International Journal of Solids and Structures 000 (2018) 1–24

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Scattering of plane elastic waves by a multi-coated nanofiber with deformable interfaces

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ARTICLE INFO

Article history:
Received 5 November 2017
Revised 31 January 2018
Available online xxx

Keywords:
Curved deformable interfaces
Interface excess kinetic energy
Interface momenta
Interface inertial parameters
Interface equations of motion
Scattering cross section
Plane elastic waves

ABSTRACT

The scattering of in-plane P- and SV-waves by a multi-coated circular nanofiber with deformable interfaces is of interest. To this end, in the present work, after introducing two kinds of interface momenta defined as the derivative of the interface excess kinetic energy with respect to the average and relative velocities at the interface, we extend the elastostatic theory of Gurtin et al. (1998) on deformable interfaces to the elastodynamic theory and derive the interface equations of motion using Hamilton principle. The effects of the generalized interface properties including the interface inertial parameters and interface stiffness towards stretch and slip on the dynamic stress concentration factor and the scattering cross section will be examined through some numerical examples. These results reveal that the effect of the interface inertial parameters becomes significant as the frequency of the incident wave increases. Moreover, as it will be shown, in the case where the interfaces are treated to be deformable, a larger number of resonance modes are captured for low-frequency waves as a result of the compliancy of the interfaces. It will also be seen that the resonant frequencies pertinent to the local deformations of the interface, increase with the interface stiffness parameters and decrease with the interface inertial parameters introduced in this work. These results can be used for tuning the resonant frequencies by selecting appropriate geometrical sizes and materials. Such phenomena can also be useful for designing locally resonant sonic materials with nano-sized lattice parameters.

1. Introduction

Motivated by abundant application of nanomaterials and nanostructures in the fabrication of such cutting edge technologies as micro- and nano-electromechanical systems, the attention of many researchers have been increasingly drawn to the study of the mechanical behavior of these materials and structures over the past three decades. Nanomaterials, due to their large surface-to-volume ratio and quantum effects can remarkably improve or tune such properties as strength, magnetic, electrical, reactivity, and optical properties when used as additives to certain host materials. Cammarata and Sieradzki (1989), through consideration of thermodynamical model have shown that the elastic moduli of thin films and small-period superlattices are strongly influenced by surface-/ incoherent interfacial- stresses.

In the literature, some authors have considered surface stresses arising in ultra-small bodies with rough surfaces. Weissmüller and Duan (2008) presented a cantilever bending model with rough surfaces and showed that the curvature is strongly related to the topology of the surface. Recently, Shaat (2017) studied the effects of surface integrity on the behavior of ultra-thin films by employing Kirchhoff plate theory.

Two methods have been widely applied to study the interface properties. One is the interphase model in which the interfacial region is treated as a three-dimensional material in accordance with classical continuum theory (Hashin, 2002; Duan et al., 2007). The second is Gibbs dividing surface model which suggests continuously varying material properties for the bulk phases up to a two-dimensional imaginary dividing interface across which the thermodynamic quantities are allowed to change discontinuously. In this method, the difference between the values of the thermodynamical quantities of the real system and that of the bulk phases are allocated to the interface as "excess quantities" (Murdoch, 2005). It is worthwhile noting that only extensive quantities yield such excesses. For instance, excess mass or mo-

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https://doi.org/10.1016/j.ijsolstr.2018.02.022
0020-7683/

Please cite this article as: H.M. Shodja, M.T. Jam, Scattering of plane elastic waves by a multi-coated nanofiber with deformable interfaces, International Journal of Solids and Structures (2018), https://doi.org/10.1016/j.ijsolstr.2018.02.022

mentum densities are meaningful, whereas excess surface velocity does not make sense. Although the idea of the second method is older, it has been observed that it is in better agreement with the atomistic simulations.

The idea of the dividing surface and the concept of the interface excess parameters were first introduced by Gibbs (1928). Shuttleworth (1950) and Herring (1951) are known as the pioneers in the development of surface elasticity theories based on the concepts of surface excess energy and surface stress in solids. Inspired by classical theory of membranes and exploiting the concepts of modern geometry, Gurtin and Murdoch (1975) provided a meticulous continuum theory for elastic material surfaces. Their theory has only focused on coherent interfaces and assumed that the surface/interface adheres perfectly to its surrounding bulk phases. Some researchers developed surface elasticity theories for incoherent and semi-coherent interfaces (Cahn and Lärché, 1982; Cermelli and Gurtin, 1994; Dingreville et al., 2014). Gurtin et al. (1998) provided a general and practical theory for deformable curved interfaces across which jumps in the displacement and the displacement gradient are permitted. In their work, the generalized elastostatic equations of equilibrium for interfaces are derived, allowing for the stretch and slip of the interface, respectively, in the normal and tangential directions at any point on the interface. In addition, their theory leads to a jump in the traction across the interface.

Many previous researchers have taken advantage of surface elasticity theory to predict the mechanical behavior of nanosized objects (Miller and Shenoy, 2000; Sharma and Ganti, 2004; Dingreville et al., 2005; Pahlevani and Shodja, 2011; Ahmadzadeh-Bakhshayesh et al., 2012; Shodja et al., 2012; Gutkin et al., 2013; Kalehbasti et al., 2014; Shodja et al., 2017). However, their contributions have been limited to coherent interfaces, an idealistic assumption which may not be justifiable for many realistic situations. For example, grain boundary sliding and grain rotation of nanocrystalline metals have been observed in many experiments and atomistic simulations (Hasnaoui et al., 2002; Markmann et al., 2003; Bachurin and Gumbsch, 2010; Grewer et al., 2011), emphasizing the importance of local deformations at the interfaces. Weissmüller et al. (2011) described the macroscopic deformation of a polycrystalline solid with grain boundary sliding. In their work, the grain boundaries are modeled by deformable interfaces introduced by Gurtin et al. (1998).

The fundamental problem of the scattering of elastic waves by a single cylindrical scatterer plays a crucial role in understanding the wave propagation phenomenon in fibrous composites (Mow and Pao, 1971). The scattering problem in the context of classical continuum theory has been widely investigated in the literature. Some authors have studied this problem using wave function expansion method (Mow and Pao, 1971; Eringen and Şuhubi, 1975; Shindo and Niwa, 1996; Shindo et al., 1998). Sarvestani et al. (2008) and Shodja and Delfani (2009) developed dynamic equivalent inclusion method (DEIM) to address the asymmetric two- and three-dimensional elastodynamic problems.

Traditional continuum theory, due to its innate incapability to capture the surface effects and the discrete nature of matters, fails to address accurately the problems involving wave lengths and body dimensions comparable to the lattice parameter of the crystalline solids. Therefore, for a realistic prediction of the behavior of solids with micro-structures and where the surfaces and interfaces have significant effects, employment of such augmented continuum theories as strain gradient, couple stress, and surface elasticity theories is inevitable. In second strain gradient theory proposed by Mindlin (1965), modulus of cohesion and surface characteristic length are linked to the surface effect. Ojaghnezhad and Shodja (2013, 2016) revisited surface elasticity theory in the context of second strain gradient theory and provided the linkage between the parameters of surface elasticity and second strain gradient theories. Some studies were conducted to address scattering problem using higher order continuum theories. Recently, Shodja et al. (2015) and Goodarzi et al. (2016), investigated the direct and inverse problems of the scattering of elastic waves by micro-/nano-fibers within couple stress theory with micro inertia. Surface elasticity theory has also been used by some researchers to study the scattering of elastic waves. Wang et al. (2006) and Ru et al. (2009) studied the diffraction of the in-plane elastic waves by a nano-cavity and an uncoated nanofiber, respectively. Shodja and Pahlevani (2012) investigated the surface/interface effects on the elastic fields induced by the scattering of anti-plane shear waves by a multi-coated nanofiber. It should be emphasized that, in all of these works, the interfaces are assumed to be coherent and no discontinuity in the displacement field is permitted across them.

The present work seeks to address the scattering of the in-plane P- and SV-waves by a multi-coated nanofiber with deformable interfaces which can suffer jumps in both the displacement and the displacement gradient. To this end, Gurtin et al. (1998) theory on elastostatics is extended to elastodynamics. More strictly speaking, the equilibrium equations of deformable interfaces introduced by Gurtin et al. (1998) are extended to the equations of motion of deformable interfaces, by accounting for the interface excess kinetic energy in addition to the excess free energy and using Hamilton principle. During the course of this development the notion of two kinds of interface momenta will be introduced. These interface momenta are defined as the derivative of the interface excess kinetic energy with respect to the average and relative velocities at the interface. Subsequently, the time derivative of the interface momenta referred to as the interface inertial forces contribute to the interface equations of motion, and consequently, affect the conditions at the interfaces accordingly.

This article is organized as follows. In Section 2, after the derivation of the dynamic equations of motion of a system with a deformable interface, the constitutive equations of a deformable interface are presented. Section 3 outlines the problem statement and the method of solution. Several numerical examples, examining the effects of various interface parameters are discussed in Section 4. Finally, Section 5 is devoted to conclusions.

2. Elastodynamics of solids with curved deformable interfaces

The work of Gurtin et al. (1998) is concerned with the theory of deformable interfaces for elastostatic problems where accretion at the interface is neglected. The current work aims to reformulate their theory to treat elastodynamic problems. Contrary to coherent interfaces in which the excess free energy is only a function of the tangential strain at the interface (Dingreville et al., 2005), for deformable interfaces the excess free energy is given as a function of three deformational quantities of the interface namely, the average tangential strain, the jump in the displacement, and the jump in the displacement gradient. Generalized interface stresses are defined as the derivative of the interface excess free energy with respect to these three deformational quantities. Gurtin et al. (1998) presented interface static equilibrium conditions for expressing the relationship between the interface stresses and stresses in the bulk phases.

The elastodynamical parameters and phenomena will be introduced and discussed as raised during the course of this development. Briefly speaking, in what follows, with the consideration of kinetic energy along with the free energy and by using Hamilton's principle, we extend the theory of Gurtin et al. (1998) to involve the dynamical aspects. In this section a brief derivation of the interface equations of motion is given. Moreover, the generalized interface parameters, including the interface momenta and the interface inertial parameters, are introduced.

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