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A screw dislocation interacting with a coated nano-inhomogeneity incorporating interface stress

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A B S T R A C T

Effect of interface stress on the interaction between a screw dislocation and a coated nano-inhomogeneity is investigated in the framework of surface elasticity. By using the complex variable function method, the stress fields in heterogeneous materials and the image force acting on the screw dislocation are derived analytically. The results indicate that, when the radius of the coated inhomogeneity is reduced to nanometers, the influence of interface stress on the motion of the dislocation near the inhomogeneity becomes significant and the image force acting on the screw dislocation depends on the size of the coated inhomogeneity, which differs from the classical solution. And it is showed that the thicker coated layer relative to inclusion decreases or increases the influence of a coated inclusion on the image force of dislocation, not as expected.

1. Introduction

Interactions between dislocations and inhomogeneities play an important role in the strength and stiffness of crystalline materials, and have attracted much attention since the pioneering work of Head [1,2]. For example, Dundurs [3] calculated the displacement and stress fields of a screw dislocation near a circular elastic inhomogeneity. Sendeckyj [4] extended this problem to the case of multiple inhomogeneities. Recently, the elastic interaction of screw dislocations with interphase boundaries of the circular inhomogeneities coated by one [5–7], two [8–10] and many [11] intermediate layers has been studied. In their researches, the circular interface boundaries are assumed to be either perfect (continuous displacement and traction across the interface) or imperfect.

In the aforementioned studies, however, the effect of interface stress is not taken into account. The interface of solids is a special region with a very small thickness. Since the interface-to-volume ratio in the nano-scale domain is relatively high compared to that in the macro-scale domain, the interface stress plays a significant role on the size-dependent behavior of nanoscale elements or devices [12,13]. Since there is no intrinsic length scale involved in the constitutive laws of the classical elastic theory, it is unable to predict the size-dependent behavior of nanosized structures and devices. A general model for elastic isotropic solids incorporating interface stress was proposed by Gurtin and Murdoch [14,15] and Gurtin et al. [16]. In their work, an interface is regarded as a negligibly thin layer adhering to the bulk without slipping. The material constants of the interface are different from the bulk materials. The equilibrium and constitutive equations of the bulk solid are the same as those in classical elasticity, but the presence of interface stress gives rise to a non-classical boundary condition. Utilizing this model, some authors investigated the elastic responses of nanoscale structures [17–19] and the elastic fields around nanoscale inclusions [20–24], etc. All these studies show that the presence of interface stress results in size-dependent elastic responses. Recently, the interaction between a screw dislocation and a circular nano-inhomogeneity incorporating interface stress has been considered by Fang's research group [25,26]. In their papers, a two-phase (inclusion/matrix) is considered and the interface stress is restricted at the interface between the inhomogeneity and the infinite matrix of negligible thickness.

It is well known that the three-phase (inclusion/interphase/matrix) model is of great practical and theoretical value in composite mechanics researches. In most fiber-reinforced composite materials, coated fibers are widely employed in the design stage to improve the bonding strength between the fibers and the matrix. In the present paper, we study the problem of the elastic interaction between a screw dislocation and a coated nano-inhomogeneity incorporating interface stress. The interface stresses at the inner and outer interfaces

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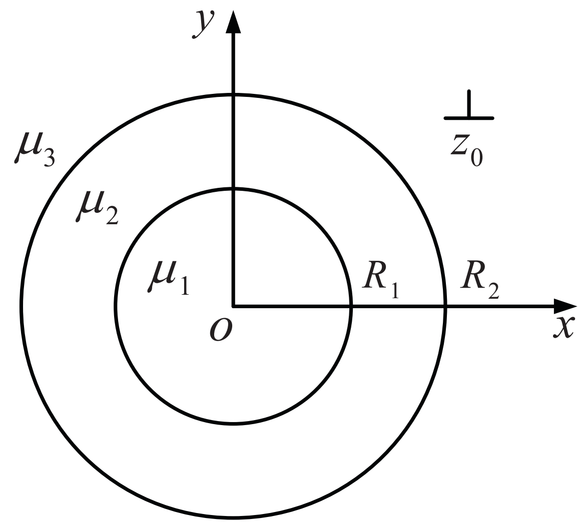

Fig. 1. A screw dislocation interacting with the coated inhomogeneity.

of the annular coated layer are considered. By means of a complex variable technique, the explicit solutions of the complex potentials are obtained. The image forces exerted on the screw dislocations are derived. The results show that the influence of the interface stresses on the motion of the dislocation becomes significant and the direction of the image force acting on the dislocation may be altered due to the presence of the interface stresses when the radius of the coated inhomogeneity is reduced to nanometers. Our results are helpful in the understanding of the motion mechanism of the dislocation and relevant physical phenomena in three-phase nano-composite materials.

2. Boundary value problem of coated inhomogeneity with interface effect

Let us consider an infinite isotropic medium containing a circular inhomogeneity and an annular coating layer under anti-plane problem, as shown in Fig. 1, where R_1 and R_2 are the inner and outer radii of the coated annulus. L_1 and L_2 indicate the interfaces between the inhomogeneity and the coating layer, the coating layer and the matrix, respectively. A screw dislocation is located at the point z_0 in the matrix (z_0 is plotted in the matrix in Fig. 1). In anti-plane state, the displacement w, the shear stress components σ_{xz} and σ_{yz} of the materials can be expressed in terms of a single analytical function (complex potential function) with respect to the complex variable $z=x+jy$ ($j^2=-1$). Following Gurtin and Murdoch [14,15], the interface L_1 and L_2 can be regarded as layer of vanishing thickness adhering to the solid without slipping. The elastic fields of bulk solids are described by the differential equations of classical elasticity, while the interfaces have their own elastic constants and are characterized by additional constitutive laws. Force balances of the interfaces lead to a coupled system of boundary conditions for the abutting bulk solid. For the considered anti-plane problem, we obtain in the bulk [27]:

$$\frac{\partial^2 w^{(i)}}{\partial x^2}+\frac{\partial^2 w^{(i)}}{\partial y^2}=0, \tag{1}$$

$$\tau_{rz}^{(i)}=2\mu_i\varepsilon_{rz}^{(i)}, \qquad \tau_{\theta z}^{(i)}=2\mu_i\varepsilon_{\theta z}^{(i)} \tag{2}$$

and in the interfaces [6,20,25,26]:

$$\tau_{\theta z}^{(L_\alpha)}=2\mu_{L_\alpha}\varepsilon_{\theta z}^{(L_\alpha)} \tag{3}$$

$$\left[\tau_{rz}^{(\alpha)}(t)\right]=\frac{1}{R_\alpha}\frac{\partial\tau_{\theta z}^{(L_\alpha)}}{\partial\theta}, \tag{4}$$

where super- and sub-script i having values of 1, 2, 3, refer to the inhomogeneity, coating layer and the matrix region, respectively; μ_i are shear moduli, $\tau_{rz}^{(i)}$ ($\varepsilon_{rz}^{(i)}$) and $\tau_{\theta z}^{(i)}$ ($\varepsilon_{\theta z}^{(i)}$) are stress (strain) components in the polar coordinates system (r, θ); L_α with $\alpha=1, 2$ denote the inner and outer interfaces, respectively; μ_{L_α} ($\alpha=1,\ 2$) are the elastic constants of the interfaces and $t=R_\alpha e^{i\theta}$ ($\alpha=1, 2$) denote the points on the circular arc interface L_α. In addition, $[\tau_{rz}^{(\alpha)}(t)]$ represents the jump in the interface stresses and points to the positive outward normal direction of the inclusion and the matrix. The interface strain $\varepsilon_{\theta z}^{(L_\alpha)}$ ($\alpha=1, 2$) equals to the associated tangential strain in the abutting bulk materials.

Referring to the work of Muskhelishvili [27], in the bulk solid, the displacements $w^{(i)}$, shear stresses $\tau_{rz}^{(i)}$ and $\tau_{\theta z}^{(i)}$ can be written in terms of the analytical functions $\Phi_i(z)$ as follows

$$w^{(i)}=\frac{\Phi_i(z)+\overline{\Phi_i(z)}}{2}, \tag{5}$$

$$\tau_{rz}^{(i)}-j\tau_{\theta z}^{(i)}=\left[\tau_{xz}^{(i)}-j\tau_{yz}^{(i)}\right]e^{j\theta}=\mu_i e^{j\theta}\varphi_i(z), \tag{6}$$

where $\varphi_i(z)=\Phi_i'(z)$ and the overbar represents the complex conjugate and the prime denotes the derivative with respect to the argument z.