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Cracks in inhomogeneous materials: Comprehensive assessment using the configurational forces concept ☆

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ABSTRACT

The concept of configurational forces is applied to demonstrate the application of the concept of configurational forces in the numerical simulation of crack growth and fracture processes. It is shown, how material property variations at an interface affect the crack driving force and how the criterion of maximum dissipation is used to evaluate the direction of crack propagation. Fatigue crack growth experiments were conducted on diffusion welded bimaterial specimens consisting of a high-strength steel and soft ARMCO iron. Two cases are considered: (1) specimens with an interface perpendicular to the initial crack orientation, and (2) specimens with an inclined interface. The numerical simulation with the concept of configurational forces show that not only variations of the elastic modulus and/or the yield stress have a tremendous influence on the crack driving force, the crack growth rate, and the curvature of the crack path, but also the thermal residual stresses that resulted from a rather small difference of the coefficient of thermal expansion.

1. Introduction

A very interesting and actual topic in fracture research is the behavior of cracks in inhomogeneous materials and components. Most natural and technical materials have per se a heterogeneous micro- and nano-structure. Often the material properties are intentionally varied, e.g. to combine high hardness and wear resistance at the surface and good toughness in the interior in a cutting tool. Advanced multi-phase or composite materials are increasingly applied in all fields of engineering, and many components exist that are made of combinations of different material types, e.g. think of nitrided steels, brazed or welded components, materials with coatings, functionally gradient materials, multilayered components, fiber reinforced composites, or microelectronic systems.

Multi-phase and composite materials exhibit spatial variations in the local material properties; terms such as "elastically" or "plastically inhomogeneous materials" have been introduced for materials with a variation of the Young's modulus or the yield strength, respectively. Many inhomogeneous materials exhibit also spatial variations in the local residual stresses. Residual stresses are generated most often by cooling during the production route, caused by a difference in the coefficient of thermal expansion (CTE) of the components of the material, but they may be caused also due to phase transformations or plastic pre-deformation, e.g. due to machining.

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It is well known that material inhomogeneities influence both the crack driving force and the crack path. Quantitative descriptions of the behavior of cracks were available in the past only for linear elastic materials and special geometries, see the literature reviews presented in [1]. Recently, the concept of configurational forces has been extended to quantify the behavior of cracks in inhomogeneous materials [1,2]. This concept allows us:

1. To evaluate the crack driving force in arbitrary inhomogeneous materials and components, see e.g. [3].
2. To take into account the influences of eigenstrains and residual stresses [4–6].
3. To estimate the crack growth direction using the criterion of maximum dissipation [7].

In the current paper, first a short overview shall be given about theory and some computational aspects. Then exemplary examples are presented in order to demonstrate the abilities of the concept with respect to the points listed above.

2. The concept of configurational forces for the description of crack growth in inhomogeneous materials

The concept of configurational (or material) forces, which rests on ideas by Eshelby [8], is outlined in the books by Maugin [9], Gurtin [10], or Kienzler and Herrmann [11]. The theory is appropriate for analyzing the behavior of all kinds of defects in materials, such as point defects, dislocations, cracks, interfaces, phase boundaries, voids, or inclusions. The great versatility of the concept is shown, for example, in the papers [12–16]. The importance of the configurational forces for studying fracture has been noticed, for example in [17–19]. Only few papers exist, where the configurational forces approach has been used for the description of fracture processes in inhomogeneous materials, e.g. Honein and Herrmann [20].

Fig. 1 shows a two-dimensional (2D) body B containing a crack and a sharp interface Σ. The material properties exhibit a jump at the interface. The configurational body force $\mathbf{f}$ can be derived from the divergence of the configurational stress, $\mathbf{C}$,

$$\mathbf{f} = -\nabla \cdot \mathbf{C} = -\nabla \cdot (\phi \mathbf{I} - \mathbf{F}^{\mathrm{T}}\mathbf{S}), \tag{1}$$

where ∇ is the Lagrangian gradient operator, ϕ the strain energy density, $\mathbf{I}$ the identity tensor, $\mathbf{F}^{\mathrm{T}}$ the transposed of the deformation gradient, and $\mathbf{S}$ the 1st Piola–Kirchhoff stress [2]. The configurational force at the crack tip $\mathbf{f}_{\mathrm{tip}}$ is given by

$$\mathbf{f}_{\mathrm{tip}} = -\lim_{r \to 0} \int_{\Gamma_r} (\phi \mathbf{I} - \mathbf{F}^{\mathrm{T}}\mathbf{S})\mathbf{m}\, dl, \tag{2}$$

and the configurational forces along the interface $\mathbf{f}_{\Sigma}$ by

$$\mathbf{f}_{\Sigma} = -([[\phi]]\,\mathbf{I} - [[\mathbf{F}^{\mathrm{T}}]] \cdot \langle \mathbf{S} \rangle)\mathbf{n}. \tag{3}$$

The vector $\mathbf{m}$ is the unit normal to a circle Γ_r centered at the crack tip, the vector $\mathbf{n}$ is the unit normal to the interface Σ. The jump of a quantity $\mathbf{a}$ at the interface is designated $[[\mathbf{a}]] = (\mathbf{a}^+ - \mathbf{a}^-)$; the average of a quantity $\mathbf{a}$ across the interface is designated $\langle \mathbf{a} \rangle = (\mathbf{a}^+ + \mathbf{a}^-)/2$, where $\mathbf{a}^+$ and $\mathbf{a}^-$ denote the limiting values of the quantity on either side of the interface.

The configurational force at the crack tip can be related to the near-tip J-integral,

$$J_{\mathrm{tip}} = \mathbf{e} \cdot \mathbf{f}_{\mathrm{tip}}, \tag{4}$$

with $\mathbf{e}$ as the unit vector in the direction of crack growth. The dissipation at the crack tip follows as

$$\Psi_{\mathrm{tip}} = (-\mathbf{f}_{\mathrm{tip}}) \cdot \mathbf{v}_{\mathrm{tip}} \geqslant 0. \tag{5}$$

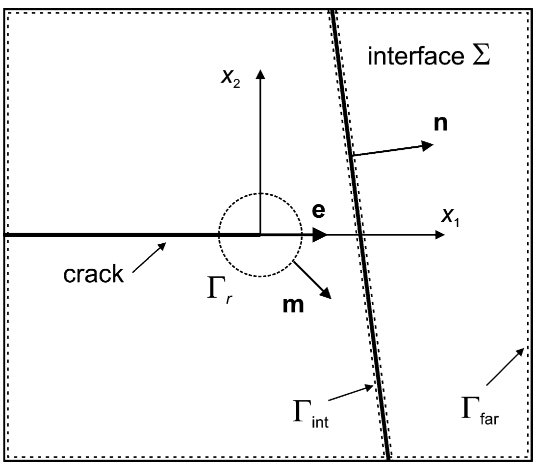

Fig. 1. A two-dimensional bimaterial body containing a crack and a sharp interface.