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Improvements of strength and fracture resistance by spatial material property variations

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Abstract

A material with spatial variation in the elastic modulus E can have a much higher apparent fracture resistance and fracture stress than a comparable homogeneous material. The effect occurs due to the strong decrease of the crack driving force, which leads to crack arrest when the crack tip is located in the region with low elastic modulus. From the results of exemplary numerical studies and simple fracture mechanical considerations, models are derived in order to predict the fracture stress and fracture toughness of the inhomogeneous materials. It is shown that high values of fracture stress and fracture toughness can be reached if the amplitude of the E variation is high enough to provide crack arrest and the wavelength of the E variation is small. The beneficial effect of material property variations also occurs if the width of the compliant region is very thin and the loss in stiffness of the structure is almost negligible. The concept is applicable for various types of composite materials; examples are presented.

Keywords: Multilayered materials; Composites; Fracture toughness; Finite element modeling; Configurational forces

1. Introduction

A common feature that is inherent to all classes of multiphase and composite materials is that a spatial variation of material properties influences the crack driving force and thus affects the fracture resistance. This effect is fundamentally different from the effects of crack deviation and interface opening that are often observed in composite materials. The fact that spatial variations of material properties influence the crack driving force has been known for a long time already, e.g. see the literature reviews given in Refs. [1,2]. However, an appropriate tool for the accurate quantification of this effect has been found only recently in form of the concept of configurational forces (see Section 2). Compared to other studies in the literature (e.g. [3–7]), a big advantage of the concept of configurational forces is that it does not rely on specific constitutive relations of the material or on the applicability of linear elastic fracture mechanics.

By applying the concept of configurational forces, the crack driving force of a long crack in a layered material with smooth, periodic variations of the elastic modulus E was estimated by a semi-analytic model in Ref. [8]. Although the results might be blurred by the simplicity of the model, the study shows that the crack driving force exhibits local variations, which might lead to crack arrest when the ratio between maximum and minimum elastic modulus is large and the transition between the stiff and compliant regions is rather sharp. In a more recent paper

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[9], it has been shown by finite element computations and analytical derivations that an elastic, lamellar composite consisting of a brittle bulk material and thin, compliant interlayers has a much higher fracture stress than the corresponding homogeneous bulk material, provided that certain architectural criteria are fulfilled. The basic mechanism is the strong decrease of the crack driving force when a small crack, which has been initiated in the bulk, enters the soft layer.

The purpose of this paper is to generalize the findings of the two above-mentioned papers. Numerical investigations of the effect of material property variations on the crack driving force and the fracture resistance will be presented for elastic materials with spatial variations of the elastic modulus E. General conclusions will be drawn about the fracture resistance and the fracture stress of the materials. The findings will be compared to experimental results. A thorough understanding of the material inhomogeneity effect will allow us (i) to understand better the influence of the microstructure on the fracture and fatigue properties and (ii) to design materials with highly improved resistance against fracture and fatigue.

The following section presents a short review of the material inhomogeneity effect on the crack driving force.

2. Crack driving force in inhomogeneous materials and material inhomogeneity effect

We consider configurations where the material properties exhibit a variation in the nominal direction of crack extension. Hereby, the crack driving force, expressed in terms of either the stress intensity factor K or the near-tip J integral J_{tip} [10], is a function of the location of the crack tip with respect to the material property variation. Analytical solutions are available for several specific geometries and specific functional forms of the variation of the elastic modulus (e.g. [11,12]). Several semi-analytic procedures have been developed for calculating the crack driving force (e.g. [4,6]); a recent review can be found in Ref. [2]. An analytical model for the effect of the variation of the yield stress can be found in Ref. [13]. Numerous conventional numerical studies have been published where the crack driving force is evaluated for specific material systems and configurations. In most cases it is difficult, however, to draw general conclusions from such studies.

The concept of configurational forces [14–19] has brought new insight into this topic; see Refs. [1,20,21] for summaries of the state of the art. According to this concept, the driving force of a crack in an inhomogeneous material is determined by the relation

$$J_{\text{tip}} = J_{\text{far}} + C_{\text{inh}}. \tag{1}$$

In Eq. (1), the parameter J_{tip} denotes the crack driving force in terms of the near-tip J integral; the far-field J integral J_{far} represents the driving force that is inserted by the applied load into the body. The parameter C_{inh} is called the material inhomogeneity term; it represents the driving force term induced by the material inhomogeneity in the body. In a homogeneous body, $C_{\text{inh}} = 0$ and the J integral is path-independent, $J_{\text{tip}} = J_{\text{far}}$ [10]. The material inhomogeneity has a crack tip shielding effect, if C_{inh} is negative and J_{tip} becomes smaller than J_{far}. Results of case studies [1,21–23] demonstrate that crack tip shielding occurs when a crack propagates from a material with a lower elastic modulus towards a material with a higher elastic modulus (compliant/stiff transition). For a stiff/compliant transition, crack growth is promoted, since C_{inh} is positive and J_{tip} becomes larger than J_{far}; the material inhomogeneity has an anti-shielding effect. It is also important to note that the material inhomogeneity effect can become large. The theoretical limit of the crack driving force J_{tip} becomes zero or infinity, if the crack tip reaches the interface. A material inhomogeneity effect occurs also in components with constant elastic modulus but a spatial variation in yield stress [13,20,23].

A material inhomogeneity effect occurs also in components with constant elastic modulus but a spatial variation in yield stress [13,20,23]. The material inhomogeneity term is negative, i.e. a shielding effect occurs, for a soft/hard transition; anti-shielding occurs for a hard/soft transition. The yield stress inhomogeneity effect is more local than the effect of elastic modulus inhomogeneity, since a jump in strain or strain energy density occurs only if the crack tip plastic zone is in contact with the interface. The application of the J integral for elastic–plastic materials as a parameter, which characterizes the crack driving force for stationary and growing cracks, has been investigated in Refs. [24,25].

In the following two sections, principles are used to calculate how the material inhomogeneity effect influences both the fracture resistance and the fracture stress of materials. In order to do this, the case of a material with sinusoidal variation of the elastic modulus is reconsidered, which has been treated in Refs. [2,8] already. In these two papers, semi-analytic models have been applied to estimate the variation of the crack driving force in such materials for different positions of the crack tip. In this paper, more accurate numerical results are presented and the consideration is extended by calculating the variation of the crack driving force during crack extension. This will allow us to assess the increase in fracture resistance and fracture stress of a material with sinusoidal E variation compared to a homogeneous material. For the estimate of the improvement in fracture stress, we will adopt a procedure that has been worked out in Ref. [9].

3. Crack growth resistance of a material with sinusoidal variation of elastic modulus

We consider a linear elastic material where the elastic modulus E exhibits a sinusoidal variation with respect to the horizontal direction X,