Mechanics of Materials 89 (2015) 72–84

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

Irreversible deformation of metal matrix composites: A study via the mechanism-based cohesive zone model

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ARTICLE INFO

Article history:
Received 26 February 2015
Received in revised form 26 May 2015
Available online 11 June 2015

Keywords:
Cohesive zone model
Irreversible deformation
Metal matrix composites
Interfacial damage

ABSTRACT

An elastic–plastic interface model at finite deformations is utilized to predict the irreversible deformation of metal matrix composites (MMCs) under the transverse loading and unloading conditions. The associated benefit of the cohesive model is to provide a physical insight on the main irreversible deformation mechanisms, i.e., the geometrically nonlinear, localized plastic deformation and damage induced debonding, at the interface of MMCs. The extensive parametric study is conducted using this cohesive model to investigate the effects of the cohesive parameters on the stress–strain response of MMCs under transverse loading. Further, the ductile mechanism of the matrix is considered to characterize the competition between the plastic flow of the matrix and the inelastic interface induced irreversible deformation. Moreover, the predictions using the cohesive model are compared with those available experimental data in the literature to demonstrate the inelastic behaviors, including the interfacial plasticity and damage induced debonding, as well as the plastic flow of the matrix. The numerical results of the stress–strain responses for both loading and unloading conditions show good agreements with those obtained by the experiment. The deformation and failure modes of MMCs predicted by the model are also consistent with the observations of the experiment.

1. Introduction

Metal matrix composites (MMCs) have shown considerable potential for high temperature aerospace applications due to their excellent properties such as high stiffness, strength and wear resistance, even at elevated temperatures. Moreover, MMCs usually exhibit inelastic response with multiple modes involving the irreversible inelastic separation of fiber/matrix interface and the plastic flow of the matrix when subjected to loading and unloading conditions (Majumdar and Newaz, 1992; Wang and Siegmund, 2006). For example, the typical stress–strain curve of MMCs under transverse loading and unloading conditions exhibits three stages denoted as I, II, and III, see Fig. 1. In stage I, the response is approximately linear in spite of the emergence of slip band in the matrix around the interface. The reduced loading slope in stage II is due to the inelastic deformation at the fiber–matrix interfacial zone in the form of debonding. It should be noted, however, that a small residual strain is retained after the load is completely removed, and the unloading slope is lower than the initial loading slope. The almost zero loading slope in stage III suggests the matrix yield involving intense shear band formation. Thus, the nonlinear irreversible response is captured in stage II. Without a proper description for the inelastic interfacial separation including the plasticity and damage behavior during the loading and unloading processes, such irreversible deformation

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http://dx.doi.org/10.1016/j.mechmat.2015.06.003
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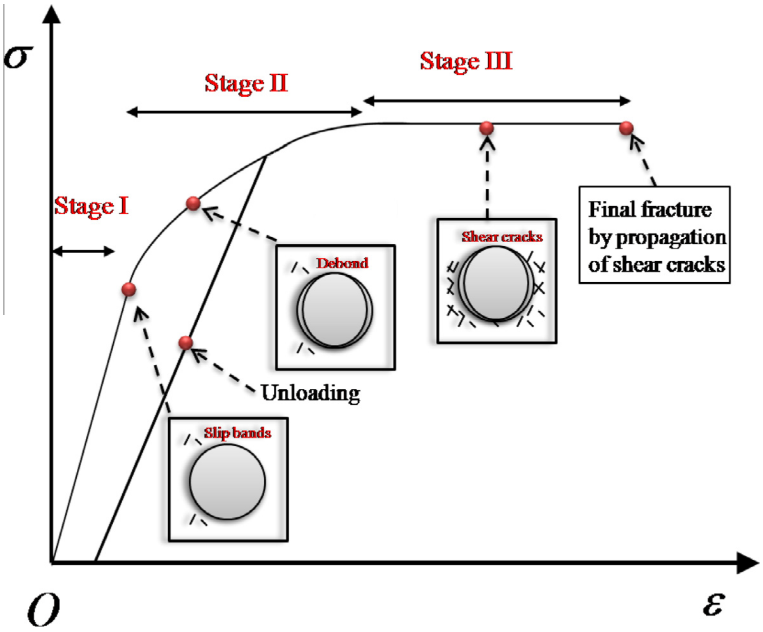

Fig. 1. Illustration of the primary stress–strain responses of MMCs under transverse loading–unloading conditions (Majumdar and Newaz, 1992).

mechanism cannot be explained at small strains if only the inelastic behavior of the matrix is considered.

In fact, the fiber–matrix interface plays an important role on the irreversible deformation mechanism of MMCs. The nonlinear response of the interface could be captured by the finite element simulations using the cohesive zone model (CZM). Numerous CZMs have been developed to represent the interface tractions or fracture energy potential as functions of separation distances, such as the cohesive models of polynomial and exponential types (Needleman, 1987, 1990; Tvergaard, 1990; Xu and Needleman, 1994; Park et al., 2009), the traction–separation model of trapezoidal shape (Tvergaard and Hutchinson, 1992), and the bilinear traction–separation equations (Camacho and Ortiz, 1996; Alfano and Crisfield, 2001; Hu et al., 2008). These cohesive models were further improved and applied in a wide range of fracture and failure problems in MMCs (Chandra et al., 2002; Raghavan and Ghosh, 2005; Ghosh et al., 2007). Moreover, quite a few mechanism-based cohesive models that account for large scale nonlinearity (Ortiz and Pandolfi, 1999), frictional sliding (Gearing et al., 2001; Xu et al., 2015), rate-dependence (Coker et al., 2005; Vena et al., 2008), temperature effect (Hattiangadi and Siegmund, 2004; Fagerstrom and Larsson, 2008), and the rotational discontinuity (Larsson and Zhang, 2007) appeared in the framework of generalized continuum theory. Recently, Mosler and Scheider (2011) presented a thermodynamically consistent anisotropic cohesive model by incorporating the interfacial deformation gradients and their corresponding stress tensors at finite deformations. These stress tensors were interpreted as deformational surface shear. In order to describe the multiscale phenomena associated with the cohesive failure processes in heterogeneous adhesives, Matous et al. (2008) developed a multiscale cohesive model for heterogeneous adhesives by a computational homogenization method. Further, the effect of particle decohesion on the macroscopic failure response of heterogeneous adhesives was also emphasized by Kulkarni et al. (2009). But only two-dimensional plane strain problems were considered. Furthermore, a more complex three dimensional problem was solved by Aragon et al. (2013) using the interface-enriched generalized finite element method (IGFEM). More recently, Xu and Lu (2013) presented an interface model based on the geometrically nonlinear theory of plasticity that accounts for inelastic behaviors at finite deformations, such as plasticity, hardening/softening, and damage. Further, Lu and Xu (2013) extended this cohesive formulation to capture the interface traction relaxation and rate-dependent plastic flow by incorporating a viscoplastic flow rule.

Although most of the existing models can capture some peculiar features of deformation at interface, there are few mechanistic interfacial models focusing on the unloading response of an interface, especially for the irreversible change at interface in MMCs. Such an unloading behavior has a significant effect on the fatigue problems and mixed-mode cohesive fracture (Siegmund, 2004; Moreo et al., 2007). Several researchers have attempted to extend cohesive laws for monotonic loading into forms suitable for loading–unloading behavior by an extra set of unloading path. These unloading responses can be classified as linear to origin models (Camacho and Ortiz, 1996; Ortiz and Pandolfi, 1999), where the degradation of interface elastic stiffness through damage leaving zero separation upon complete unloading, and linear to residual opening models (Roe and Siegmund, 2003), where the unloading path conforms to a linear relationship with a slope equal to that of the original elastic stiffness and sustain permanent residual opening displacement. However, these