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Vibration analysis of multi-phase nanocrystalline silicon nanoplates considering the size and surface energies of nanograins/nanovoids

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ABSTRACT

Nanocrystalline nanoplates are composed from three phases which are nano-grains, nano-voids and interface. This paper develops a higher order refined plate model with a sinusoidal shear strain function for vibration analysis of porous nanocrystalline nanoplates based on modified couple stress theory. Nano-voids or porosities inside the material have a stiffness-softening impact on the nanoplate. Modified couple stress theory is employed to capture grains rigid rotations. The governing equations obtained from Hamilton's principle are solved applying Galerkin's method which satisfies various boundary conditions. The reliability of present approach is verified by comparing obtained results with those provided in literature. Finally the influences of couple stress parameter, grain size, porosities and shear deformation on the vibration characteristics of nanocrystalline nanoplates have been explored.

1. Introduction

In the modern technologies, the combination of materials to construct an engineered product can be described through micromechanical models (Shaat & Abdelkefi, 2015a). In fact, nanoscale structural components are constructed from nanostructured materials due to possessing small size. It is known that nanostructured materials such as nanocrystalline materials (NcMs) and nanoparticle composites (NpCs) have an inhomogeneous structure and their properties are significantly influenced by the essence of their material structure. In fact, nanocrystalline materials are multi-phase composites consist of grain phase, porosities and interface phase. In NcMs, several atoms are separated from the grains and create a new phase which is called as the interface.

Several investigations have been performed for the modeling and simulation of nanocrystalline materials. Wang, Feng, Yu and Nan (2003) examined the influence of interface or matrix phase on the effective elastic moduli of nanocrystalline materials. They reported that the effective moduli of nanocrystalline materials are smaller than their coarse-sized counterparts due to the softening influence of interface phase. Meyers, Mishra and Benson (2006) presented a comprehensive investigation on the most important synthesis methods and mechanical properties of nanocrystalline materials. Zhou, Wang and Ye (2013) presented a micromechanical modeling of nanovoids growth in nanocrystalline materials.

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Size-dependency of nanostructures can't be described using classical continuum mechanics without any scale parameter. To incorporate the scale parameters into the classical continuum mechanics, several higher order theories such as nonlocal elasticity theory (Eringen, 1983) and modified couple stress theory (Yang, Chong, Lam & Tong, 2002) are developed. Nonlocal elasticity theory has the potential to describe long-range interactions between atoms inside the material, while the modified couple stress theory takes into account the strain gradients or material micro-rotations. Based on these size-dependent theories, several papers have been published on bending, buckling, vibration and wave propagation analysis of homogenous and non-homogenous nanostructures (Akgöz & Civalek, 2014; Ansari & Sahmani, 2011; Arani & Jalaei, 2016; Barati, 2017; Barati & Shahverdi, 2016; Barati & Zenkour, 2017; Barati, Zenkour & Shahverdi, 2016; Belkorissat, Houari, Tounsi, Bedia & Mahmoud, 2015; Daneshmehr & Rajabpoor, 2014; Daneshmehr, Rajabpoor & Hadi, 2015; Ebrahimi & Barati, 2017a, 2017b; Ebrahimi, Barati & Dabbagh, 2016; Khajeansari, Baradaran & Yvonnet, 2012; Kiani, 2016; Lei, Adhikari & Friswell, 2013; Li & Hu, 2016; Li, Li & Hu, 2016; Naderi & Saidi, 2014; Nejad & Hadi, 2016a, 2016b; Nejad, Hadi & Rastgoo, 2016; Pavlović, Karličić, Pavlović, Janevski & Ćirić, 2016; Roque, Ferreira & Reddy, 2011; Shafiei, Kazemi, Safi & Ghadiri, 2016a, 2016b; Şimşek, 2016; Thai, 2012; Thai & Choi, 2013; Thai & Vo, 2012; Tounsi, Benguediab, Adda, Semmah & Zidour, 2013). It is evident that in Refs. (Akgöz & Civalek, 2014; Ansari & Sahmani, 2011; Arani & Jalaei, 2016; Barati, 2017; Barati & Shahverdi, 2016; Barati & Zenkour, 2017; Barati et al., 2016; Belkorissat et al., 2015; Daneshmehr & Rajabpoor, 2014; Daneshmehr et al., 2015; Ebrahimi & Barati, 2017a, 2017b; Ebrahimi et al., 2016; Khajeansari et al., 2012; Kiani, 2016; Lei et al., 2013; Li & Hu, 2016; Li et al., 2016; Naderi & Saidi, 2014; Nejad & Hadi, 2016a, 2016b; Nejad et al., 2016; Pavlović et al., 2016; Roque et al., 2011; Shafiei et al., 2016a, 2016b; Şimşek, 2016; Thai, 2012; Thai & Choi, 2013; Thai & Vo, 2012; Tounsi et al., 2013) related to the mechanical analysis of nanostructures, only constant values of material properties are used which are independent of grains and voids size. Since nanostructures are often constructed from nanostructured materials, it is crucial to employ a micromechanical model considering the effects of nano-grains, nano-voids and interface for more reliable analysis of nanoplates. It is experimentally observed (Ke, Hackney, Milligan & Aifantis, 1995) that the strain gradients are of high magnitude near the interfaces in nanocrystalline materials due to the mismatch of neighboring grains of different orientation. Accordingly, a strain gradient theory with the couple stress effect for crystalline structures is presented by Chen and Wang (2001). Also, interested readers can find more details in the related papers (Keckes et al., 2012; Ren, Sun & Hao, 2013; Sun, Song, Guo, Ma & Xu, 2010; Wang, Li, Li, Wang & Chen, 2007) on the synthesis methods and mechanical characteristics of nanocrystalline nanoplates.

In respite of the significance, static and dynamic analysis of nanocrystalline nanostructures with the effects of nanograins and nanovoids is still very rare in the literature. To accurately model structural elements in micro/nano-scale applications, the heterogeneity nature of the material structure in addition to the non-classical physical phenomena have to be simultaneously considered into the mathematical model. Shaat and Abdelkefi (2015b) presented microstructural effects on pull-in voltages and bio-mass sensing of nanocrystalline silicon nanobeams. In another study, Shaat (2015) examined the influences of nanograins size and their rigid rotations on the static bending behavior of nanocrystalline nanobeams. Most recently, Ebrahimi and Barati (2017c) presented size-dependent vibration analysis of nanocrystalline silicon nanobeams resting on a viscoelastic medium based on a higher order beam theory. In these works, the effect of nanograins micro-rotation is considered via couple stress parameter. As one can see, there is no published study on vibration analysis of nanocrystalline nanoplates.

In this paper, a size-dependent plate model is developed for vibration analysis of nanocrystalline nanoplates considering the size of nanograins and nanovoids as well as their surface energies. The model employs the modified couple stress theory to explore the influence of nanograins rigid rotations. Based on refined two-variable plate model, it is possible to study the vibration behavior of thicker nanocrystalline nanoplates considering shear deformations effects needless of the shear correction factor. A micromechanical model based on Mori–Tanaka technique is implemented to describe the multi-phase composite nanoplate with the nanograin/nanovoid size dependent material properties. After the derivation of governing equations via extended Hamilton's principle, they are solved for various boundary conditions employing Galerkin's method. Parametric studies are presented to show the importance of scale parameter, nanograins size, nanograins rotation, nanovoids size, nanovoids percentage, interface thickness, foundation constants and boundary conditions on the vibration behavior of nanocrystalline nanoplates.

2. Governing equations

2.1. Material properties of nanocrystalline plates

Consider a nanocrystalline silicon nanoplate which is a three-phase composite having nano-grains and nano-voids randomly distributed in the interface region, as indicated in Fig 1. In this figure, a Representative Volume Element (RVE) is proposed in which distinct surface phases of inhomogeneities are indicated. A size-dependent micromechanical model (Shaat, 2015) is used to describe the effective material constants. In this model, influences of the size of grains and voids and their surface energies are included in the Mori–Tanaka micromechanical model. Elastic properties of interface or grain boundary, nano-grains and nano-voids are presented in Table 1. According to the suggested model, the elastic properties of a