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Boundary element analysis of nanoinhomogeneities of arbitrary shapes with surface and interface effects

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ABSTRACT

In this paper, a boundary element method (BEM) is proposed to analyze the stress field in nanoinhomogeneities with surface/interface effect. To consider this effect, the continuity conditions along the internal interfaces between the matrix and inhomogeneities are modeled by the well-known Gurtin–Murdoch constitutive relation. In the numerical analysis, the interface elastic moduli and the geometry of the nanoscale inhomogeneity are varied to show their influence on the induced stress field. The interaction between nanoscale inhomogeneities and the effect of different geometric shapes of inhomogeneities, including ellipse, triangle, and square are also investigated for different interface material parameters. It is shown that the elastic field can be greatly influenced by the interfacial energy and geometry of nanoscale inhomogeneities. The proposed BEM formulation is very general, including the complete Gurtin–Murdoch model and is further convenient for arbitrary shapes of inhomogeneity.

1. Introduction

Nanocomposites have been widely applied to the microelectromechanical system, bioengineering, and optics/photonics devices due to their unique mechanical, electronic, and optical properties [1–4]. Unlike bulk materials, the effective elastic properties of nanomaterials strongly depend on the material and geometric parameters of the nanostructure as well as on the interface diffusion between the nanoinhomogeneity and matrix. While the surface/interface stresses of the nanostructure can be determined either experimentally [5,6] or computationally [7,8], its size-dependent properties can be explained by considering the effect of the surface/interface stresses, which comes from the excess free energy along the surface/interface (e.g., Refs. [9,10]).

A linearized stress–strain constitutive relation in surface elasticity was proposed by Gurtin and Murdoch [11], Murdoch [12], and Gurtin et al. [13]. This so-called Gurtin–Murdoch model has become increasingly popular and is now widely applied to investigate the mechanical behavior of nanoscale inhomogeneities. For instance, the size-dependent problem of the mechanical behavior of nanoscale inhomogeneities, Eshelby's tensor for embedded nanoinclusions, and the effective elastic constants of nanoscale inhomogeneities have been studied using the Gurtin–Murdoch model [10,14,15].

A couple of other recent studies represent the increasing interests in this direction: He and Li [16] considered the effect of the surface stress on the stress concentration near a spherical void in an elastic medium using the Papkovitch–Neuber displacement potential and Gurtin–Murdoch model. Also using the Gurtin–Murdoch model, Lim et al. [17] studied the influence of the interfacial stress on the elastic field in an infinite solid containing a nanoscale spherical inclusion with an axisymmetric eigenstrain. Tian and Rajapakse [18,19] presented analytical solutions for a single circular/elliptical nanoinhomogeneity embedded in an infinite isotropic elastic matrix. The corresponding finite-element method was also introduced to analyze the effect of surface and interfacial energy on the field quantities [20,21]. By incorporating surface/interface tension, Sharma and Wheeler [22] investigated the size-dependent elastic field of an ellipsoidal nanoinclusion under a pure dilatation eigenstrain. Ou et al. [23] discussed the effect of the residual surface tension on the stress concentration around a nanoscale spheroidal cavity under arbitrary uniform remote loadings. Luo and Wang [24] studied the anti-plane elastic field of an infinite matrix containing a nanoscale elliptical inhomogeneity.

In most of the works cited above, the simplified Gurtin–Murdoch stress–strain constitutive relation was used where the whole or part of the displacement–gradient term was neglected [25,26]. Using the complex variable method, Mogilevskaya et al. [27] recently studied the multiple interactions between the circular nanoinhomogeneities and nanopores using the "complete" Gurtin–Murdoch model. In their formulation, the precise component form of the three-dimensional Gurtin–Murdoch

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