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# Size-effects on yield surfaces for micro reinforced composites

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ABSTRACT

Size effects in heterogeneous materials are studied using a rate independent higher order strain gradient plasticity theory, where strain gradient effects are incorporated in the free energy of the material. Numerical studies are carried out using a finite element method, where the components of the plastic strain tensor appear as free variables in addition to the displacement variables. Non-conventional boundary conditions are applied at material interfaces to model a constraint on plastic flow due to dislocation blocking. Unit cell calculations are carried out under generalized plane strain conditions. The homogenized response of a material with cylindrical reinforcing fibers is analyzed for different values of the internal material length scale and homogenized yield surfaces are presented. While the main focus is on initial yield surfaces, subsequent yield surfaces are also presented. The center of the yield surface is tracked under uniaxial loading both in the transverse and longitudinal directions and an anisotropic Bauschinger effect is shown to depend on the size of the fibers. Results are compared to conventional predictions, and size-effects on the kinematic hardening are accentuated.



## 1. Introduction

Reinforcement of metals by stiff elastic fibers is used to obtain increased stiffness, strength and creep resistance, but often on the cost of decreased ductility and fracture properties (see McDanels, 1985). A significant amount of research has analyzed how geometry and material parameters affect the overall properties of the composite material (see Christman et al., 1989; Bao et al., 1991; Tvergaard, 1990, 1995; Ltissenden et al., 2000; Legarth, 2003, 2004, 2005). These studies are based on conventional gradient independent plasticity models, and hence predict no effect of reinforcement size.

Recent interests in size-effects in metals have confirmed experimentally that 'smaller is stronger'. This has been shown for different materials and under different loading conditions such as bending (Stölken and Evans, 1998; Haque and Saif, 2003; Lou et al., 2005), torsion (Fleck et al., 1994), indentation and contact compression (Ma and Clarke, 1995; Swadener et al., 2002; Wang et al., 2006). For metal matrix composites, a non-trivial size-effect was observed by Lloyd (1994) who compared tests for two different SiC particle sizes in aluminum, 16 μm and 7.5 μm, while keeping the volume fraction constant. Shu and Barlow (2000) have compared an experimentally obtained TEM map of the lattice misorientation with computed deformation fields around a whisker, obtained using a strain gradient crystal plasticity model in a plane strain cell model of the composite. It was found that a classical crystal formulation tends to over-predict deformation gradients near whiskers, while a strain gradient crystal plasticity model predicted a more smooth field with lower gradients that correlated better with the measurements.

Conventional theories of plasticity lack the ability to model size-effects, as no constitutive length parameters are used. Based on the experimental evidence on size-effects in metals, various size-dependent strain gradient plasticity theories have been proposed. Aifantis (1984) proposed one of the earliest models that accounts for size effects in the plastic regime by

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