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Strain Gradient Effect on Initiation of Adiabatic Shear Localization in Metal Matrix Composites

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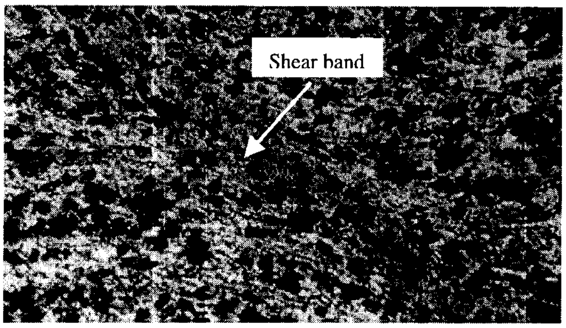
ABSTRACT

In this paper, the strain gradient effect on the initiation of adiabatic shear localization in particle reinforced metal matrix composites (MMCp) is investigated. By incorporating our newly developed strain gradient law into the classical scheme of the stability analysis, the analytical form of the critical strain is determined. The results demonstrate that high strain gradient in the matrix provides a strong driving force for the initiation of adiabatic shear localization in MMCp.

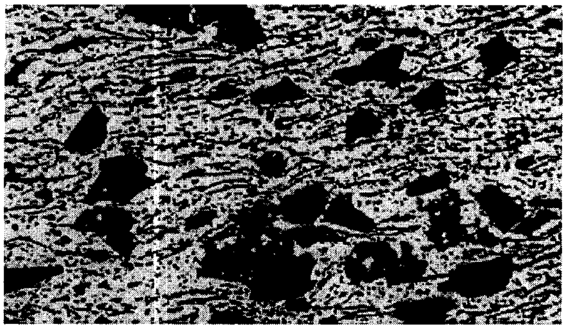
1. INTRODUCTION

Adiabatic shear localization in the form of shear bands is one particular kind of microdamage in materials at high strain rates. Shear bands are usually the precursors of ductile failure. Therefore, an in-depth understanding in adiabatic shear localization is of great practical interest. During the past several decades, extensive research activities have been made to explore the formation and evolution of shear bands [1-8]. The primary mechanism for shear bands formation is the thermo-mechanical mechanism. Due to interactions of microstructures of materials, the initial uniform pattern of plastic deformation may be broken down into nonuniform one. At high strain rate of loading, this nonuniform deformation will induce local intensive heating which in turn leads to material softening so that the localized deformation bands are finally formed. Bai and Dodd [9] recently presented a review of the different mechanisms proposed for the analysis of shear bands as it is observed in different materials and loading conditions.

For particle reinforced metal matrix composites (MMCp), recent experimental investigations made by Ling *et al* [10-11] have demonstrated that the initiation of adiabatic shear bands depend strongly on the reinforcing particle size. Apparently, the previous deformation localization theories, which were based on the conventional plasticity theory, can not capture such a size effect. To clarify the size dependency, the strain gradient term is required to be incorporated into the constitutive equation of materials. In this paper, the strain gradient effect on the initiation of adiabatic shear localization in MMCp is addressed by making use of a mechanism-based strain gradient law which was recently developed by Dai *et al* [12].



(a) $d_p = 3\,\mu\text{m}$



(b) $d_p = 13\,\mu\text{m}$

(c) $d_p = 37\,\mu\text{m}$

Fig.1 SEM pictures of deformation patterns in SiCp/2124 Al composite materials under dynamic compression [11]

2. EXPERIMENTAL OBSERVATIONS

To investigate the particle size effect on the initiation of the adiabatic shear bands, a series of impact compression tests of 17%vol. SiCp/2124 Al particulate composites with average particle diameter of 3,13, and 37 μm were carried out recently by Ling *et al* [10-11]. The experimental results have demonstrated that shear bands and localized deformation in MMCp reinforced with small particles (3 μm) are more readily observed than those in MMCp with larger SiC particles for fixed particle volume fraction, which is shown in Fig. 1. A question naturally arises: what is the physical origin of this size-dependent behavior ? From Fig.1, the nonuniform plastic deformation in the matrix regions between particles is observed clearly. Apparently, the size-dependent deformation localization behavior is closely related to such nonuniform plastic deformation pattern.

3. GRADEINT DEPENDENT CONSTITUTIVE BEHAVIOR

For a two-phase MMCp subjected to a compressive loading, a certain number of geometrically necessary dislocations are generated to accommodate the distortion deformation resulted from the elastic modulus mismatch between the phases in the composite. According to the deformation condition, the density of the geometrically necessary dislocation in the composite is obtained as

$$\rho_G = \frac{3\varepsilon}{b\lambda_G} \tag{1}$$

where ε is macroscopic strain and $\lambda_G = d_p / 2f_p$ is the geometrical slip distance, with d_p and f_p being the diameter and the volume fraction of the reinforcing particles respectively.

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

$$\sigma_c = \sqrt{3}\alpha b \mu_m \sqrt{\rho_T} = \sqrt{3}\alpha b \mu_m \sqrt{\rho_S + \rho_G} \tag{2}$$

where ρ_T is the total dislocation density, ρ_S the statistically stored dislocation density, μ_m the shear modulus of the matrix material and α is a dimensionless parameter. Combining Eq. (1) with Eq. (2) yields the following strain gradient-strengthening law [12]:

$$(\frac{\sigma_c}{\sigma_m})^2 = 1 + l\eta \tag{3}$$

where $\eta \equiv \varepsilon / \lambda_p$ is strain gradient, σ_m is the flow stress of the unreinforced matrix, with λ_p being the average edge-edge spacing between particles. While l is the characteristic microstructural length scale and defined by

$$l = \beta b \frac{\lambda_p}{\lambda_G} (\frac{\mu_m}{\sigma_m})^2 \tag{4}$$

where the constant factor $\beta = 9\alpha^2$. Eq. (3) 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 strain gradient and 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 strain gradient η and the characteristic microstructural length scale l. For MMCp with a fixed volume fraction of the reinforcing particle, the strengthening 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 [10-11].

Under dynamic loading, high strain gradients are initiated in MMCp which are accompanied by a change in temperature due to the adiabatic character of high rate of deformation processes. In order to investigate the size-thermomechanical behavior, the strain gradient term should be incorporated into the conventional constitutive equation. This can be realized by making use of the aforementioned strain gradient strengthening law (Eq. (3)). We assume the metal matrix is a gradient-independent viscoplastic material. One of the most widely used empirical constitutive equations for this class of materials is as follows

$$\sigma_m = g_1(\theta)g_2(\varepsilon)g_3(\dot{\varepsilon}) \tag{5}$$

Combining Eq. (3) with Eq. (5) suggests the following strain gradient-dependent constitutive equation for MMCp :

$$\sigma_c = f_1(\theta)f_2(\varepsilon)f_3(\dot{\varepsilon})f_4(\eta) \tag{6}$$

where $f_4(\eta)$ is defined by

$$f_4(\eta) = (1 + l\eta)^{1/2} \tag{7}$$

It is noted that incorporating the strain gradient term into the conventional constitutive equation in our present approach is based on the deformation mechanism and dislocation model, instead of adopting some phenomenological assumptions [14-15]. Therefore, the strain gradient effect or size effect on deformation behavior of two-phase MMCp can be investigated with this gradient-dependent constitutive equation.

4. STRAIN GRADIENT EFFECT

In this section, we investigate the strain gradient effect on the initiation of adiabatic shear localization. The strain gradient constitutive equation (6) is revised as the following form:

$$\tau = f_1(\theta)f_2(\gamma)f_3(\dot{\gamma})f_4(\eta) \tag{8}$$

where τ, γ, η and θ are shear stress, shear strain , shear strain gradient and temperature respectively. The adiabatic shear localization forms along the direction of the maximal shear stress, the stability condition for the maximal shear stress leads to:

$$d\tau/d\gamma = 0 \tag{9}$$

By differentiating (8), Eq. (9) can be written as

$$\frac{d\tau}{d\gamma} = \frac{\partial\tau}{\partial\theta}\frac{d\theta}{d\gamma} + \frac{\partial\tau}{\partial\gamma} + \frac{\partial\tau}{\partial\dot{\gamma}}\frac{d\dot{\gamma}}{d\gamma} + \frac{\partial\tau}{\partial\eta}\frac{d\eta}{d\gamma} = 0 \tag{10}$$

As a preliminary attempt, we consider a specific process that the adiabatic shear deformation is at constant strain rate and strain gradient. In this case, equation (10) reduces to

$$\frac{d\tau}{d\gamma}=\frac{\partial\tau}{\partial\theta}\frac{d\theta}{d\gamma}+\frac{\partial\tau}{\partial\gamma}=0 \tag{11}$$

For adiabatic deformation, the increase in temperature due to the plastic work is

$$\rho c d\theta=\xi\tau d\gamma \tag{12}$$

where ρ, c and ξ are the material density, the specific heat and the fraction of plastic work converted into heat, respectively. Therefore,

$$\frac{d\theta}{d\gamma}=\frac{\xi f_1(\theta)f_2(\gamma)f_3(\dot\gamma)f_4(\eta)}{\rho c} \tag{13}$$

Since only $f_2(\gamma_c)$ depends on the critical strain, it can be expressed in an explicit form

$$f_2(\gamma_c)=\left[-\frac{(\partial f_2/\partial\gamma)\rho c}{(\partial f_1/\partial\theta)\xi f_3(\dot\gamma)f_4(\eta)}\right]^{1/2} \tag{14}$$

Analytical solution for γ_c is possible to be obtained for some simple constitutive equations, for example

$$\tau=A\gamma^n\dot\gamma^m\theta^{-v}(1+l\eta)^\lambda \tag{15}$$

Then the explicit expression for the critical strain γ_c is given by

$$\gamma_c=\left[\frac{n\rho c}{\xi v\dot\gamma^m(1+l\eta)^\lambda}\right]^{\frac{1}{n+1}}\theta^{\frac{v+1}{n+1}} \tag{16}$$

Existence of the real $f_2(\gamma_c)$ is only possible if the expression inside the square brackets in Eq. (14) is positive. Since ρ, c and ξ are always positive and the functions of strain rate and strain gradient are also assumed to be positive, the only term which may be negative is $(\partial f_2/\partial\gamma)/(\partial f_1/\partial\theta)$. The most common case is the thermal softening which leads to negative value of $(\partial f_1/\partial\theta)$, if $(\partial f_2/\partial\gamma)$ is positive at the same time. If $f_3(\dot\gamma)$ is an increasing function of the strain rate, the positive rate sensitivity has a negative effect on onset of adiabatic shear instability.

On the other hand, we know $f_4(\eta)$ is an increasing function of the strain gradient according to Eq. (7). The effect of the strain gradient on the initiation of adiabatic localization can be seen clearly from Eq. (16), namely, the critical strain γ_c is decreased when the strain gradient is increased. This means that high strain gradient provides a strong driving force for the onset of localization. For MMCp, the strain gradient in the composite with small particles is higher than in the composite with large particles. Therefore, the adiabatic shear localization in MMCp with small particles is more prone to occur than in MMCp with large particles. Recent experiments carried out by Ling *et al* [10-11] have demonstrated that adiabatic shear bands and localized deformation in MMCp reinforced with small particles ($3\mu m$) are more readily observed than those in MMCp with larger SiC particles under the identical loading condition (as is show in Fig. 1). Our present theory gives a reasonable explanation for Ling's experimental phenomena.

5. CONCLUSIONS

By incorporating a strain gradient law into the conventional scheme of stability analysis, the analytical form of the critical strain is derived. We find that the essence of the particle size effect is characterized by the strain gradient effect and the smaller in particle size, the higher in the strain gradient induced in the matrix. The analytical results demonstrate that the initiation of adiabatic shear localization in MMCp with small particles is more prone to occur than in MMCp with large particles. This indicates that high strain gradient in the matrix will provide a strong deriving force for onset of adiabatic shear localization in MMCp.

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