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A model for the prediction of debond onset in spherical-particle-reinforced composites under tension. Application of a coupled stress and energy criterion

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ABSTRACT

A theoretical model is developed to predict debond onset in spherical-particle-reinforced composites subjected to uniaxial tension. The coupled stress and incremental energy criterion of the finite fracture mechanics is applied employing an axisymmetric boundary element method code, which is highly accurate in the analysis of interface cracks in presence of contact. The model enables to predict the value of the critical remote load and the spherical angle of the debond after the onset as a function of the particle, matrix and interface properties and particle size. Results predicted are compared with experimental observations found in the literature.

1. Introduction

Particle-reinforced composites are extensively used in a variety of industrial applications. Their main advantages over the fiber-reinforced composites are cost-effectiveness and manufacturing flexibility since they can be machined with the majority of traditional manufacturing processes designed for metals. In particular, spherical particles are usually employed as a reinforcement to enhance tensile strength, stiffness, tear and abrasion resistances of polymeric matrices [1,2] or to increase fracture toughness of ceramic matrices [3].

The manner in which the reinforcement modifies the failure properties of the unreinforced matrix is closely related to the reinforcement geometry, the contrast in elastic properties between reinforcement and matrix, and the mechanical behavior of the interface between them. The dependence between the macroscopic properties of the composite and these parameters has been observed in several experiments, see [1] for a review. In particular, experiments show that the particle size affects significantly the tensile strength. In the specific case of reinforcements at a micro scale, composites with smaller particles present a higher tensile strength [4–6]. This is due to the influence of the microstructure on the first stages of the failure mechanisms. In fact, microscopic observations [6] show that failure initiates as debonds at the particle–matrix interface which subsequently grow along the interface up to an angle for which the debonds kink out of the interface to coalesce with others.

The importance of these composites and the observed influence of the reinforcement and interface properties on the strength have encouraged a wide variety of analysis at the reinforcement scale which is usually micro or nano. The problem of a spherical particle embedded in a matrix has been intensively studied since the seminal works by Goodier [7] and Eshelby [8] who introduced solutions and formalisms for this geometry assuming isotropic elastic materials. The solution of the basic problem of a spherical particle embedded in an infinite matrix, assuming a perfect particle–matrix interface, subjected to a uniaxial tension [7] is fundamental in understanding micromechanics of particle-reinforced composites. When the spherical particle is stiffer than the matrix, this solution shows a stress concentration at the poles of the sphere axis parallel to the tension direction. As a consequence, these are *a priori* preferred points for a failure initiation in the form of a debond at (or a void near) the interface. A broad variety of works have been presented dealing with the interface debond onset and growth by different approaches, e.g. stress analysis assuming an elastoplastic matrix [9,10], cohesive zone models for the interface [11–15] or using an energy criterion assuming a material-dependent critical debond angle [16].

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This work aims to develop a model to predict the debond onset at the particle–matrix interface as a function of the particle, matrix and interface properties using the coupled criterion [17] of the finite fracture mechanics (FFM) [18]. This criterion is based on two key assumptions: (i) the debond size at the onset is assumed to be finite, and (ii) the condition for the debond onset is given by the simultaneous fulfillment of two criteria: a criterion on stresses at points where the debond will appear and an energy criterion assuring that the debond onset is energetically allowed. This coupled criterion has been applied to different problems to predict crack initiation in an intermittent manner during the last half-century, see, e.g., [19] for a similar problem to that studied here but assuming particles and matrix to be similar materials. Since the publication of Leguillon's formal proposition [17] on the need of fulfilling both criteria, referred to hereinafter as Leguillon's hypothesis, a wide variety of models studying other problems applying this idea has been presented which agree with experiments [20–26]. In particular, some works applying the coupled criterion dealing with similar problems to the present one have been presented in [26–28], for long fiber inclusions, and in [29], for nano-spherical inclusions subjected to hydrostatic-tension loading.

2. A theoretical model based on the finite fracture mechanics

Consider a piece of a composite reinforced by spherical particles subjected to a remote uniaxial tension $\sigma^\infty > 0$ as shown in Fig. 1(a). Under the assumption of dilute packing (with a low reinforcement volume fraction), the present work focuses on the debonding process at the interface of a single particle by neglecting the influence of the neighboring ones. Thus, the geometry under study is simplified to that shown in Fig. 1(b): a spherical particle of radius a perfectly bonded to an infinite surrounding matrix. In the context of the present model, the spherical particles are assumed to be stiffer than the surrounding matrix. Both particles and matrix are assumed to be isotropic and linear elastic. For the sake of illustration of the model, we take as a reference a glass/vinylester composite used in experiments in [6] with Young's modulus $E_1 = 70$ GPa and $E_2 = 3.5$ GPa for glass and vinylester respectively and Poisson's ratio $\nu_1 = 0.25$ and $\nu_2 = 0.35$. As will be justified in Section 2.1, preferred points for debonding are situated at the poles of the sphere axis parallel to the load direction. In view of this, for a certain critical value of the remote load σ_c^∞, two debonding modes will be studied in the following: the onset of either a single debond at one of the poles or two symmetric debonds at both poles, see Fig. 1(c). As both geometries and loads are axisymmetric, the problem is solved as an axisymmetric one, see [30], measuring all the angles from the symmetry axis.

Following the FFM approach [17,18,20], next subsections will be devoted to obtain the independent conditions imposed by the stress and energy criteria for the debond onset. Finally, and according to Leguillon's hypothesis [17], the critical value for the remote load leading to the debond onset σ_c^∞ is obtained as the minimum value of σ^∞ fulfilling both criteria.

2.1. Stress criterion

In general, the stress criterion (sometimes referred to as strength criterion) imposes that stresses prior to the debond onset along the path assumed for it have to exceed a certain critical value. Several forms of such a stress criterion have been proposed to apply this condition. First tensile criteria considered only normal stresses pointwise [17,27,28] or in average sense [20,23–25], see [24] for a comparison. Subsequently and in order to take into account the influence of the shear stresses, polynomial expressions for the stress criterion combining normal σ and shear τ stresses were proposed [26,31] based on experimental evidences [32,33]. These expressions were proposed assuming the absence of compressions. In fact, when the polynomial degree is even, these expressions predict a reduction of the critical value for the shear stresses in presence of compressions, which has not physical sense. The following generalization, which agrees with previous polynomial expressions for $\sigma \geqslant 0$, is proposed here to avoid this problem:

$$\sigma_{eq}(\sigma,\tau) = \sqrt[p]{\left\langle \mathrm{sgn}(\sigma)|\sigma|^p + \left(\frac{|\tau|}{\mu}\right)^p \right\rangle_+}, \tag{1}$$

where $\mu = \tau_c/\sigma_c$, with σ_c and τ_c being the interface tensile and shear strength, $p > 0$, and $\langle\cdot\rangle_+$ denotes the positive part of a real number. A similar proposal of an equivalent stress with $p = 2$ can be found in [34] (Section 7.7.2). For the sake of illustration, $p = 2$ and $\mu = 1$ are chosen in the present work. According to this criterion, a debond can appear at those points of the interface where

$$\sigma_{eq}(\sigma,\tau) \geqslant \sigma_c. \tag{2}$$

In view of (1) and (2), the interface tractions in the case of undamaged interface, see Fig. 1(b) are required in this criterion. The analytic solution of this problem, assuming an infinite matrix subjected to the remote tension σ^∞ and defining the angle θ measured from the axisymmetry axis,

$$\sigma(\theta) = \sigma^\infty\hat{\sigma}(\theta) = \sigma^\infty(k + m\cos 2\theta), \quad \tau(\theta) = \sigma^\infty\hat{\tau}(\theta) = \sigma^\infty m \sin 2\theta \tag{3}$$

was deduced in [7], from where explicit expressions of the dimensionless parameters $k(E_1,\nu_1,E_2,\nu_2)$ and $m(E_1,\nu_1,E_2,\nu_2)$ can

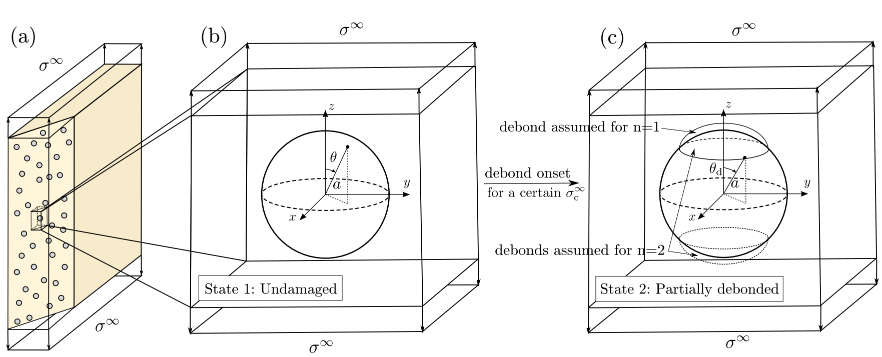

Fig. 1. Schematic of the models employed to study the process of debond initiation at microparticles-reinforced composites under the assumptions of the finite fracture mechanics. (a) Particle-reinforced composite specimen subjected to tension, spherical particle (b) perfectly bonded to the surrounding matrix or (c) partially debonded at the interface.