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A variational method for non-linear micropolar composites

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Abstract

Built upon Ponte Castañeda's method for a Cauchy medium, a variational method for evaluating the effective non-linear behavior of micropolar composites is proposed. The same as for a Cauchy medium, it is shown that the proposed variational method can be interpreted as the secant moduli method based on second-order stress and couple stress moments. With simple examples, the interplay between material length parameters of a higher-order medium and its geometrical dimensions and/or material constants is highlighted. By using the new variational method, the influence of reinforcement size on the yielding and strain hardening of particulate composites is examined in a *simple and analytical* manner. The predictions agree well with existing experimental data for selected particulate metal matrix composite systems. The particle size effect is found to be more pronounced for shear loading and hard particles.
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1. Introduction

There has been rekindled interest in studying the size dependence of material properties, both experimentally and theoretically. The recent trend is driven largely by the practical need in the design, fabrication and characterization of miniaturized electronic, photonic and mechanical systems with length scales spanning from nanometers to submicrometers. Consequently, the applicability of classical continuum mechanics for ideal homogeneous materials in small structures has been subjected to acute scrutiny. For instance, for a thin film with only one or two layers of grains across the thickness, it is found that the homogenized material must have a non-local character in order to accurately describe the strain distribution in the film thickness (Haque and Saif, 2003).

In addition to the pronounced size dependence observed in macroscopically homogeneous solids, particle/fiber-reinforced metal matrix composites

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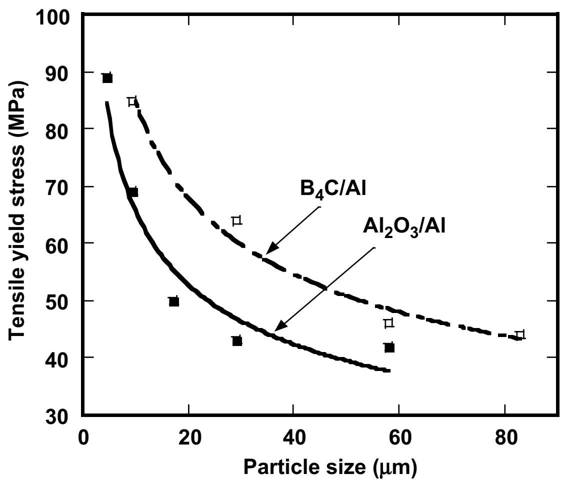

Fig. 1. Tensile yield stress (at 0.02% offset strain) of ceramic particle-reinforced aluminum matrix composite plotted as a function of particle size. Open and solid square symbols represent experimental data taken from Kouzeli and Mortensen (2002), whilst solid and dash lines represent curve-fitting.

also exhibit strong size dependent yielding/strengthening at the micron scale; see Fig. 1 plotted using the recent experimental data of Kouzeli and Mortensen (2002). However, in comparison with crystalline solids, theoretical studies on the size dependence of the non-linear overall properties of such composites are few. This paper aims to couple the higher-order, phenomenological elasticity and plasticity theory with Ponte Castañeda's variational method (Ponte Castañeda, 1991) to provide a simple analytical tool for predicting the non-linear behavior of particle-reinforced metal matrix composites as the reinforcement size is systematically decreased. We start by briefly reviewing the different length scales existing in composite materials, and the implications on higher-order non-local continuum theories.

1.1. Crystalline solids: length scales, size effects and higher-order plasticity theories

Experimentally, it has been well established that, in a crystalline solid such as copper wires with diameter ranging from 12–170 μm (Fleck et al., 1994), nickel foils of thickness in the range of 12.5–50 μm (Stölken and Evans) and 0.1–0.5 μm thick aluminum films (Haque and Saif, 2003), the yield stress and strain hardening are strongly dependent upon the interplay amongst the characteristic geometric size of the material L (e.g., film thickness), the internal geometric length scale D (e.g., grain or void size), and the plasticity length scale l characterizing, say, the gradient of plastic strains due to geometrically necessary dislocations. When $L \approx D \approx l \sim 1$ μm, the material becomes harder than its bulk counterpart, and the hardening/strengthening increases with the further decrease of L.

Theoretically, the current consensus is that a higher-order theory is necessary in order to capture and predict the experimentally observed size dependence (Fleck and Hutchinson, 2001). Whenever a high-order stress measure and the associated higher-order strain are introduced in addition to the classical Cauchy stresses and strains, one or more material length scales arise naturally due to dimensional consistency. From the continuum mechanics point of view, to include the non-local nature of the material into a continuum formulation, extra degrees of freedom (e.g., strain gradients and microrotations) must be introduced: such a non-local Cauchy medium will be referred to as the higher-order continuum in the following. In this paper, the Cauchy medium means that any material point in such medium can be considered as infinitesimally small, and any surface of such material element transmits only force. The higher-order continuum theory is introduced to describe more accurately the structural response of the material. According to different length scale conditions, different homogenization strategies should be adopted (Forest et al., 1999; Hu et al., 2004), as summarized in Table 1.

There exist different classes of higher-order plasticity theories, some phenomenological and some mechanism-based. The phenomenological theory is popular due to its simplicity, the representative being the strain gradient plasticity of Fleck and Hutchinson (1993), and its subsequent refinements/variations (e.g., Fleck and Hutchinson, 2001; Gao et al., 1999a,b; Chen and Wang, 2001). The Fleck–Hutchinson theory is built essentially upon the general framework of couple stress theory (see, e.g., Toupin, 1962; Midlin, 1964; Erin-

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