Theoretical and Applied Fracture Mechanics 80 (2015) 242–252

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

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

# Crack-tip shielding by the dilatant transformation of particles/fibers embedded in composite materials

Qun Li, Junnan Lv, Junling Hou, Hong Zuo *

*State Key Laboratory for Strength and Vibration of Mechanical Structures, School of Aerospace, Xi'an Jiaotong University, 710049, PR China*

ARTICLE INFO

*Article history:*
Available online 2 September 2015

*Keywords:*
Fracture toughness
Configurational force
*J*-integral
Dilatant transformation
Crack-tip shielding

ABSTRACT

The fracture toughness can be enhanced by a specific dilatant transformation occurring in particle or fiber-reinforced composites. The enhanced toughness is attributed to the crack-tip shielding from the residual strain fields which develop following the transformation of particles or fibers dispersed near the crack tip. In the present study, the crack-tip shielding is estimated from the reduction of the crack tip *J*-integral compared to the remote *J*-integral. The reduction of *J*-integral can be elucidated by the configurational forces integrated over the transformation areas. The configurational forces are inherently related to the change of the total potential energy due to phase transformation. Numerical analysis is performed for a system with sufficiently small particles or fibers in the fully transformed zone near the crack tip. The influence of dilatant transformation on fracture toughness is investigated for one individual particle, multi-particles, one individual fiber, multi-fibers, respectively, dispersed in composite materials. It is found that a reduction of the crack tip *J*-integral can be developed by the presence of the dispersed particles or fibers. The crack tip shielding effect is strongly dependent of the location and size of particles or fibers. The larger/longer the particles/fibers are, the greater effect of the transformed particles/fibers on the crack-tip shielding. The present analysis provides a better understanding of the role of dilatant transformed particles/fibers on crack-tip shielding in composite materials.



## 1. Introduction

Particle/fiber-reinforced composite materials have gained popularity in high-performance products that need to be lightweight, yet strong enough to take harsh loading conditions. Moreover, some composite materials have smart capabilities, that is, they are able to sense, actuate and respond to the surrounding environment by embedding phase transformed constituent e.g., shape memory alloys in the form of particles, ribbons or fibers into brittle materials. These smart or intelligent composites have increasingly been used in the aerospace and automotive industries [35]. The enhancement of fracture toughness can be achieved from the reversible phase transformation of the particle/fiber by the application of heat or stress in composite materials. Meanwhile, the phase transformation can give rise to a superelastic deformation which lead to substantial enhancements in tensile ductility and fracture toughness of high-strength, brittle materials [8,33,32,14,10,37]. The fracture toughness of certain composites can be optimally designed through the controllable use of phase transformation.

Extensive experimental and computational literatures have demonstrated that phase transformation can lead to substantial enhancements of fracture toughness in particles/fibers-reinforced composite materials [36,30,25,24,2,21,27,1,9,37,18]. For instance, Nakazawa et al. [30] studied mechanical properties of Ti–Ni shape memory particle dispersed copper composite material and found crack arrest effect on brittle clack propagation in steels, by using shape memory effect/stress induced transformation of dispersed SMA particles. Li et al. [24] presented the results of a combined experimental and analytical study of transformation toughening in NiAl composites reinforced with 20 vol.% of 2 mol% yttria stabilized zirconia particles. Lee et al. [21] studied the influence of dispersed-alumina particle size on the fracture toughness of 3 mol% yttria-stabilized zirconia polycrystals (3Y-TZP), and they concluded that the fracture toughness can be improved by the alumina dispersion and its toughening effect is higher in the specimen with large particles compared with that of small ones. Loughran et al. [27] studied the fracture behavior of shape memory CuAlNi single crystals in tension, and found that the martensitic transformation band emanating from the notch tip has great influence on controlling crack growth and material toughness in SMAs. A few of efforts are also made for the fiber-reinforced composites. Shimamoto et al. [36] used shape memory NiTi fibers in an epoxy

* Corresponding author. Tel.: +86 29 82663657.
*E-mail address:* zuohong@mail.xjtu.edu.cn (H. Zuo).

http://dx.doi.org/10.1016/j.tafmec.2015.06.005
0167-8442/

matrix to increase the fracture toughness of the composite. Hu et al. [18] studied the effect of tensile deformation on the phase transformation behaviors of NiTi fibers, which were embedded in a pure aluminum matrix. Kim and Jang [20] observed that the martensitic transformation behaviors of Ti-rich Ti–Ni alloy fibers fabricated by melt overflow and found that the recoverable elongation associated with B2-B19 martensitic transformation of $Ti_{50.5}Ni_{49.5}$ fibers is two times larger than that of $Ti_{51.5}Ni_{48.5}$ alloy fibers. Wang et al. [37] found that $ZrB_2$–SiC nanocomposite ceramics are greatly toughened by $ZrO_2$ fiber and concluded that the content, microstructure, and phase transformation of $ZrO_2$ fiber exhibited remarkable effects on the fracture toughness of the $ZrO_2$(f)/$ZrB_2$–SiC composites. Additionally, Aoki and Shimamoto [1] found that epoxy matrix composite beams with NiTi fibers embedded are applied to enhance the strength and fracture toughness of the machinery components. Coughlin et al. [9] observed the mechanical behavior of NiTi shape memory alloy fiber reinforced Sn matrix "smart" composite and found that embedding shape memory alloy fibers into a Pb-free solder alloy could potentially improve fatigue and mechanical shock properties of the materials.

Although many significant progresses have been made in studying mechanical mechanism of transformation-toughening in brittle materials, the influence of dilatant transformation of specific particles or fibers on fracture toughness near the crack tip remains inadequately treated. The main purpose of the paper is to address the crack-tip shielding due to the presence of transformation particles or fibers via the concept of material configurational forces. The fracture toughness of the crack can be dominated by the fracture parameter of *J*-integral near the crack tip. The crack-tip shielding can be estimated from the reduction of the crack tip *J*-integral compared to the remote *J*-integral, that is, the reduction of *J*-integral is of particular interest with regard to fracture toughening induced by the transformed particle. Herein, the *J*-integral which dominates the fracture toughness consists of two contributions, one is due to externally applied field and the other is due to the dilatant transformation of dispersed particles/fibers around the crack tip. The reduction of the crack tip *J*-integral due to the presence of transformation can be achieved from the concept of material configurational forces which play an important role in treating the effect of transformation toughening in composites.

It is of importance that material configurational mechanics as a new branch of solid mechanics emerges as a strong tool to deal with crack problems associated with structural deformation and damage evolution [28,19,15, among many others]. The significant physical meanings of the material configurational forces as the basic concept within material configurational mechanics is inherently related to the change of the total potential energy due to the change of configuration (e.g., shape, size, and location) for the material defects (e.g., inclusion, cavity, dislocation, crack, plastic zone et al.). Zhou et al. [44] and Li et al. [23] obtained a general and approximate solution for the configurational forces between crack and an inclusion of arbitrary shape by treating an inhomogeneous inclusion as a homogeneous one with transformation strain according to Eshelby equivalent inclusion theory. It is demonstrated that the reduction of the crack tip *J*-integral compared with the remote *J*-integral can be elucidated by the configurational forces integrated over the transformation areas. It is confident that the configurational forces can provide a proper tool for understanding the fracture toughness reinforced by transformed particles or fibers in composites.

Thus, in the present paper, attention is limited to systems with sufficiently small particles or fibers in the fully transformed zone near the crack tip. We assume that the onset of the dilatant transformation occurs at an enough large loading over $\sigma_{AS}$ (starting stress value for transformation) or the dilatant transformation is triggered by the application of cooling process. Hence, it is appropriate to treat that the transformation of particles or fibers happens simultaneously in the fully transformed zone near the crack tip [13,41,38,40]. The contribution of dilatant part of the transformation on fracture toughening is taken into account where the phase transformation is specialized to the case of a dilatant transformation [29,4,31,5,43]. In fact, a shear transformation accompanies the dilatation but the amount which occurs at the continuum level is uncertain because a particle or fiber usually transforms into multiple layers with alternating shearing [17]. In this study we neglect any shear component of the transformation and we shall focus mostly on understanding the effect of dilatant transformation on the fracture behaviors of dispersed composite materials. Additionally, the fracture toughening associated with particles or fibers can be readily computed for spherical particles of circular cross section, or for the cylindrical fibers with rectangular cross section [29]. This shape can be regarded as representing a number of spherical particles or cylindrical fibers aligned along the crack front. Consequently, a two dimensional analysis is performed for a plane crack in composites.

The paper is organized as follows: Section 2 presents the reduction of crack-tip *J*-integral elucidated by the configurational forces. In Section 3, transformation toughening at the crack tip is investigated in explicit forms. In Section 4, numerical results of the crack-tip shielding by the dilatant transformation of particles/fibers embedded in composite materials are performed and discussed. Some concluding remarks are given in Section 5.

## 2. The crack-tip *J*-integral elucidated by the configurational forces

The basic concepts within the frame of material configurational mechanics can be generally referred to Noether's theorem of certain conservation or balance laws [3,16,12] . A systematic derivation of configurational force as a key quantity can be based on Noether's first theorem with a Lagrangian function in material space. It turns out to be effective way to explicitly define the configurational forces associated with the invariant integrals having the aid of energy or energy moment theorem. Therefore, the present methodology for establishing the configurational forces associated with the *J*-integral is referred to the Lagrangian density. In the absence of inertia terms and body force, the Lagrangian function $\Lambda$ may be looked upon as a potential and it can be identified as the negative of the strain energy density $W$ of the elasticity system which depends, in general, on the independent coordinate variable $x_i$, and the first derivatives of displacement $u_{k,j}$, i.e.,

$$\Lambda = -W(x_i, u_{k,j}) \tag{1}$$

The balance laws of the configurational forces can be deduced by subjecting the Lagrangian density to the gradient operation. It is performed by

$$\nabla(\Lambda) = -(W)_{,i} = -\left(\frac{\partial W}{\partial x_i}\right)_{\text{expl}} - \frac{\partial W}{\partial u_{k,j}} u_{k,ji} \tag{2}$$

where $(\partial W/\partial x_i)_{\text{expl}}$ denotes the explicit dependence of $w$ on $x_i$.

By using the definition of the Cauchy stress tensor $\sigma_{kj}$ from the strain energy density and its symmetry,

$$\sigma_{kj} = \sigma_{jk} = \frac{\partial W}{\partial \varepsilon_{kj}} = \frac{\partial W}{\partial u_{k,j}} \tag{3}$$

where the components of strain tensor $\varepsilon_{kj}$ in an elastic solid regarding as the gradient of displacements are

$$\varepsilon_{kj} = \frac{1}{2}(u_{k,j} + u_{j,k}) \tag{4}$$

Eq. (2) can be rearranged to arrive at