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Grain size–inclusion size interaction in metal matrix composites using mechanism-based gradient crystal plasticity

Ramin Aghababaei, Shailendra P. Joshi *

Department of Mechanical Engineering, National University of Singapore, Singapore

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ABSTRACT

Metal matrix composites (MMCs) comprising nano/microcrystalline matrices and reinforcements exhibit impressive mechanical behaviors derived by exploiting the size effects due to development of geometrically necessary dislocations. In such nanostructured MMCs intricate interactions between the grain size d_g and inclusion size d_i may exist in their overall response, but are difficult to isolate in experiments and are also not accounted for in the size-dependent homogenized models. In this paper, we computationally investigate the grain size–inclusion size interaction in model MMCs architectures wherein the grains and inclusions are explicitly resolved. A mechanism-based slip-gradient crystal plasticity formulation (Han et al., 2005a) is implemented in a finite element framework to model polycrystalline mass as an aggregate of randomly oriented single crystals that host elastic inclusions. The slip gradients that develop across grain boundaries and at inclusion–grain interfaces during deformation result in length-scale dependent responses that depend on both d_g and d_i, for a fixed inclusion volume fraction f. For a given d_i and f, the overall hardening exhibits a nonlinear dependence on grain size for $d_g \leqslant d_i$ indicating that interaction effects become important at those length-scales. Systematic computational simulations on bare polycrystalline and MMC architectures are performed in order to isolate the contributions due to grain size, inclusion size and the interaction thereof. Based on these results, an analytical model developed for the interaction hardening exhibits a Hall–Petch type dependence on these microstructural sizes that can be incorporated into homogenized approaches.

1. Introduction

The advent of nanostructuring techniques have led to an unprecedented growth in the area of synthesizing metal matrix composites (MMC) with exceedingly superior strengths. It is possible to significantly enhance the strength of MMCs over that achieved by conventional strengthening from load transfer, by synthesizing microstructures with nanocrystalline matrices, incorporating small sized reinforcing inclusions, or a combination of both (Lloyd, 1994; Mortensen and Llorca, 2010; Nan and Clarke, 1996; Sekine and Chent, 1995). Grain boundaries (gb's) create strong barriers to dislocations providing higher baseline matrix strength that can be further improved by the addition of reinforcing inclusions MMCs through a load-transfer mechanism. Thus, one may rely on synthesizing high-strength MMCs solely by using nanocrystalline matrices. Alternatively, the size-dependent strengthening from micron or sub-micron sized inclusions attributed to the geometrically necessary dislocations (GNDs) may also provide another path to strength enhancement. However, both the strengthening strategies have to deal with one common caveat – the enhancement in the strength usually comes at the cost of precipitous reduction in the ductility. The latter alternative might be attractive, because it allows using smaller inclusion volume fractions (v.f.) that may help mitigate the strength-ductility dichotomy to some extent.

Recent experimental and analytical efforts have aimed at understanding the size-effects in MMCs (e.g. Cleveringa et al., 1997; Dai et al., 1999, 2001; Joshi and Ramesh, 2007; Kiser et al., 1996; Lloyd, 1994; Mortensen and Llorca, 2010; Nan and Clarke, 1996; Van Der Giessen and Needleman, 1995) and have led to the development of novel composite micro-architectures (Habibi et al., 2010; Joshi and Ramesh, 2007; Ye et al., 2005). These investigations indicate that one has to judiciously choose appropriate values for the microstructural design degrees of freedom in imparting optimal functional characteristics to an MMC. To first order these may be restricted to only the grain size d_g, inclusion size d_i and its v.f., say f. Analytical and computational investigations have focused on implementing length-scales in the conventional plasticity theory based on the GND argument as applied to MMCs (e.g. Cleveringa et al., 1997; Dai et al., 2001; Han et al., 2005a,b; Joshi and Ramesh, 2007; Nan and Clarke, 1996; Suh et al., 2009; Xue et al., 2002; Zhou et al., 2010). Many of these ef-

* Corresponding author. Tel.: +65 6516 4496; fax: +65 6779 1459.
E-mail address: Shailendra@nus.edu.sg (S.P. Joshi).

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