it is vital to incorporate the influence of interface stresses in the inclusion tip field quantities (such as the stress intensity factor and the energy release rate). There are several works which formulate the surface effect on the cracking problems and have proved that when considering fracture behaviors of nanomaterials, the influence of surface stress is inevitable (Fu et al., 2011; Huang et al., 2009; Kim et al., 2010; Wang et al., 2008; Wu, 1999; Zhang et al., 2005). However, the works listed above did not give the analysis of interface effect on the fracture of nanomaterials. Therefore, the problem of a line inclusion in an infinite bimaterial matrix is still very limited at nanoscale. This paper studies the interface effect on the inclusion tip field of an interface inclusion in an infinite bimaterial medium with the consideration of residual interface stresses. Since we ignored the transverse stress which is considered in the constitutive equations of the interface in the Dingreville and Qu (2008) model, Gurtin and Murdoch (1975, 1978) surface/interface model is adopted. Using Fourier integrals and singular integral methods, the solutions to the problem are derived. The solutions to the inclusion opening displacement, energy release rate and stress intensity factor are obtained and some useful conclusions are drawn.

2. Description of the problem

Now we start from a 2D plane problem of two dissimilar isotropic elastic half-plane perfectly bonded together. There is a line nano-inclusion embedded along the bimaterial interface (x-axis) with length of $2a$ and height of h in the y-direction shown in Fig. 1, where (x,y) is a coordinate system. Here, we investigate a symmetric problem. It is assumed that all the field variables are functions of x and y only, respectively. Let the medium be loaded by a remote uniform normal stress σ_∞. We consider a coherent interface between the medium and the inclusion. Then the continuum surface/interface model can be used (Gurtin and Murdoch, 1975).

The inclusion and the matrix are both assumed to be isotropic elastic. Denote the superscripts of m and i as the material properties and the field variables in the matrix and the inclusion, respectively. According to the generalized Young–Laplace equations (Chen et al., 2006), the boundary condition for solids at the interface between the matrix and the inclusion can be expressed as

$$[\boldsymbol{\sigma}]\boldsymbol{n} = -\nabla_s \bullet \boldsymbol{\sigma}^s, \tag{1}$$

where ∇_s denotes the interface gradient operator; $[\boldsymbol{\sigma}] = \boldsymbol{\sigma}^m - \boldsymbol{\sigma}^i$; $\boldsymbol{\sigma}^m$ and $\boldsymbol{\sigma}^i$ are respectively stress in the bulk and in the inclusion; $\boldsymbol{n}$ is the a unit vector normal to the interface. The elastic properties of the inclusion (Poisson's ratio ν_i and Young's modulus E^i) are assumed to be different from the matrix region (Poisson's ratios ν^{I} (ν^{II}) and shear moduli μ^{I} (μ^{II}) for the lower and upper half-planes, respectively). For a coherent interface, the normal stress components are assumed to be continuous across the interface of the bimaterials. The presence of the surface and interface stresses yield to non-classical boundary conditions, that is:in the bulk

$$\sigma_{xy}^{\mathrm{I}} = \sigma_{xy}^{\mathrm{II}} = 0, \quad \sigma_{yy}^{\mathrm{I}}(x,+0) = \sigma_{yy}^{\mathrm{II}}(x,-0) = \sigma_{yy}^{m}(x,0), \tag{2a}$$

in the interface:

$$[\boldsymbol{\sigma}^{\mathrm{I}} - \boldsymbol{\sigma}^{i}]\boldsymbol{n} = -\nabla_s \bullet \boldsymbol{\sigma}^s, \quad |x| \leqslant a, \tag{2b}$$

$$[\boldsymbol{\sigma}^{\mathrm{II}} - \boldsymbol{\sigma}^{i}]\boldsymbol{n} = -\nabla_s \bullet \sigma^s, \quad |x| \leqslant a, \tag{2c}$$

According to the Gurtin and Murdoch (1975), the surface constitutive equations are:

$$\boldsymbol{\sigma}^s = \tau_0\mathbf{I} + (\lambda_s + \tau_0)(tr\boldsymbol{\varepsilon}^s)\mathbf{I} + 2(\mu_s - \tau_0)\boldsymbol{\varepsilon}^s + \tau_0\nabla_s\mathbf{u}, \tag{3a}$$

where τ_0 is the residual interface stress, $\mathbf{I}$ is the unit tangent tensor, λ_s and μ_s are interface elastic constants, tr $\boldsymbol{\varepsilon}^s$ is the trace of the interface strain tensor $\boldsymbol{\varepsilon}^s$ and $\boldsymbol{u}$ is the displacement vector. For two-dimensional materials surface, the Eq. (3) can be rewritten as follows:

$$\sigma^s = \tau_0 + (2\mu_s + \lambda_s)\varepsilon^s, \tag{3b}$$

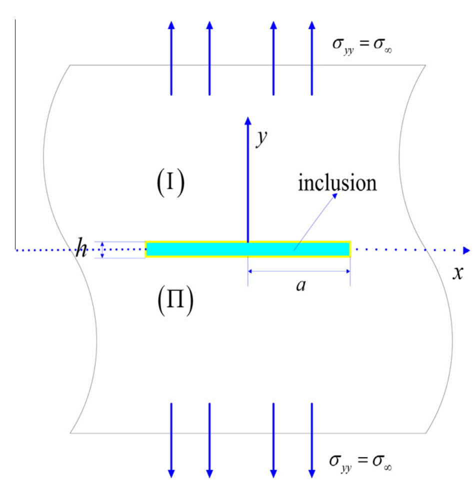

Fig. 1. An infinite bimaterials with a line nano-inclusion embedded along the interface.