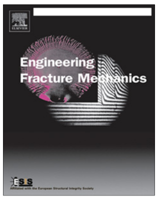
Engineering Fracture Mechanics 149 (2015) 170–190

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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



Cohesive-zone modelling of crack nucleation and propagation in particulate composites

Sathiskumar A. Ponnusami *, Sergio Turteltaub, Sybrand van der Zwaag

Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands

ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form 14 August 2015
Accepted 30 September 2015
Available online 22 October 2015

Keywords:
Crack–particle interaction
Cohesive elements
Self-healing material
Particle fracture and interface debonding
Particle flaw

ABSTRACT

A cohesive-zone approach is used to study the interaction between an approaching crack and a particle embedded in a matrix material as a function of the mismatch in elastic and fracture properties. Crack-particle interaction is a crucial issue governing fracture behavior of particle-dispersed materials. Special attention is given in the present work to the effect of the mismatch in fracture properties, namely fracture strength and energy, which has not been fully-explored in the literature. Based on extensive finite element simulations using cohesive elements, the basic fracture mechanisms governing the crack-particle interaction are identified, namely particle fracture, crack deflection and interface debonding. The details of the cracking sequences are elucidated and the role of secondary cracks is highlighted. The effect of pre-existing flaws on the fracture behavior is analyzed both for flaws inside the particle as well as flaws on the particle/matrix interface. Several flaw configurations in terms of size, orientation and location are considered. In addition, the effect of the mismatch between the matrix and the interface fracture properties is also considered for a wide range of adhesive characteristics. The results of the simulations are summarized in the form of several fracture maps for different configurations, whereby the main fracture mechanisms are identified in regions inside a two-dimensional space of strength and toughness mismatch between the particle and the matrix. It is observed that the mismatch in the fracture properties usually plays a more dominant role on the crack trajectory than the mismatch in elastic properties in a particle-dispersed system. Pre-existing flaws/defects in the particle and the interface are found to be one of the principal controlling factors that alter the crack propagation characteristics. These results can be used as a guideline for designing particulate composite system with a preferred fracture mechanism, namely matrix cracking, interface debonding or particle fracture.

1. Introduction

Particulate composites is an important class of heterogeneous materials in which the secondary phase are particles, embedded in a suitable matrix material. Particles are typically combined with the host matrix material to increase its functionality, particularly its effective fracture behavior. For example, hard second phase particles are dispersed in an otherwise homogeneous material to strengthen it. An illustrative example of material strengthening is a metal matrix

---

* Corresponding author.
E-mail addresses: S.AnusuyaPonnusami@tudelft.nl (S.A. Ponnusami), S.R.Turteltaub@tudelft.nl (S. Turteltaub), S.vanderZwaag@tudelft.nl (S. van der Zwaag).

http://dx.doi.org/10.1016/j.engfracmech.2015.09.050
0013-7944/

Nomenclature

T	effective traction
Δ	effective opening displacement
$\boldsymbol{t}$	traction vector
$\boldsymbol{\delta}$	cohesive crack opening displacement vector
$t_{\mathrm{n}},\ t_{\mathrm{s}}$	cartesian components of traction vector
$\delta_{\mathrm{n}},\ \delta_{\mathrm{s}}$	cartesian components of cohesive opening displacement vector
K	initial slope of cohesive law
σ_{c}	cohesive strength
G_{c}	fracture energy (toughness)
l_{fpz}	fracture process zone length or cohesive zone length
E	Young's modulus of the material
γ	non-dimensional weighting factor
f^{d}	loading function
κ^{d}	damage history variable
g	effective traction-separation law
ω	damage variable
Δ_0	equivalent crack opening at onset of damage
Δ_{f}	equivalent crack opening at complete failure
$\delta_{\mathrm{n},0},\ \delta_{\mathrm{s},0}$	crack opening at onset of damage for pure mode I and mode II respectively
$t_{\mathrm{n,c}},\ t_{\mathrm{s,c}}$	cohesive strength for pure mode I and mode II respectively
$\delta_{\mathrm{n,f}},\ \delta_{\mathrm{s,f}}$	crack opening at complete failure for pure mode I and mode II respectively
L	length of the two-dimensional domain
W	height of the two-dimensional domain
r	radius of the particle
a	initial crack length
b	horizontal distance between initial crack plane and center of the particle
c	vertical offset between initial crack plane and center of the particle
$\sigma_{\mathrm{c}}^{\mathrm{p}},\ \sigma_{\mathrm{c}}^{\mathrm{m}},\ \sigma_{\mathrm{c}}^{\mathrm{i}}$	cohesive (fracture) strength of particle, matrix and interface respectively
$G_{\mathrm{c}}^{\mathrm{p}},\ G_{\mathrm{c}}^{\mathrm{m}},\ G_{\mathrm{c}}^{\mathrm{i}}$	fracture energy (toughness) of particle, matrix and interface respectively
$E^{\mathrm{p}},\ E^{\mathrm{m}}$	Young's modulus of particle and matrix respectively
$\nu^{\mathrm{p}},\ \nu^{\mathrm{m}}$	Poisson's ratio of particle and matrix respectively
$l_{\mathrm{fpz}}^{\mathrm{m}}$	fracture process zone length of the matrix
$\bar{l}_{\mathrm{fpz}}^{\mathrm{m}}$	non-dimensional fracture length scale parameter of the matrix
l_e	characteristic element length

reinforced with ceramic particles (see, e.g., [1–3]). Conversely, soft ductile particles are dispersed in a brittle matrix to enhance its fracture toughness such as metallic particles dispersed in a ceramic matrix (see, e.g., [4,5]). More recently, a distinct mechanism using embedded particles has been proposed to enhance the long-term resistance against failure. In particular, in the so-called self-healing materials, particles containing a suitable healing agent are dispersed in the matrix [6,7]. Upon loading the material, existing microcracks interact with the healing particles, thereby activating the self-healing mechanism. In order to successfully trigger the healing mechanism, it needs to be ensured that a propagating crack gets attracted towards the healing particles instead of deflecting away from them.

The fracture behavior in heterogeneous materials strongly depends on how cracks interact with the individual constituent phases at the microstructural level. In the aforementioned examples, a critical issue is the effect that a particle has on a nearby crack running through the matrix, henceforth referred to as *crack–particle interaction*. A key aspect that governs this interaction is the change in crack tip driving force due to the presence of a particle, which in turn depends upon the mismatch in the properties of the particle and the matrix. Shielding effect is observed when the particle is stiffer than the surrounding matrix material and amplification effect is observed if the particle is softer. As a consequence, a change in the crack trajectory occurs in the presence of particle. In the context of a particulate composite system, three basic fracture mechanisms could be identified, namely particle fracture, crack deflection and interface debonding as depicted in Fig. 1.

Several analytical studies have been performed to address the issue of a crack interacting with particles [8–14]. The basic goal of all those studies is to quantify the effect of the particle on the crack tip driving force through parameters like stress intensity factor (SIF) or energy release rate (ERR). The studies establish a key conclusion, namely that a reduction in SIF or crack driving force occurs if the particle ahead of the crack tip is stiffer than the surrounding material and an amplification of crack driving force occurs in the presence of a softer particle leading to shielding and antishielding effects respectively. With the advent of finite element (FE), boundary element (BE) and other numerical methods, studies have been carried out to further analyze crack–particle interaction [15–25]. The advantage of the numerical methods is that it is possible to consider more complex scenarios where analytical solutions are not feasible, such as irregular particle shapes and distribution of