ON STRAIN-RATE SENSITIVITY OF METAL MATRICES REINFORCED WITH CERAMIC PARTICLES

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Abstract A micromechanics study is carried out for the high strain-rate deformation of ceramic particle reinforced metal matrix composites. The ceramic particles are taken to be elastic, equal-sized, spherical, and uniformly distributed in the matrix. The stress-strain behavior of the matrix material is assumed to be elastic-perfectly plastic or power-law strain hardening of the Ramberg-Osgood type, coupled with power-law strain rate hardening. Systematic predictions are made of the composite flow stress as determined by inclusion volume fraction, the applied strain rate, and the strain hardening exponent and strain rate sensitivity of the matrix. A simple constitutive expression is obtained which allows one to predict readily the rate-dependent plastic flow behavior of the composite. Comparison between the model predictions and experimental measurements for the strain rate dependence of an Al/Al₂O₃ composite shows good agreement.

1. Introduction

Metal matrix composites (MMCs) such as Al, Ti and Ni alloys reinforced with Al₂O₃ and SiC particulates or whiskers have the potential to provide desirable mechanical properties including high specific stiffness, high plastic flow strength and creep resistance, and good oxidation and corrosion resistance. This suite of properties makes particle reinforced MMCs attractive to a wide range of applications in automobile, aerospace and defense industries. Largely driven by these applications, extensive theoretical and experimental studies have been made in recent years to uncover the mechanics and mechanisms underlying the behavior of particle reinforced metal matrix composites [e.g., 1-7]. In particular, a systematic nonlinear analysis has been performed in [6] to predict plastic flow and creep behavior of the composites as determined by particle volume fraction, shape, distribution and behavior of the matrix. More recently, the work in [6] has been extended to the high strain-rate deformation regime [8].

Rate sensitivity of MMCs is controlled by rate sensitivity of the matrix and the interaction of particles and the matrix. As demonstrated by Gray and his co-workers [9-10], dislocation mechanisms such as dislocation punchout from stress concentrations near particle/matrix interfaces and channeled plastic flow in the matrix between particles result in elevation of the composite flow stress. The constraining effect of the particles becomes stronger when the applied strain rate is larger [11]. When the size of particles is small, dislocation-particle interactions can have significant influence. The interaction
between particles and the matrix also depends on the geometry and distribution of the particles which can be quite complicated. For example, the particles are usually polyhedra with different sizes, aspect ratios and orientations [5, 12]. To gain insight into the rate sensitivity of the composite, and to limit the number of variables, in this study, the particles are taken to be spherical, equal-sized and uniformly distributed. The particles are assumed to be large enough so that the analysis can be made based on a continuum plasticity theory.

To facilitate the analysis, it is assumed that no interface debonding and particle cracking occur in the composite. It is recognized, however, that these damage mechanisms are responsible for softening and failure of the composite under static or dynamic loadings [13-16]. In addition, upon impact loading, elastic and inelastic waves propagate in the composite which further complicate the stress analysis in the transient regime. Attention in this paper is restricted to the overall composite steady-state behavior under uniaxial compression; deformation of the composite in the transient regime or under shear and multiaxial loading conditions is left for future studies.

Figure 1. Uniaxial stress-strain curves for composite and matrix defining the limit flow stress $\sigma_0$ in (a) and the asymptotic reference stress $\sigma_N$ in (b).

2. The Mechanics Model

The stress-strain relation for the rate-dependent matrix material considered in this paper is fully specified by its quasi-static behavior and the rate-dependence. Two types of quasi-static behavior of matrix are considered: elastic-perfectly plastic, and power-law strain hardening of the Ramberg-Osgood type. As depicted in Fig. 1, the quasi-static uniaxial stress-strain curve of an elastic-perfectly plastic matrix material is characterized by

$$\sigma_s = \sigma_0 (\varepsilon/\varepsilon_0) \quad \varepsilon \leq \varepsilon_0$$

$$= \sigma_0 \quad \varepsilon > \varepsilon_0$$  \hspace{1cm} (1)$$

where $\sigma_0$ is the uniaxial flow stress, $\varepsilon_0 = \sigma_0/E$, and $E$ is Young's modulus. The power-law strain hardening matrix material is defined by the Ramberg-Osgood uniaxial stress-strain curve

$$\varepsilon = \frac{\sigma_s}{E} + \alpha \frac{\sigma_0}{E} \left( \frac{\sigma_s}{\sigma_0} \right)^n$$  \hspace{1cm} (2)$$