Computational Materials Science 85 (2014) 200–205

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

A micromechanical model of particle-reinforced metal matrix composites considering particle size and damage

A. Abedini, Z.T. Chen *

Department of Mechanical Engineering, University of New Brunswick, Fredericton, NB E3B 5A3, Canada

ARTICLE INFO

Article history:
Received 19 August 2013
Received in revised form 7 December 2013
Accepted 9 January 2014
Available online 25 January 2014

Keywords:
Particle-reinforced composites
Homogenization
Nonlinear behavior
Size effects
Damage

ABSTRACT

The strengthening behavior of particle-reinforced metal matrix composites is mainly due to the load transfer and the dislocation strengthening effects. To account for both effects in a unified way a hybrid model is proposed by modifying the tangent-based homogenization method with incorporation of dislocation strengthening. By making use of this hybrid model, the nonlinear behavior of the composite in uniaxial tension is dependent on the particle size as well as particle volume fraction. In addition, in order to consider the influence of damage on the stress–strain behavior of the composites, a Weibull function for damage evolution is coupled with the hybrid model. The predictions of the aforementioned methods were compared with the experimental results from the literature, and good agreement was achieved.

1. Introduction

Particle-reinforced metal matrix composites (MMCs), like all composites, consist of at least two chemically and physically distinct phases, suitably distributed to provide properties not obtainable with either of the individual phases. The particle phase is distributed into a metallic phase which results in several advantages over the unreinforced matrix, such as higher strength-to-weight ratios, and higher elevated temperature stability [1].

The strengthening mechanism of particle-reinforced MMCs generally includes two types: direct strengthening and indirect strengthening. Direct strengthening results from the load transfer from the metallic matrix to the reinforcing particles due to the significantly higher stiffness of the reinforcement phase compared with that of the matrix. Indirect strengthening is due to the influence of particles on the microstructure of the matrix, which leads to dislocation strengthening.

To account for the load transfer effect, a number of modeling techniques have been proposed in the literature. In general, these continuum-based models rely on the equivalent inclusion method of Eshelby [2] and their mean-field extensions [3–5]. The tangent-based [6,7] and secant-based [8,9] homogenization approaches have been relatively successful in describing the nonlinear behavior of the composite materials. These models lead to a dependence of predicted material properties on volume fraction of particles. However, they fail to predict the influence of particle size on the overall behavior of the composites. This is attributed to the fact that these models do not inherently include an intrinsic length scale and therefore cannot accommodate size effects.

The second group of modeling strategies are dislocation-based [10–12] and strain gradient plasticity models [13–15]. Particle size dependence is incorporated in these methods, and indirect strengthening can be simulated. Nevertheless, these models lead to a relatively small increase in the flow stress in comparison with that observed in experiments owing to neglecting the load transfer strengthening of the composites [16].

Therefore, both continuum-based and dislocation-based models suffer from lack of incorporating some microstructural details, while experimental results [16–19] have shown that both volume fraction and size of the particles can have a strong influence on the mechanical behavior of the composites. In addition, these modeling techniques are based on damage free materials; therefore they neglect the influence of the damage evolution on the mechanical behavior of the composites.

Recently, some hybrid approaches [20–22] have been developed by combining a continuum approach with the key features of dislocation plasticity to address the size effect in composites. Nan and Clarke [20] extended the effective medium approach by introducing some of the key features of dislocation plasticity into the matrix stress–strain relation. Dai and Huang [21] developed a hybrid model by combining dislocation theories and their micromechanical method. Tohgo et al. [22] extended the incremental damage model of MMCs [23] by introducing the particle size effect using Nan-Clarke's method.

* Corresponding author. Tel.: +1 (506) 458 7784; fax: +1 (506) 453 5025.
E-mail address: ztchen@unb.ca (Z.T. Chen).

0927-0256/$ - see front matter
http://dx.doi.org/10.1016/j.commatsci.2014.01.012

The present paper attempts to present a hybrid model which combines a modified tangent-based method of homogenization and a dislocation plasticity method for an elasto-plastic metallic matrix reinforced with elastic, spherical particles. The model takes into account the nonlinear behavior of the material. The shortcoming of the inherent lack of a length scale is overcome by introducing dislocation plasticity into the stress–strain relation of the tangent-based model of the in situ matrix of the composite. Also a Weibull function is coupled with the hybrid model to incorporate the influence of the damage evolution of particle-reinforced MMCs. The results of this study can provide insight into optimizing the microstructure with particle size, and shed some light on the influence of damage evolution within the particles of MMCs.

2. Tangent-based method

An extension of homogenization models from linear plasticity to rate-independent nonlinear behavior of composites is provided by Hill's so-called incremental formulation [6]. In this method, the stress and strain rates of a composite are related by

$$\dot{\sigma} = \mathbf{C} : \dot{\varepsilon} \tag{1}$$

where σ and ε represent the volume averaged stress and strain, and $\mathbf{C}$ is the tangent stiffness tensor of the composite. Throughout this paper, bold letters refer to fourth-order tensors. Similar equations can be written for each of the phases as

$$\dot{\sigma}^M = \mathbf{C}^M : \dot{\varepsilon}^M \tag{2}$$

$$\dot{\sigma}^P = \mathbf{C}^P : \dot{\varepsilon}^P \tag{3}$$

in which superscripts "*M*" and "*P*" refer to matrix and inclusions respectively.

Eqs. (1)–(3) are similar to linear elasticity except that stress and strain rates are used as well as tangent operator, $\mathbf{C}$, which should not be confused with the elastic stiffness tensor.

The nonlinearity arises since the tangent stiffness tensor, $\mathbf{C}$, is a function of the instantaneous moduli of the phases and its computation requires an iterative algorithm. The algorithm starts with an initial partitioning of the phases according to the rule of mixtures. Having the initial strain increment for each phase, the stresses are updated and the corresponding moduli of the phases are determined. The next step is to calculate the stiffness tensor of the composite. To do so, a linear mean-field theory can be used to obtain the strain concentration tensor and overall stiffness tensor of the composite. In the present paper the Mori–Tanaka method [4] was used, which states that

$$\mathbf{C} = \mathbf{C}^M + f(\mathbf{C}^P - \mathbf{C}^M) : [\mathbf{I} + (1-f)\mathbf{S} : (\mathbf{C}^M)^{-1} : (\mathbf{C}^P - \mathbf{C}^M)]^{-1} \tag{4}$$

in which f is the volume fraction of particles, $\mathbf{I}$ is a fourth-order identity tensor, and $\mathbf{S}$ is the Eshelby's tensor [2]. Calculating the stiffness tensor of the composite results in new strain increments. The iteration continues until there is no change in the composite's stiffness tensor.

Incremental methods of this type tend to overestimate the macroscopic strain hardening in the plastic regime to such an extent that their applicability is rather limited. Recent developments have involved the use of tangent operators that reflect the macroscopic symmetry of the composite (e.g. isotropized operators) for statistically isotropic materials such as particle-reinforced composites [24]. These improvements have succeeded in markedly reducing the over prediction of the strain hardening behavior of the incremental method.

The present work adopts the modified tangent-based formulation of Doghri and Ouaar [24] who employed algorithmic tangent operators everywhere in the model except for the computation of the Eshelby tensor. Interested readers are encouraged to see Doghri and Ouaar [24] and Perdahcioglu and Geijselaers [25] for more details on the implementation of this method.

3. Effects of particle size

In order to consider the effects of particle size, it is necessary to consider how the matrix work-hardens. When a material is deformed, dislocations are generated, moved and stored. The storage of dislocations causes the material to work-harden. In particle-reinforced composites, dislocations become stored for two reasons; they accumulate by trapping each other, or they are required for the compatible deformation of various parts of the material [10].

The present study incorporates the particle size effects by using the Nan and Clarke [20] method. In the plastic region, the modified flow stress of the matrix, σ_y^M can be obtained by

$$\sigma_y^M = \sigma_{y_o}^M + \Delta\sigma_y^M \tag{5}$$

where $\sigma_{y_0}^M$ is the flow stress of the unreinforced matrix and $\Delta\sigma_y^M$ is the dislocation strengthening effect due to the presence of particles. The current work neglects the strengthening due to thermal expansion mismatch. Therefore, the dislocation strengthening effect can be determined as [20]

$$(\Delta\sigma_y^M)^2 = (\Delta\sigma_{OR}^M + \Delta\sigma_{KIN}^M)^2 + (\Delta\sigma_{ISO}^M)^2 \tag{6}$$

where $\Delta\sigma_{OR}^M$ is the strengthening caused by the resistance of closely spaced hard particles to the passing of dislocations, known as the Orowan stress. It can be obtained by

$$\Delta\sigma_{OR}^M = \alpha\frac{\mu^M b}{L} \tag{7}$$

where α is a constant giving the obstacle strength, μ^M is the elastic shear modulus of the matrix, b is Burger's vector of the metallic matrix, and L is the mean particle spacing, which is related to the particle size and volume fraction by

$$L = \left(\frac{\pi d^2}{4f}\right)^{\frac{1}{2}} \tag{8}$$

here d is the particle diameter. The second and third terms in Eq. (6) are those due to geometrically necessary dislocations required to accommodate the plastic strain mismatch between the particles and matrix. These isotropic and kinematic strain gradient contributions are written as

$$\Delta\sigma_{ISO}^M = \beta\mu^M\sqrt{\frac{f\varepsilon_p b}{d}} \tag{9}$$

$$\Delta\sigma_{KIN}^M = \gamma\mu^M f\sqrt{\frac{\varepsilon_p b}{d}} \tag{10}$$

where β and γ are two geometric constant factors which are related to the crystal structure of the metal (i.e. fcc, bcc, etc.), and ε_p is the plastic strain of the matrix. At each increment of the tangent-based method, the matrix flow stress is replaced with the modified flow stress of Eq. (5) to account for dislocation plasticity effects. This provides particle size dependence for the calculated mechanical behavior of the composite.

4. Effects of particle fracture

Internal damage exerts a strong influence on the ductility of particle-reinforced metal matrix composites. The high content of particles in these composites strongly influences the overall properties of the composite through a reinforcing effect due to intact particles and a weakening effect due to damaged particles. Damage