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Onset of Adiabatic Shear Instability in Strain Gradient Dependent Metal Matrix Composites

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Abstract

In this paper, effect of strain gradient on adiabatic shear instability in particle reinforced metal matrix composites is investigated by making use of the strain gradient dependent constitutive equation developed by Dai *et al.* [9] and the linear perturbation analysis presented by Bai [10]. The results have shown that the onset of adiabatic shear instability in metal matrix composites reinforced with small particles is more prone to occur than in the composites reinforced with large particles. This means that the strain gradient provides a strong deriving force for onset of adiabatic shear instability in metal matrix composites.

Keywords: strain gradient, adiabatic shear localization, metal matrix composites

1 Introduction

Adiabatic shear bands are commonly observed during the high strain rate plastic deformation of various materials, arising in such situations as impact of projectiles and vehicles, high speed materials processing and forming. During past several decades, extensive research activities have been made to explore the formation and evolution of adiabatic shear localization in monolithic materials[1-3]. It is widely recognized that the primary mechanism for adiabatic shear localization formation is the thermoplastic instability mechanism. Due to interactions of microstructures of materials, the initial uniform plastic deformation may become inhomogeneous. At high loading rates, the lack of time for global heat conduction combined with inhomogeneous plastic deformation induce inhomogeneous heating which in turn leads to local material softening and additional plastic deformation so that localized shear bands are finally formed. Under favorable conditions, the formation of shear bands is often followed by ductile fracture. Hence, an in-depth understanding in the mechanisms leading to the formation and development of adiabatic shear instability is of great practical interest.

It is well known that the microstructures of materials have a significant influence on the onset and growth of shear instability. This is especially true for composite materials. The different combinations of thermomechanical properties constitute an environment for thermomechanical coupling between the phases and provide a deriving force for nonuniform deformation. For particle reinforced metal matrix composites

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(MMCp), recent experimental investigations made by Ling *et al.* [4] have demonstrated that the onset of adiabatic shear bands is more readily observed in MMCp with small reinforcing particles than that in the larger particle composite. This phenomenon has also been demonstrated by Zhou in his numerical investigations on the initiation and propagation of adiabatic shear bands in tungsten matrix composites[5]. Apparently, the previously developed deformation localization theories that were based on the conventional plasticity theory can not capture this size-dependent deformation localization behavior. To clarify the size dependency, the strain gradient term is required into the constitutive equation of materials. Motivated by this point, Aifantis *et al* [6-7] and Bara *et al.*[8] developed some phenomenological strain gradient plasticity theories and applied them to size-dependent shear banding. It is noted that the aforementioned investigations were concentrated on monolithic materials. Furthermore, all these investigations give the analogous result that the strain gradient delays the onset of shear instability, although different strain gradient theories and analytical strategies are adopted. However, this result cannot give a reasonable explain for the size-dependent deformation localization behavior of MMCp demonstrated in [4]and [5]. Therefore, how to understand the effect of the strain gradient or the reinforcing particle size on adiabatic shear localization in two-phase MMCp is still open.

In the view of the aforementioned observations, the effect of the strain gradient on the onset of adiabatic shear instability in gradient-dependent particle reinforced metal matrix composites is investigated by using of linear perturbation analysis in this paper. The analytical results demonstrate that high strain gradient will provide a strong a deriving force for the onset of adiabatic shear instability in MMCp.

2 Strain gradient dependent constitutive equation

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 characterize the size dependent thermomechanical behavior of MMCp, the strain gradient term should be incorporated into the conventional constitutive equation. This can be realized by making use of the strain gradient strengthening law for MMCp which was recently developed by Dai *et al.*[9] According to this strain gradient strengthening law, the flow stress of the composite σ_c can be written as

$$\left(\frac{\sigma_c}{\sigma_m}\right)^2 = 1 + l\eta \qquad (1)$$

where σ_m is the flow stress of the matrix, η strain gradient, and l is the characteristic microstructure length scale and related to the microstructure parameters of constituents. If the metal matrix is assumed to be a strain gradient-independent thermovisoplastic material and its flow stress is represented by a product of three separate functions of temperature θ, strain ε and strain rate $\dot{\varepsilon}$:

$$\sigma_m = g_1(\theta)g_2(\varepsilon)g_3(\dot{\varepsilon}) \qquad (2)$$

According to the strain gradient-strengthening law (1), the strain gradient-dependent flow stress of MMCp can be characterized by

$$\sigma_c = f_1(\theta)f_2(\varepsilon)f_3(\dot{\varepsilon})f_4(\eta) \qquad (3)$$

where

$$f_4(\eta) = (1 + l\eta)^{1/2} \qquad (4)$$

Since the main objective of this paper is to investigate the strain gradient effect on the onset of adiabatic shear instability. To this end, we revised the strain gradient constitutive equation (3) as the following form:

$$\tau_c = f_1(\theta) f_2(\gamma) f_3(\dot{\gamma}) f_4(\eta) \quad (5)$$

where $\tau, \gamma, \dot{\gamma}, \eta$ are shear stress, shear strain, shear strain rate and shear strain gradient, respectively.

It is noted that incorporating the strain gradient term into the conventional constitutive equation in our present approach is based on the deformation mechanism, instead of adopting some phenomenological assumptions. By using of this gradient-dependent constitutive equation, the strain gradient effect or particle size effect on deformation localization behavior of two-phase MMCp can be investigated.

3 Perturbation analysis and results

Base on above strain gradient dependent constitutive equation for MMCp, the effect of the strain gradient on onset of adiabatic shear instablity can be investigated. We consider the dynamic thermomechanical deformation of a strain gradient-dependent therovicoplastic two-phase MMCp under the one-dimensional simple shearing. The govern equations are given by

$$\tau = f(\theta, \gamma, \dot{\gamma}, \eta) \quad (6)$$

$$\frac{\partial^2 \tau}{\partial y^2} = \rho \frac{\partial^2 \gamma}{\partial t^2} \quad (7)$$

$$K\tau \frac{\partial \gamma}{\partial t} = \rho c_v \frac{\partial \theta}{\partial t} - \lambda \frac{\partial^2 \theta}{\partial t^2} \quad (8)$$

We examine the effect of the strain gradient on the initiation of the instability of the homogeneous shear deformation of MMCp characterized by Eqs. (5) ~ (8). To this end, the linear perturbation method is used for the system of governing equations. Following Bai [10], we obtain

$$\tilde{\alpha}^3 + L\tilde{\alpha}^2 + M\tilde{\alpha} + N = 0 \quad (9)$$

where

$$\left.\begin{aligned} L &= [C + (1 + A)\tilde{k}^2 \\ M &= [A\tilde{k}^2 + 1 - B - D]\tilde{k}^2 \\ N &= (1 - D)\tilde{k}^2 \end{aligned}\right. \quad (10)$$

and $A, \mathrm{B}, \mathrm{C}, \mathrm{D}$ are the dimensionless variables which are given by

$$\left.\begin{aligned} \tilde{\alpha} &= \frac{\lambda \alpha}{c_v Q_0} & \tilde{\mathrm{k}}^2 &= \frac{\lambda^2 k^2}{\rho c_v^2 Q_0} \\ \mathrm{A} &= \frac{\mathrm{c}_v R_0}{\lambda} & \mathrm{B} &= \frac{\mathrm{K}\tau_0 F_0}{\rho c_v Q_0} \\ C &= \frac{\mathrm{K}\lambda P_0 \dot{\gamma}_0}{\rho c_v Q_0} & \mathrm{D} &= \frac{\mathrm{iS}_0}{Q_0} \end{aligned}\right\} \quad (11)$$

As an example, we select SiC particle reinforced 6061Al matrix composite (SiCp/6061Al) as model material. The 6061Al matrix is assumed to be a strain gradient-independent material and its constitutive behavior is characterized by Johnson-Cook constitutive equation [11]:

$$\tau_m = (1 - \frac{\theta - \theta_r}{\theta_m - \theta_r})(\frac{\sigma_{m0}}{\sqrt{3}} + \frac{E_m}{3}\gamma)(1 + (\frac{\dot{\gamma}}{\sqrt{3}D_0})^{1/p})$$

According to the analysis of the second section in this paper, the strain gradient-dependent thermoviscoplastic constitutive equation for SiCp/6061Al composite can be written as

$$\tau = \tau_m (1 + l\eta)^{1/2} \quad (12)$$

The material parameters used in the constitutive equation (12) are as follows:

$\sigma_{m0} = 286.8$ MPa, $E_m = 542.6$ GPa,

$D_0 = 6500$ 1/s, $\theta_m = 652\ ^0C$,

$\theta_r = 20\ ^0C$, $p = 4$

$\rho = 2686\ Kg/m^3$, $c_v = 937.4$ J/KgK,

$\lambda = 167.3$ W/mK

In our numerical analysis, the nominal shear strain rate $\dot{\gamma}_0 = 2000$ 1/s was used. For this given MMCp, the effects of the strain gradient η and the characteristic microstructure length scale l on the critical instability shear strain γ_c are investigated. The calculated results are demonstrated in Fig. 1.

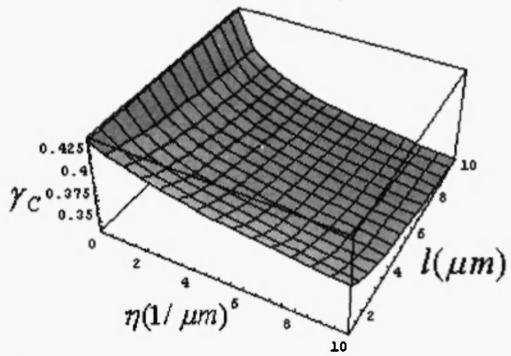

Fig.1 Variation of critical shear strain with strain gradient and length scale parameter

It is clear from Fig.1 that the critical strain γ_C reduces as the strain gradient η increase. Instead of delaying adiabatic shear localization in the *monolithic* materials as demonstrated by Aifantis *et al.*[6-7] and Batra *et al.*[8], the strain gradient provide a deriving force for onset of adiabatic shear instability in two-phase MMCp. For MMCp, our previous theoretic analysis has shown that the smaller the reinforcing particle size, the higher the strain gradient in the metal matrix [12]. Combining this result with the present linear perturbation analysis result leads to the conclusion: the onset of adiabatic shear instability in MMCp reinforced with small particles are more prone to occur than in MMCp with large particles. Apparently, this analytical result is in accordance with the experimental observations of Ling, *et al.* and the numerical simulation results of Zhou .

4 Conclusions

In this paper, adiabatic shear instability in strain gradient dependent thermo-viscoplastic particle reinforced metal matrix composites is analyzed by using of linear perturbation method. The results have demonstrated that adiabatic shear instability in metal matrix composites reinforced with small particles is prone to occur than in large particle case. This tells us that the strain gradient will provide a strong deriving force for onset of adiabatic shear instability in metal matrix composites.

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