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A STRAIN GRADIENT-STRENGTHENING LAW FOR PARTICLE REINFORCED METAL MATRIX COMPOSITES

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Introduction

Particle-reinforced metal matrix composites (MMCp) are promising candidates for a number of aerospace and automotive applications due to their higher specific stiffness and specific strength and better wear resistance. It is well known that the mechanical behavior of this class of materials is significantly affected by their microstructures. During the past several decades, many attempts have been made to explore the relationship between microstructure and deformation behavior in MMCp. Continuum models including the cell model [1,2], the modified shear lag theory [3] and the homogenization models [4] lead to a dependence of flow stress on volume fraction of reinforcing particles but not on particle size. Current experimental results, however, have demonstrated that both particle size and volume fraction exert influence [5–8]. Conversely, dislocation models predict both reinforcement volume fraction and particle size effects on strengthening behavior of MMCp [9–10], however, there is no consensus on the strengthening mechanism responsible for the observed strength increase with decreased particle size. In order to explain the size effect in materials, some phenomenological strain gradient plasticity theories were developed by Fleck *et al.* [11,12]. Very recently, Nix and Gao [13] proposed a new strain gradient plasticity theory. Dissimilar to the phenomenological theory, the length scale involved in N-G theory [13] is naturally introduced from the indentation experimental results and Taylor relation. Furthermore, such a length scale has been proven to be related to the real microstructural dimension of crystalline materials. Therefore, the N-G theory is of solid physical basis. Although the strain gradient theory gives a reasonable prediction of mechanical behavior-size effects for monolithic-phase metal materials, nevertheless, how to understand the reinforcement size effect in two-phase MMCp is still open.

In view of the aforementioned observations, a strain gradient strengthening law is developed in the present work, in which the role of Ashby's [14] geometrically-necessary dislocation idea is emphasized. From this law, the essence of the strengthening-particle size effect in MMCp is clearly revealed.

Experimental

In order to investigate the particle size effect, a series of uniaxial compression tests of 2124Al and 17% vol. SiCp/2124Al composites with average particle sizes of 3, 13, and 37μm were carried out by Ling *et al.* [5,6]. We refer to [5,6] for details. The experimental results display a pronounced increase in yield

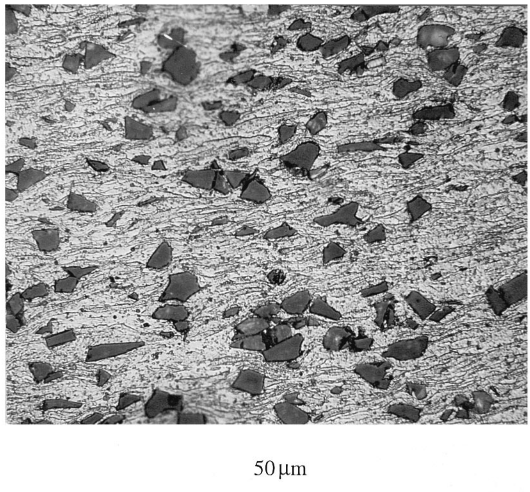

Figure 1. Nonhomogeneous plastic deformation pattern in 13 μm-SiCp/2124 Al composite under uniaxial compressive loading.

and flow stresses of the composites with decreased particle size. Microscopic observations on the longitudinal sections cut from the loaded-specimens present inhomogeneous plastic deformation patterns in MCCp, as shown in Fig. 1. Obviously, the dependence of macromechanical behavior of MMCp on particle size is closely related to such inhomogeneous plastic deformation.

Dislocation Model

In general, dislocations stored in metals during straining can be divided into two kinds: geometrically necessary dislocations and statistically-stored dislocations. Ashby [14] found that the size effect for metals is only controlled by the geometrically necessary dislocations required for the compatible deformation of various parts in materials. The experimental results of Fleck *et al*. [11] have demonstrated that monolithic metals subjected to uniform loading display no the mechanical behavior-size effect. However, this is not the case for two-phase MMCp due to the elastic modulus mismatch between the particle and the matrix. So, in this paper, we adopt the idea of geometrically necessary dislocation and Taylor relation, as Nix and Gao [13] did for indentation study, to examine the strengthening effect of a two-phase MMCp.

Consider an MMCp subjected to a compressive loading, as is shown in Fig. 2a. Subscripts “m,” “p,” and “c” stand for the matrix, the particle and the composite respectively. To determine the geometrically necessary dislocation density, an idea similar to Eshelby’s equivalent inclusion principle [15] is adopted. Firstly, imagine all particles in MMCp sample of Fig. 2a are replaced by the matrix material, thus particles turning into “matrix spheres.” So, the whole body of this “matrix sample” will experience a uniform deformation ϵ when the sample is subjected to a uniform compressive loading. In this case, those “matrix spheres” will be distorted into “matrix ellipsoids.” However, in the real MMCp sample such a distortion will not be allowed to take place because of the existence of the reinforcing particles. Hence, a lot of geometrically necessary dislocations must be stored near the surfaces of particles for accommodating this distortion deformation (Fig. 2b). According to the deformation-geometry condition, the number of the geometrically necessary dislocation loops imposed on the surfaces of particles to accommodate the mismatch of plastic deformation n is given by

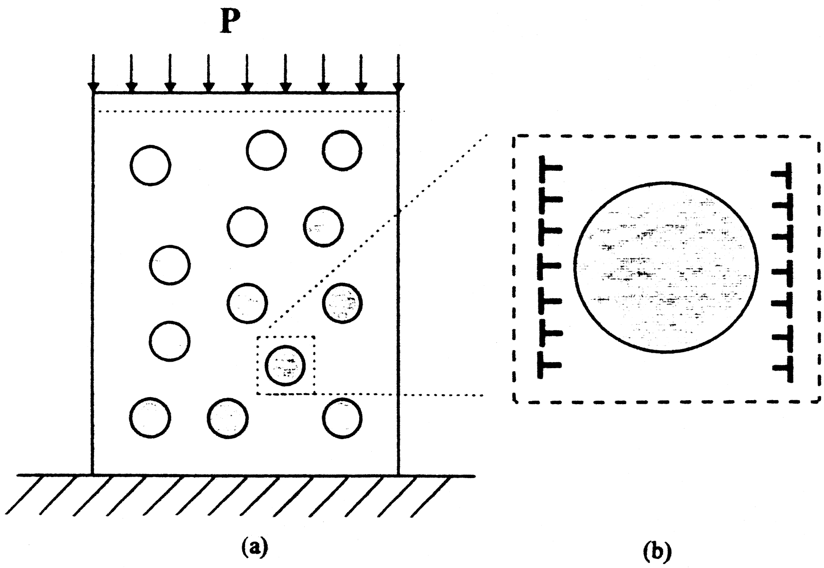

Figure 2. Configuration and dislocation model for particle reinforced metal matrix composite under compressive loading: (a) configuration; (b) dislocation model.

$$nb = \xi \varepsilon d_p \tag{1}$$

where b is Burges vector, ξ is a dimensionless geometric parameter, d_p is the diameter of particles. Assume the volume fraction of particles is denoted by f_p, then the total number of particles N_p is

$$N_p = \frac{6f_p}{\pi d_p} \tag{2}$$

If the length for each dislocation loop is taken as πd_p, then the geometrically necessary dislocation density ρ_G is

$$\rho_G = \frac{3\xi\varepsilon}{b\lambda_G} \tag{3}$$

where $\lambda_G = d_p/2f_p$ is the geometrical slip distance [14]. It is found from this equation that the dislocation loop density to accommodate the deformation mismatch for the small particle is higher than that for the large particle.

Strain Gradient-Strengthening Law

Assume the strengthening for MMCp is mainly attributed to the deformation resistance induced by the reinforcing particle. According to Taylor relation, the flow stress of MMCp is written as

$$\sigma_c = \sqrt{3}\alpha b \mu_m \sqrt{\rho_T} = \sqrt{3}\alpha b \mu_m \sqrt{\rho_S + \rho_G} \tag{4}$$

where ρ_T is the total dislocation density, ρ_S is the statistically-stored dislocation density, μ_m is the shear modulus of the matrix material and α is a dimensionless parameter. The flow stress for the unreinforced matrix is

TABLE 1
Comparison of the Flow Stresses for $13\mu m$-SiCp/2124Al Composite with the Corresponding Experimental Results [2]

	$\varepsilon = 0.02$	$\varepsilon = 0.10$	$\varepsilon = 0.20$	$\varepsilon = 0.30$	$\varepsilon = 0.40$
Experimental σ_{sh} (MPa)	457	686	843	982	1130
Calculated σ_{th} (MPa)	404	618	752	868	971
$\frac{\sigma_{sh}-\sigma_{th}}{\sigma_{sh}} \times 100\%$	11.6	9.9	10.8	11.6	13.5

$$\sigma_m = \sqrt{3}\alpha b \mu_m \sqrt{\rho_S} \tag{5}$$

Suppose the deformation of the hard reinforcing particle can be neglected. Define the average strain gradient of the matrix by

$$\chi_m = \frac{\varepsilon}{\lambda_p} \tag{6}$$

where λ_p is the average edge-edge spacing between particles and is given by [9]

$$\lambda_p = \frac{1}{2}d_p\left(\sqrt{\frac{2\pi}{3f_p}} - \frac{4}{\pi}\right) \tag{7}$$

From (3) ~ (7), we obtain the following strain gradient-strengthening law for MMCp:

$$\left(\frac{\sigma_c}{\sigma_m}\right)^2 = 1 + \beta b \frac{\lambda_p}{\lambda_G}\left(\frac{\mu_m}{\sigma_m}\right)^2 \chi_m \tag{8}$$

where the constant factor $\beta = 9\alpha^2\xi$. Now, define a characteristic microstructural scale $\widehat{l}$ by:

$$\widehat{l} = b\frac{\lambda_p}{\lambda_G}\left(\frac{\mu_m}{\sigma_m}\right)^2 \tag{9}$$

Combining (8) with (9) leads to

$$\left(\frac{\sigma_c}{\sigma_m}\right)^2 = 1 + \beta \widehat{l} \chi_m \tag{10}$$

Eq.(10) appears to be similar to that obtained by Nix and Gao [13] for indentation. However, here, the strengthening effect of the two-phase MMCp is straightforwardly and clearly related to the average strain gradient of matrix as well as the reinforcing particle size.

It is seen from this strain gradient-strengthening law that the strengthening (σ_c/σ_m) is controlled by both the matrix average strain gradient χ_m and the characteristic microstructural scale $\widehat{l}$. For an MMCp with fixed volume fraction of the particle, the strengthening for the composite is completely determined by the particle size, namely, the smaller the particle size, the higher the strengthening effect. This is qualitatively in accordance with the available experimental results [5–8].

To verify the aforementioned model, we make a comparison with the experimental results presented in [5,6]. Firstly, the factor $\eta(\epsilon) = \beta\widehat{l}$ is determined by making use of the experimental data of 2124Al and $3\mu m$-SiCp/2124Al composite. Then, the flow stresses of $13\mu m$-SiCp/2124Al and $37\mu m$-SiCp/2124Al composites at five straining points are calculated by equation (10). Table 1 and Table 2 present a comparison of the calculated flow stresses with the corresponding experimental results respectively

TABLE 2
Comparison of the Flow Stresses for 37 μm-SiCp/2124Al Composite with the Corresponding Experimental Results [2]

	$\varepsilon = 0.02$	$\varepsilon = 0.10$	$\varepsilon = 0.20$	$\varepsilon = 0.30$	$\varepsilon = 0.40$
Experimental σ_{sh} (MPa)	444	661	764	889	1056
Calculated σ_{th} (MPa)	378	583	721	831	914
$\frac{\sigma_{sh}-\sigma_{th}}{\sigma_{sh}} \times 100\%$	14.8	11.8	5.6	6.5	13.4

for 13μm-SiCp/2124Al and 37μm-SiCp/2124Al composites. From Tables 1 and 2, we can see that the results from the model are lower than those from the experiment, the relative errors at all straining points are less than 15%. The relative low predicted values may be due to the fact that some other secondary contributions to the strengthening, namely, the strain rate-size effect, the thermal mismatch between the particle and the matrix, are not incorporated into the model. In spite of this, it is seen from the comparison that the theoretical results are in accordance with the experimental ones on the whole.

Discussion

Now, turning back to equation (10) for discussing the possible physical significance implicated in it. From (10), one can see that the characteristic microstructural scale $\widehat{l}$ plays an important role in the strengthening for MMCp. If the strain gradient in the matrix is fixed, the larger the characteristic microstructural scale $\widehat{l}$, the higher the strengthening effect. It is easily found that $\widehat{l}$ is irreverent of the particle size if the volume fraction of particle keeps fixed. However, $\widehat{l}$ is not a material constant and depends on the deformation state of the matrix. Figs. 3 and 4 present the variations of $\widehat{l}$ with the volume fraction of particle and the matrix flow stress, respectively. From Fig. 3, one can see that there is a characteristic volume fraction $\tilde{f}_p$ which corresponds to the peak $\widehat{l} = \widehat{l}_{\max}$ under various deformation states. Since the strengthening for MMCp is controlled by $\widehat{l}$ and χ_m, and the strengthening of MMCp increases monotonously with f_p increasing, Fig. 3 tells us, at least, that the strain gradient effect (size effect) is especially remarkable for the case of high concentration of particle. This is qualitatively in accordance with the experimental observation by Hunt *et al.* [8]

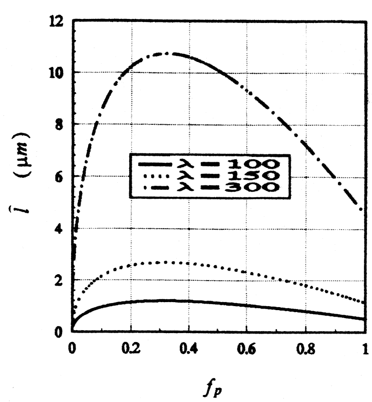

Figure 3. Variations of characteristic scale with particle volume fraction ($\lambda = \mu_m/\sigma_m$).

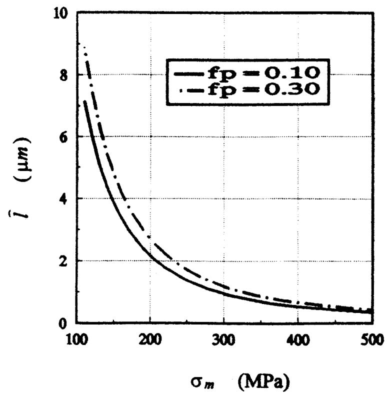

Figure 4. Variations of characteristic scale with the matrix flow stress.

Moreover, from Fig. 4 one can see that $\hat{l}$ decreases in the course of the matrix work hardening. This indicates that the strain gradient effect in the latter stage of the deformation is higher than that in the initial stage. When the flow localization occurs in the metal matrix, i.e., the matrix becomes soft, $\hat{l}$ becomes large once more, thus leading to higher resistance to the flow localization. Therefore, filling the metal matrix with hard particles can not only enhance the flow strength but also resist the flow localization.

Conclusions

Based on a simple geometrically necessary dislocation model, a strain gradient-strengthening law for MMCp is developed in this paper. From this law, one can see that the strengthening in MMCp is controlled by both the characteristic microstructural scale and the strain gradient of the matrix. Further, the particle size effect should be included in the strain gradient effect. This means that the strain gradient effect may be an important factor controlling the deformation and fracture behavior in MMCp.

Acknowledgments

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