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An enhanced FEM model for particle size dependent flow strengthening and interface damage in particle reinforced metal matrix composites

J.C. Shao, B.L. Xiao, Q.Z. Wang, Z.Y. Ma *, K. Yang

Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, China

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ABSTRACT

By incorporating the dislocation punched zone model, the Taylor-based nonlocal theory of plasticity, and the cohesive zone model into the axisymmetric unit cell model, an enhanced FEM model is proposed in this paper to investigate the particle size dependent flow strengthening and interface damage in the particle reinforced metal matrix composites. The dislocation punched zone around a particle in the composite matrix is defined to consider the effect of geometrically necessary dislocations developed through a mismatch in the coefficients of the thermal expansion. The Taylor-based nonlocal theory of plasticity is applied to account for the effect of plastic strain gradient which produces geometrically necessary dislocations due to the geometrical mismatch between the matrix and the particle. The cohesive zone model is used to consider the effect of interfacial debonding. Lloyd's experimental data are used to verify this enhanced FEM model. In order to demonstrate flow strengthening mechanisms of the present model, we present the computational results of other different models and evaluate the strengthening effects of those models by comparison. Finally, the limitations of present model are pointed out for further development.

1. Introduction

Particle reinforced metal matrix composites (MMC_P) are of interest for a variety of industrial applications due to their higher stiffness and strength than the matrix alloys. Deep understanding of the strengthening behavior of the MMC_P is a critical issue in development of those materials [1,2]. Experimental observations [1] indicated that the fine particles yielded the increasing strengthening and hardening effects. The continuum models [3,4] based on the classical plasticity theories could explain the load transfer effect from the composite matrix to the reinforcing particle and successfully predict the plastic work hardening behavior of the MMC_P depending on the particle volume fraction and other nondimensional parameters (e.g. particle aspect ratio), but they all failed to explain the particle size dependent strengthening since their constitutive laws possessed no intrinsic material lengths.

In order to explain the particle size effects on the flow strengthening of the MMC_P, a lot of dislocation models have been proposed in the past few decades [5–15]. A number of dislocation punching models [5–10] have been proposed to interpret and predict the observed particle size dependent strengthening of the MMC_P after quenching. Arsenault and Shi [6] proposed a prismatic dislocation punching model to calculate the strengthening which considered the enhanced density of geometrically necessary dislocations (GNDs) resulting from the coefficient of thermal expansion (CTE) mismatch due to quenching. Base on the work of Taya et al. [7], Dunand and Mortensen [8], Shibata et al. [9], and Suh et al. [10] presented an enhanced continuum model for the size dependent strengthening and failure of the MMC_P by defining a CTE mismatch induced GNDs punched zone around the particle and using the cohesive surface model. Except for the dislocation punching models, many researchers introduced particle size effects into the various continuum models by incorporating dislocation plasticity to alter the flow stress in the composite matrix, which achieved good results [11–15]. Nan and Clarke [12] extended the effective medium approach (EMA) by introducing some of the key features of dislocation plasticity into the stress–strain relation of composite matrix. Dai et al. [13] developed a hybrid micromechanical approach by combining the GNDs model with the incremental micromechanical scheme. Tohgo et al. [15] extended the incremental damage model of the MMC_P by introducing the particle size effects using Nan–Clarke's simple method.

Based on the notion of GNDs induced by the geometrical mismatch between the matrix and the particle, strain gradient plasticity theories [16–22] have been developed in order to characterize the particle size dependent strengthening of the MMC_P. Gao et al. [16] proposed a mechanism-based theory of strain gradient plasticity (MSG) to account for the plastic strain gradient in the MMC_P. Gao and Huang [17] developed a Taylor-based nonlocal theory

* Corresponding author. Tel./fax: +86 24 83978908.
E-mail address: zyma@imr.ac.cn (Z.Y. Ma).

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(TNT) of plasticity which was more direct and simple than other gradient plasticity theories. Huang et al. [20] established a conventional theory of mechanism-based strain gradient plasticity (CMSG) to account for particle size effects, and Qu et al. [21] extended the CMSG by including the effects of quenching hardening and accounted for the particle/matrix interfacial debonding via the cohesive zone model.

Based on the summary of previous works, in this paper we consider the following mechanisms responsible for the particle size dependent flow strengthening and interface damage of the MMC_P and construct an enhanced FEM model:

(1) CTE mismatch induced GNDs are not counted as part of the background dislocation density distributed over the entire composite matrix volume but as a dislocation punched zone around the particle;
(2) Taylor-based nonlocal theory of plasticity is used to account for the plastic strain gradient which produces GNDs due to the geometrical mismatch between the matrix and the particle when the MMC_P is plastically deformed;
(3) An axisymmetric unit cell model containing three zones with an imperfect particle/matrix interface (through cohesive zone model) is employed to represent the representative cell of the MMC_P with a regular array of spherical particle.

2. Dislocation strengthening behavior in the MMC_P

It has been proposed by Ashby [5] that there are two possible sources of the GNDs. The first is the CTE mismatch between particle and matrix induced GNDs when the composite is cooled down from the processing temperature. The second is the geometrical mismatch, i.e. it is a result of the deformation-induced plastic strain gradient that arises when the composite is plastically deformed. Here, we consider that the strengthening effects include both the CTE mismatch induced GNDs and the geometrical mismatch induced GNDs as follows.

2.1. Enhancement due to CTE mismatch induced GNDs

In order to illustrate the strengthening effect of CTE mismatch induced GNDs, Taya et al. [7] proposed a dislocation punching mechanism which was schematically illustrated in Fig. 1a–c. According to their theory, the temperature change induced CTE mismatch strain can be represented by arrays of prismatic dislocation loops adhered uniformly to the matrix–particle interface before punching (Fig. 1b). When the thermal stress exceeds the yield strength of the composite matrix, these dislocation loops near the interface are punched out into the composite matrix with a punching distance R to relax the thermal stress and form a dislocation punched zone in the composite matrix, as illustrated in Fig. 1c.

2.1.1. Size of the dislocation punched zone

In order to determine the size of the dislocation punched zone, Shibata et al. [9] calculated the punching distance of the CTE mismatch induced GNDs using a combined plastic energy dissipation and Eshelby theory, accounting for the effect of particle volume fraction. Adopting the approach in Ref. [9], the punching distance R, which stands for the size of the dislocation punched zone from the center of the spherical shape particle, is:

$$R = r\left\{\frac{B(1-2Pf)+\sqrt{B^2(1-2Pf)^2+16(\tau_{ym}/G_m)PB}}{4(\tau_{ym}/G_m)}\right\}^{\frac{1}{3}} \tag{1}$$

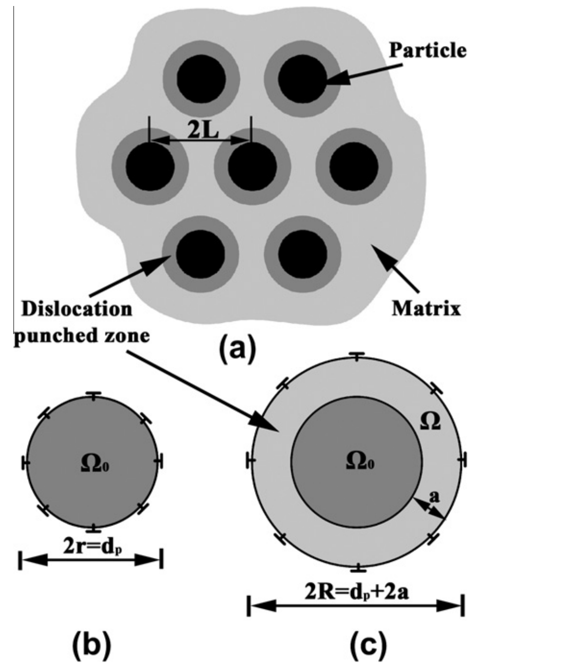

Fig. 1. (a) Schematic illustration of distribution of dislocation punched zones around individual particles [7,10]. (b) CTE mismatch induced arrays of prismatic dislocation loops adhered uniformly to the matrix–particle interface before punching. (c) Punched zone corresponding to equilibrium of punched dislocations after punching.

where f is the particle volume fraction and r is the particle radius. The coefficients B and P are determined from the elastic coefficients and the thermal mismatch as:

$$B = \frac{(1+\nu_m)|\Delta CTE \cdot \Delta T|}{(1-\nu_m)} \tag{2}$$

$$P = \frac{2(1-\nu_m)(3\bar{\lambda}+2\bar{G})}{(1-\nu_m)\{(1-f)(3\bar{\lambda}+2\bar{G})(\frac{1+\nu_m}{1-\nu_m})+3[f(3\lambda_p+2G_p)+(1-f)(3\lambda_m+2G_m)]\}} \tag{3}$$

Here subscripts "m" and "p" stand for the matrix and particle, respectively. In Eqs. (1)–(3), ΔCTE is the difference in the CTE between the matrix and the particle, ΔT is the temperature change, τ_{ym} is the shear yield strength of the matrix, which can be identified as the frictional stress for the glide motion of dislocations, and is assumed to be constant without considering the work hardening effect [9], G is the shear modulus, ν is the Poisson's ratio, and $\bar{\lambda}=\lambda_p-\lambda_m$ and $\bar{G}=G_p-G_m$ are the mismatches of the Lame constants.

It should be noted that there is an upper bound on the punching distance R to be determined geometrically by the condition of $R \leqslant L$ (where $2L$ is the interparticle distance). When the CTE mismatch strain is sufficiently large leading to $R > L$, the dislocation punched zone boundary of a particle touches that of the neighboring particle and the GNDs from a particle annihilate those generated by its neighboring particle. This may be realized in special cases, e.g., a high volume fraction of particle (>20%) or a local-cluster distribution.

2.1.2. Flow strengthening due to dislocation punching

The enhanced density of the CTE mismatch induced GNDs (ρ_{GNDs}^{CTE}) is estimated as the total length of punched prismatic dislocation loops that are needed to relieve the thermal mismatch strain in simple configurations divided by the punched zone volume size a, bounded by an outer radius R (the punching distance calculated