Engineering Fracture Mechanics 92 (2012) 101–113

Contents lists available at SciVerse ScienceDirect

Engineering Fracture Mechanics

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

Micromechanical modeling of damage in periodic composites using strain gradient plasticity

Reza Azizi *

Department of Mechanical Engineering, Solid Mechanics, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark

ARTICLE INFO

Article history:
Received 13 September 2011
Received in revised form 10 April 2012
Accepted 24 April 2012

Keywords:
Damage
Cohesive zone model
Metal matrix composite
Strain gradient plasticity

ABSTRACT

Damage evolution at the fiber matrix interface in Metal Matrix Composites (MMCs) is studied using strain gradient theory of plasticity. The study includes the rate independent formulation of energetic strain gradient plasticity for the matrix, purely elastic model for the fiber and cohesive zone model for the fiber–matrix interface. For the micro structure, free energy holds both elastic strains and plastic strain gradients. Due to the gradient theory, higher order boundary conditions must be considered. A unit cell with a circular elastic fiber is studied by the numerical finite element cell model under simple shear and transverse uniaxial tension using plane strain and periodic boundary conditions. The result of the overall response curve, effective plastic strain, effective stress and higher order stress distributions are shown. The effect of the material length scale, maximum stress carried by the interface and the work of separation per unit interface area on the composites overall behavior are investigated. The results are compared with those for strong interface.

1. Introduction

The increasing application of reinforced Metal Matrix Composites (MMCs) is due to the improved properties like high stiffness, high tensile strength, creep resistance, wear resistance, low density and damping capabilities. These useful properties are accessible with the cost of poor ductility and fracture properties. Therefore, a comprehensive knowledge of all types of the properties is necessary, which requires an understanding of both constitutive and failure behaviors. Several works have studied the perfectly bonded reinforced metal matrix composites (e.g. [19,2]). However, experimental evidences show the availability of damage upon deformation in composites by debonding at the fiber–matrix interface, particle fracture and void growth in the matrix (e.g. [26,21]). The most notoriously critical area for the growth of the crack is fiber–matrix interface. One of the widely used method in the literature for simulation of the interfacial debonding in composites is the cohesive zone model. The idea for the cohesive model is based on the consideration that the damage analysis knows the existence of the crack in advance. In MMCs, fiber–matrix interface appears to be a critical region for the damage and a reasonable presuppose for the cohesive elements as was shown by Niordson and Tvergaard [20] and Legarth and Niordson [14]. Several cohesive zone models have been developed to face different type of crack propagation (e.g. [24,27]). Xu and Needleman [27] used polynomial and exponential types of traction separation equations to study the void nucleation at the interface of particle and matrix metal. Tvergaard [24] extended the Needleman [17] model of pure normal separation to both normal and tangential separation. Tvergaard and Hutchinson [25] used a trapezoidal shape of the traction separation model to calculate the crack growth resistance in elastic–plastic materials.

* Corresponding author.
E-mail address: reaz@mek.dtu.dk

0013-7944/$ - see front matter
http://dx.doi.org/10.1016/j.engfracmech.2012.04.033

Nomenclature

$\mathbf{a}$	cohesive modulus
$\mathbf{b}$	bottom of the unit cell
B_{ij}^{N}	spatial derivative of shape function for the displacement
D_{ijkl}	isotropic tensor of elastic moduli
$\mathbf{D}_e,\ \mathbf{D}_p,\ \mathbf{D}_h$	isotropic elastic moduli, plastic moduli, higher order moduli
$E_f,\ E_m$	Young's modulus of fiber, Young's modulus of matrix
$E_{ij},\ E_0$	overall strain, penalty factor
f	micro yield function
$\dot{\mathbf{f}}_u,\ \dot{\mathbf{f}}_p$	nodal force increment, nodal higher order force increment
G	elastic shear modulus
h	height of the unit cell
H	hardening modulus of matrix
$\mathbf{I}_{(8\times8)}$	identity matrix
$K_1,\ K_2$	stress proportionality factors
$\mathbf{K}_u,\ \mathbf{K}_p,\ \mathbf{K}_{up}$	elastic stiffness, plastic stiffness, coupling stiffness
$\mathbf{l},\ L$	left of the unit cell, width of the unit cell
L_*	material length scale parameter
m_{ijk}	higher order stress
M_{ij}^{I}	work-conjugate to plastic strain at the fiber–matrix interface
$\dot{M}_{ij}$	moment traction increment
N_i^N	shape function for the displacement
$p^n,\ p^t$	normal, tangential unit vector at the fiber–matrix interface
P_{ij}^{M}	shape function for the plastic strain component
q_{ij}	work conjugate to the plastic strain
q_e	effective micro stress
Q_{ijk}^{M}	spatial derivative of shape function for the plastic strain component
$\mathbf{r}$	right of the unit cell
r_{ij}	direction of the plastic strain increment
$R, \mathbf{R}$	radius of fiber, rotation matrix
$s^I,\ s$	surface of the fiber–matrix interfaces, surface of the unit cell
$s^I(\texttt{bonded})$	surface of the fiber–matrix interface without decohesion
$s^I(\texttt{debonded})$	surface of the fiber–matrix interface with total decohesion
s_{ij}	stress deviator
$t,\ \mathbf{t}$	thickness of the unit cell, top of the unit cell
$T_n^I,\ T_t^I$	interface normal traction, interface tangential traction
$T_n,\ T_t$	normal traction, tangential traction
$\dot{T}_i$	traction increment
$u_n^I,\ u_t^I$	interface normal displacement, interface tangential displacement
$v,\ V_f$	volume of the unit cell, fiber volume fraction
x_i	Cartesian coordinate system
$\dot{\gamma},\ \gamma_y$	plastic multiplier, shear yield strain
$\delta_n,\ \delta_t$	normal, tangential maximum separation at the total decohesion
$\dot{\Delta}_i$	prescribed displacement increment quantities
$\epsilon_{ij},\ \epsilon_{ij}^{p},\ \epsilon_{ij}^{e}$	total strain, plastic strain, elastic strain
$\epsilon_{ij,k}^{p},\ \epsilon_{ij}^{pI}$	plastic strain gradient, plastic strain at the fiber–matrix interface
$\epsilon_e^p,\ \epsilon_y$	accumulated effective plastic strain, yield strain
λ	non-dimensional separation parameter
ν_m	poisson's ratio of matrix
$\sigma_{ij},\ \sigma_y,\ \sigma_f$	cauchy stress tensor, yield stress, flow stress
$\sigma_{max},\ \Sigma_{ij}$	maximum stress carried by the interface, overall cauchy stress
$\tau_y,\ \tau$	shear yield stress, pseudo-time

Recent experiments have shown that the macroscopic behavior of MMCs depends on not only the volume fraction but also the size of reinforcing particles or fibers. Lloyd [15] showed that the response of composites with the same volume fraction of SiC particles depends on the size of the particles. Further investigations by Hutchinson [12] showed that dislocations cannot pass from matrix into the fiber (plastic strain suppression at the fiber–matrix interface) and consequently pile up at the interface. Strain gradient plasticity has capability to consider this fact since it can capture observed size-effects and non-