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A theory of plasticity for carbon nanotube reinforced composites

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ABSTRACT

Carbon nanotubes (CNTs) possess exceptional mechanical properties, and when introduced into a metal matrix, it could significantly improve the elastic stiffness and plastic strength of the nanocomposite. But current processing techniques often lead to an agglomerated state for the CNTs, and the pristine CNT surface may not be able to fully transfer the load at the interface. These two conditions could have a significant impact on its strengthening capability. In this article we develop a two-scale micromechanical model to analyze the effect of CNT agglomeration and interface condition on the plastic strength of CNT/metal composites. The large scale involves the CNT-free matrix and the clustered CNT/matrix inclusions, and the small scale addresses the property of these clustered inclusions, each containing the randomly oriented, transversely isotropic CNTs and the matrix. In this development the concept of secant moduli and a field fluctuation technique have been adopted. The outcome is an explicit set of formulae that allows one to calculate the overall stress–strain relations of the CNT nanocomposite. It is shown that CNTs are indeed a very effective strengthening agent, but CNT agglomeration and imperfect interface condition can seriously reduce the effective stiffness and elastoplastic strength. The developed theory has also been applied to examine the size (diameter) effect of CNTs on the elastic and elastoplastic response of the composites, and it was found that, with a perfect interface contact, decreasing the CNT radius would enhance the overall stiffness and plastic strength, but with an imperfect interface the size effect is reversed. A comparison of the theory with some experiments on the CNT/Cu nanocomposite serves to verify the applicability of the theory, and it also points to the urgent need of eliminating all CNT agglomeration and improving the interface condition if the full potential of CNT reinforcement is to be realized.

1. Introduction

Carbon nanotubes (CNTs) are known to possess exceptional mechanical stiffness and strength. The axial Young's modulus of both single-walled and multi-walled CNTs can be as high as 1–1.2 TPa (Treacy et al., 1996; Krishnan et al., 1998; Salvetat et al., 1999; Shen and Li, 2004, 2005a,b), as compared to diamond at about 1.2 TPa, steel at 200 GPa, and copper at 100 GPa. Their tensile strength is about 100–200 GPa, as compared to annealed steel at about 700 MPa and annealed copper at about 200 MPa. CNTs also have very superior thermal and electrical conductivities (Dai and Lieber, 1996; Hone et al., 1999; Hone, 2004), mostly because of their nearly perfect atomic structures on the surface. Theoretical calculation of CNT thermal conductivity suggests that it can be as high as 6600 W/mK for an isolated (10, 10) nanotube at room temperature (Berber et al., 2000), while experimental measurement at 3000 W/mK for an individual multi-walled nanotube has also been reported (Kim et al., 2001). This is much higher than the thermal conductivity of copper, at about 400 W/mK. Single-walled CNTs also

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