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Effects of interfacial debonding on the rate-dependent response of metal matrix composites

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Abstract

The effect of interface damage on the rate-dependent constitutive behavior of particle reinforced metal matrix composites (MMCs) is investigated. The constitutive behavior of the matrix–reinforcement interface is characterized by a cohesive zone model, and the effects of interface strength and separation energy on MMC constitutive behavior are examined over a wide strain rate range (10^{-3}–10^{4} s^{-1}). The consequences of interface failure on the overall constitutive behavior of the composite are discussed in conjunction with the influences of reinforcement volume fraction, strain rate, particle shape and aspect ratio. The computational results are compared with experimental data obtained on the quasistatic and high-rate response of MMCs subjected to compression and tension, with good correlation.

Keywords: Finite element analysis; Metal matrix composites; Interfacial debonding; High strain rates; Plastic deformation

1. Introduction

The increasing application of discontinuously reinforced metal matrix composites (MMCs) in high strain rate loading conditions, such as structural impact, blast loading, explosive forming and metal working, has led to a need for understanding of constitutive and failure behaviors under such loadings. A number of composite models, e.g., the rule of mixtures [1], shear lag [2], Eshelby's inclusion model [3] and others [4], have been developed with the aim of predicting the constitutive behaviors of composites given data on the constituent phases. However, most of these models treat the composite as a two-phase (matrix and reinforcement) material, with a perfect interface between matrix and reinforcement. This is a strong idealization and sometimes not consistent with experimental observations. Further, different kinds of damage, such as interfacial debonding, particle fracture and void growth in the matrix, may exist in MMCs. Such damage affects the overall constitutive behavior. The most common effect of damage is the decreased tensile ductility when more reinforcement particles are loaded into the matrix to enhance the stiffness and strength. High strain rate tests also show such reduced ductility [5–8], perhaps indicating an exaggerated damage effect under higher loading rate. Besides the decreasing ductility induced by higher reinforcement volume fractions or increased strain rates, a reduction in the strain hardening is also typically observed as a result of damage, see, e.g., [9]. These phenomena associated with damage evolution cannot be characterized by models that do not consider damage effects.

Different modes of damage may dominate in composites with different constituents or fabricated by different

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routes. Particle fracture is reported to be the dominant damage mode in cast A359/SiC [10] and gas pressure infiltrated Al/Al_2O_3 [11]. Other experiments show no apparent particle fractures, but interfacial debonding as the dominant damage form in $Al6061/Al_2O_3$ [5]. Interfacial-debonding-dominated damage has also been observed in hot isostatically pressed (HIPed) Al6092/B_4C composites [12].

Numerical and experimental studies of particulate reinforced MMCs have been performed relating to various damage mechanisms. For example, Needleman [13], Xu and Needleman [14] and Tvergaard [15] investigated the effect of damage due to void nucleation through inclusion debonding by introducing an imperfect and breakable matrix–reinforcement interface. Llorca et al. [16] studied the effect of damage in the form of matrix void nucleation by considering the matrix material as an elastic–viscoplastic ductile porous solid. Bao [17] considered the damage due to the fracture of brittle reinforcements using a three-phase model in which the fractured particle is surrounded by the undamaged composite. Li et al. [10] explained the observed decreased work-hardening using an analytical model that incorporates evolving damage within an A359/SiC composite. However, most of these studies examine quasi-static uniaxial and unidirectional loading. The effects of loading mode and rate-sensitivity are not well documented.

In this study, a numerical framework is developed to consider damage in the form of interfacial debonding in particulate reinforced metal matrix composites. The constitutive behavior of the matrix–reinforcement interface is characterized by a cohesive zone model, and the effects of interface strength and separation energy on MMC constitutive behavior are examined over a wide strain rate range (10^{-3}–$10^4\ s^{-1}$). The consequences of interface failure on the overall tensile and compressive constitutive behaviors are discussed in conjunction with the influences of reinforcement volume fraction, particle shape and aspect ratio.

2. Computation and modeling

2.1. Interface model

Different continuum models have been developed to characterize interface response by using an infinitely thin surface separated by springs or cohesive zones with specific traction-separation laws. A review of these interfacial models is provided by Chandra et al. [18]. In this work, a polynomial cohesive zone model [15] is used to simulate the interfacial behavior applicable for both normal and tangential loadings.

If the interface is under tension ($\delta_n \geqslant 0$), the relationship of traction $\mathbf{T}$ vs. separation $\boldsymbol{\delta}$ is described by

$$\left.\begin{aligned} T_n &= \tfrac{27}{4}\sigma_{\max}\tfrac{\delta_n}{\delta_n^c}(1-\lambda)^2 \\ T_t &= \xi\tfrac{27}{4}\sigma_{\max}\tfrac{\delta_t}{\delta_t^c}(1-\lambda)^2 \end{aligned}\right\} \quad \text{for } \lambda = \lambda_{\max} < 1 \text{ and } \dot{\lambda} \geqslant 0, \tag{1}$$

where $\sigma_{\max}$ is the maximum normal strength of the interface, δ_n^c and δ_t^c are critical separation values along normal and tangential directions, and δ_n and δ_t are the corresponding interfacial separations. The stiffness parameter ξ is the ratio of the maximum tangential strength, $\tau_{\max}$, to the maximum normal strength, $\sigma_{\max}$. In this work, an identical cohesive behavior is assumed along normal and tangential directions: $\tau_{\max} = \xi\sigma_{\max}$, so that $\xi = 1$ and $\delta_n^c = \delta_t^c$.

The non-dimensional parameter λ is used to describe the damage induced from interface separation and is defined by

$$\lambda = \left\{\left(\frac{|\delta_n|}{\delta_n^c}\right)^{\varsigma} + \left(\frac{|\delta_t|}{\delta_t^c}\right)^{\varsigma}\right\}^{1/\varsigma}, \tag{2}$$

where ς is a coupling parameter defining the interaction of the normal and tangential separations. The notation $|\,|$ refers to the absolute value. In this work, $\varsigma = 2$ is selected to present a damage indicator λ equal to the absolute value of separation. The dependence of λ on both δ_n and δ_t stresses the interaction between normal and tangential separations. λ cannot exceed unity, since when $\lambda > 1$, total failure occurs and the cohesive relationship is no longer applicable. When $\lambda = 1$, two new surfaces are created and only surface contact need be considered thereafter.

Loading and unloading of the interface can be determined by evaluating the sign of $\dot{\lambda}$ and the history of λ. For decreasing λ, a linear unloading is used to represent the partly damaged interface. Subsequently, if λ increases again, but is less than its prior maximum value $\lambda_{\max}$, the same linear relationship is applied until λ reaches $\lambda_{\max}$ again. The linear unloading and reloading are described by

$$\left.\begin{aligned} T_n &= \tfrac{27}{4}\sigma_{\max}\tfrac{\delta_n}{\delta_n^c}(1-\lambda_{\max})^2 \\ T_t &= \xi\tfrac{27}{4}\sigma_{\max}\tfrac{\delta_t}{\delta_t^c}(1-\lambda_{\max})^2 \end{aligned}\right\} \quad \text{for } \lambda < \lambda_{\max} \text{ or } \dot{\lambda} < 0. \tag{3}$$

If the interface is under compression ($\delta_n < 0$), we set

$$T_n = K\frac{\delta_n}{\delta_n^c}, \tag{4}$$

where K is large ($K > 10E_{\text{inclusion}}$). The tangential behavior in compression is the same as that under tension.

With these assumptions, Fig. 1 shows the normal traction across the interface, T_n, as a function of δ_n when $\delta_t = 0$. An identical dependence exists for tangential traction T_t.