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Stress intensity factor of a mode I crack inside a nanoscale cylindrical inhomogeneity

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ABSTRACT

Interior crack of a nanoscale cylindrical inhomogeneity with interface stresses under remote load is investigated. Utilizing the distributed dislocation technique, stress intensity factor at crack tip is obtained. The results show that both positive (negative) residual interface tension and interface elasticity suppress (promote) crack propagation under remote load. The effects of residual interface tension and interface elasticity on stress intensity factor increase with decreasing inhomogeneity radius. When inhomogeneity radius reduces to a small value, even with remote load, the crack does not propagate due to positive residual interface tension.

1. Introduction

The interaction between the crack and the microstructure at multiple length scales is important to design microstructure for damage tolerance. Therefore, this problem has received a considerable amount of attentions during the last several decades. Tamate [1] studied the effect of a circular inclusion on the stresses around a line crack in a sheet under tension. He showed that the stiff inclusion decreases the stress intensity factor (SIF) of the crack tip, while the soft inclusion increases the SIF under tension. Erdogan et al. [2] investigated the interaction between an isolated circular inclusion and a line crack embedded in an infinite matrix with the distributed dislocation method. The distributed dislocation method is an effective tool to solve various kinds of crack problems [3–8]. Zhang and Li [9,10] investigated an edge dislocation and a screw dislocation interacting with a finite length crack, respectively. Herrmann and Wang [11] studied the effect of a circular transforming inclusion on the stress field of an antiplane shear crack. They discussed the variation of stress intensity factors with the size, position and stress–free strains of the transforming inclusion. Cheeseman and Santare [12] considered the problem of a radial or circumferential matrix crack interacting with a circular inclusion surrounded by an interphase region. They found that compliant interphases increase the Mode I SIFs for radial cracks while stiff interphases shield these cracks from the inclusion relative to the no-interphase cases. Additionally, the compliant interphases were found to be more affected by the thickness of the interphase. Xiao and his co-workers [13–17] considered a series of the crack interacting with the inhomogeneity in the fiber-reinforced composite material. Luo et al. [18,19] investigated the stress relaxation of an eccentric

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Nomenclature

c	half-length of the crack
l	relative crack length
R	inhomogeneity radius
α, β	intrinsic lengths
ε	relative shear modulus
μ, υ	shear modulus and Poisson's ratio
μ^0, λ^0	interfacial Lame constants
σ_{yy}^{∞}	remotely applied stress in y-direction
σ	normalized remote load
τ^0	residual interface tension
χ	interface elasticity
B_x, B_y	dislocation density components
K_I	mode I stress intensity factor for crack tips
u_x, u_y	displacement components
$\sigma_{xy},\ \sigma_{yy}$	stress components

negative wedge disclination in an isotropic homogeneous cylinder by nucleation of a Zener crack and a Griffith crack, respectively. Wang et al. [20] investigated the nucleation of a Mode-I Zener crack from a wedge disclination dipole in the presence of a circular inhomogeneity. They found that the elastic mismatch between the inhomogeneity and matrix is the most distinct factor that influences the disclinated crack nucleation. Gao and Mai [21] studied the singularities of an interface crack between two dissimilar electrostrictive materials under electric loads. Recently, Tao et al. [22] studied the interaction problem between a Griffith crack and a circular inhomogeneity in the presence of an edge dislocation under the remote load. Experimental observations have shown that, in certain cases, material failure does not occur until the fiber begins to fracture [23]. Therefore, the interior crack of the inhomogeneity is a meaningful topic in studying the mechanical properties of materials. Chao and Chiang [24] investigated the antiplane interaction problem for an anisotropic elastic inclusion embedded in an anisotropic elastic matrix with an arbitrarily oriented crack, located either in the matrix or in the inclusion. The plane problem of an elastic elliptic inclusion containing an interior crack is solved by Anlas and Santare [25]. Amenyah et al. [26] used a semi-analytic solution to analyze the effect of an imperfect interface on the stress field inside a circular elastic inclusion with an interior radial crack under thermal loading. They showed that for a hard inclusion, as the tip-interface distance decreases, the SIF increases, while for a soft inclusion, the SIF decreases as the crack approaches the interface under thermal loading.

For nanoscale materials, with a large ratio of the surface/interface region to the bulk materials, the surface/interface stress makes a significant contribution to the property of the material. A general and mathematical model for elastic isotropic solids incorporating surface/interface stress was presented by Gurtin and Murdoch [27] and Gurtin et al. [28]. In their work, a surface/interface region is approximated as a vanishing thickness adhering to the bulk solid without slipping. The material constants of the surface/interface are different from those of the bulk materials. The equilibrium and constitutive equations of the bulk solid are the same as those in classical elasticity, but the presence of surface/interface stress gives rise to nonclassical boundary conditions. This model has been adopted by many authors in studying nanoscale structures, thin films, nanocomposites, nanoelectronics and quantum dots [29–39]. The crack formation in a disclinated nanowire has been investigated via continuum mechanics and atomistic simulations [40–44]. Zhou et al. [40] studied the Griffith crack nucleation near a negative wedge disclination in cylindrical nanowire by a combination of continuum mechanics and atomistic simulations. They found that there exists a critical disclination strength above which the disclination is unstable and an equilibrium crack can grow from it. The continuum and atomistic calculations showed very close agreement in the critical disclination strength, and general agreement in the stable crack length, the crack opening profile, and the stress field of the disclinated crack in the nanowire. However, in some cases, discrepancies may exist between the atomistic simulations and continuum calculations. It was concluded that the discrepancies were due to the surface effect of the nanowire which was neglected in the continuum model. So, Luo et al. [45] investigated the influence of the surface stress effect on the stress field and crack nucleation behavior in a disclinated nanowire. The numerical results show that the critical disclination strength and the stable equilibrium crack length are influenced by the surface stress effects. The crack may be also initiated inside a nanoscale inhomogeneity accordingly. However, the aforesaid research works do not take into account the problem of the crack inside a nanoscale inhomogeneity. The problem of the interior crack of a nanoscale cylindrical inhomogeneity with interface stress is worth studying because the interface stresses may lead to high residual stress fields in the vicinity of the inhomogeneity–matrix interface that can either suppress or enhance crack initiation and propagation within the inhomogeneity.

In the present work, the problem of a crack located within a nanoscale cylindrical inhomogeneity using the interface stress model is first investigated. The influence of such parameters as the interface stress, the elastic mismatch between