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To the design of highly fracture-resistant composites by the application of the yield stress inhomogeneity effect

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ABSTRACT

Improvement of the fracture toughness by the introduction of thin, soft interlayers is investigated. The mechanism is the strong decrease of the crack driving force when the crack tip is located in the soft region. Based on numerical simulations with the configurational forces concept, it is demonstrated that the fracture toughness of brittle materials can be greatly improved by the introduction of soft interlayers, if the architectural parameters of the multilayer are appropriately chosen. The findings are compared to experimental results of fracture tests conducted on compounds made of high-strength steel as matrix and low-strength steel as interlayer material. The design concept presented in this paper can be applied for various types of composite materials.

1. Introduction

Increasing strength leads to a decrease in fracture toughness. This general rule applies to most engineering materials and alloys. A new and innovative method to break this rule is to utilize the *material inhomogeneity effect* [1–4] by inserting soft interlayers into the material. The interlayers act as crack arresters so that the fracture toughness strongly increases. If the soft interlayers are thin, the loss in strength is almost negligible.

Numerous researchers have shown in theoretical, numerical, and experimental studies that the variations of material properties in the direction of the crack extension can significantly affect the growth or arrest of cracks. A brief survey of those studies has been given in [5]. The material inhomogeneity effect is based on the fact that spatial variations in material properties have a large influence on the crack driving force, i.e. a material inhomogeneity can hinder or promote crack propagation [1–13]. For example, the crack driving force decreases, if a crack grows from a region with lower Young's modulus towards a region with higher Young's modulus. The same occurs, if a crack grows from a region with lower yield stress towards a region with higher yield stress. In our terminology, compliant/stiff and soft/hard transitions provide a crack-tip shielding effect, which hinders crack propagation. In contrast, stiff/compliant and hard/soft transitions provide an increase of the crack driving force, i.e. anti-shielding, which promotes crack propagation.

Experimental evidence of the material inhomogeneity effect has been presented, e.g. in [9,14–17]. More recent experimental investigations have also shown that layers with different material properties are beneficial for the fracture and impact toughness of materials. For example, it has been shown that the properties of a brittle intermetallic compound Ti_3Al can be greatly improved by inserting thin ductile metal interlayers [18,19]. The ductile layers work as efficient crack arresters and, thus, the fracture strength of the composite becomes significantly higher than that the bulk Ti_3Al. Coatings made of amorphous Fe-based alloys have been reinforced by an amorphous carbon phase in [20] and by crystalline NiCrAl-layers in [21], respectively. In both cases, the new composites exhibited enhanced impact resistance (and also a higher fatigue strength in the former case) than the monolithic amorphous coating. Multilayered thin films made of alternative TiN and SiO_x layers have been found to exhibit a fracture toughness that is up to 60% higher than that of the single-layered constituents [22]. A similar behavior has been found for thin films made of CrN and Cr [22]. Multilayered films made of alternative Si and Ag layers of equal thickness on various substrate materials were investigated in [23]. It has been found that the crack initiation strains strongly increased with decreasing layer thickness. The important aspect of crack initiation in multilayers has been treated with the concept of finite fracture mechanics, see e.g. the review in [24]. Macro-scale impact tests were conducted on glass laminates with a single soft adhesive interlayer in [25,26]. The experiments have shown that the adhesive interlayers significantly improve the impact resistance of the brittle glass and the crack arrest time at the adhesive layer increases with increasing thickness of the adhesive interlayer.

The material inhomogeneity effect works for both abrupt and

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smooth spatial variations of material properties and is fundamentally different from other toughening mechanisms in composite materials, such as interface delamination [27–30], crack deflection [29,31,32] and compressive residual stresses [31,33–35].

The strength, i.e. the fracture stress in a tensile test, of intrinsically brittle materials is determined by the initiation and growth of *small* defects − in contrast to ductile materials where the strength is determined by a plastic limit load. In previous papers, we derived models for predicting the *strength* of multilayers consisting of brittle matrix materials and thin, compliant [2,3] or soft [4] interlayers. It was shown that the introduction of thin, compliant or soft interlayers can significantly improve the strength of brittle materials. An iterative procedure has been outlined in [4] in order to find, for a given matrix material and applied load, the optimum multilayer architecture, which is determined by interlayer thickness t and interlayer spacing (wavelength) λ.

Contrary to strength, *fracture toughness* is determined by fracture mechanics experiments on specimens with *long* cracks. It was demonstrated in [3] that a linear elastic material with spatial variation of the Young's modulus exhibits significantly higher fracture toughness than a corresponding homogeneous material. It was shown that the improvement depends on the amplitude of the E-variation; however, a quantification of the effect was not possible at that time.

In the current paper, the fracture toughness of a multilayer with constant Young's modulus E and spatial variation of the yield stress σ_y is considered. By numerical simulations and fracture mechanical considerations, the improvement in fracture toughness of such a multilayer structure is quantified as a function of the variation of σ_y, the architectural parameters of the multilayer (interlayer thickness t and -spacing λ), and the fracture toughness of the homogeneous matrix material. An iterative procedure is presented for predicting the fracture toughness of the multilayer. This procedure shall be applicable for designing fracture-resistant composites based on the yield stress inhomogeneity effect. The purpose of this design is to find, for a given matrix material, the appropriate interlayer material and architecture (t and λ in Fig. 1b) of the composite so that a desired improvement in fracture toughness is achieved. The findings are compared to results of experiments conducted on steel compounds consisting of a high-strength steel as matrix and a low-strength steel as interlayer material.

2. Estimate of the fracture toughness for multilayers with thin, soft interlayers

2.1. Condition for initiation of crack growth

Assume a homogeneous specimen consisting of a brittle material with an initial crack of length a_0, Fig. 1a. When the crack starts to grow, it usually does not stop growing until the whole specimen is fractured. The condition for initiation of crack growth is,

$$J_{\text{tip}} \geqslant J_{\text{c}}^{\text{M}}, \tag{1}$$

where J_{c}^{M} is the fracture initiation toughness of the material in terms of the J-integral, determined by a fracture mechanics experiment [36], and the near-tip J-integral J_{tip} characterizes the crack driving force. The J-integral is path-independent in homogenous materials. The J-integral of the homogeneous specimen can be expressed via the stress intensity factor K as [36],

$$J_{\text{far}}^{\text{hom}} = J_{\text{tip}}^{\text{hom}} = \frac{K^2(1-\nu^2)}{E} = \frac{\sigma_{\text{appl}}^2(1-\nu^2)}{E}\pi a_0\left[f_K\left(\frac{a_0}{W}\right)\right]^2, \tag{2}$$

where σ_{appl} denotes the applied global stress, E the Young's modulus, ν Poisson's ratio, W the width of the specimen, and f_K is a dimensionless geometry parameter. Eq. (2) is valid for linear elastic and small-scale yielding conditions.

2.2. Soft interlayer as a crack arrester

Now assume that the specimen is made of a multilayer consisting of the same matrix material and thin, soft interlayers (ILs), as depicted in Fig. 1b. IL1 to IL4 lie in front of the crack tip, IL0 to IL-2 behind it. Since the IL-material has equal elastic properties as the matrix material (M), but a lower yield stress, $\sigma_y^{\text{IL}} < \sigma_y^{\text{M}}$, a material inhomogeneity effect only appears if plastic deformation occurs, i.e. if the crack-tip plastic zone touches an interlayer [7]. Then the J-integral becomes path-dependent, and the far-field J-integral, J_{far}, which characterizes the driving force that is inserted by the applied load into the body, differs from the crack driving force, J_{tip} [11].

Since $\sigma_y^{\text{IL}} < \sigma_y^{\text{M}}$, the crack-tip plastic zone is larger in the interlayer material than in the matrix, $r_y^{\text{IL}} > r_y^{\text{M}}$. The radius of the plastic zone in the interlayer material can be estimated from Irwin's model [37],

$$r_y^{\text{IL}} = \beta\frac{J_{\text{far}}E}{(1-\nu^2)(\sigma_y^{\text{IL}})^2}, \tag{3}$$

where $\beta = 1/(6\pi)$ for plane strain conditions. Each interlayer has two sharp interfaces, IF1 and IF2, see Fig. 1d.

The effect of the material inhomogeneity due to the interlayer on the crack driving force can be quantified by the term $C_{\text{IL}} = C_{\text{inh1}} + C_{\text{inh2}}$, which is called "interlayer inhomogeneity term" [4,5]. The parameters C_{inh1} and C_{inh2} are the material inhomogeneity terms of the interfaces IF1 and IF2, respectively. The material inhomogeneity term C_{inh} represents the driving force term induced by the material inhomogeneity at an interface, see the derivations based on the configurational force concept presented in [38,39]. Due to a hard/soft transition, IF1 induces anti-shielding effect and C_{inh1} is always positive. A soft/hard transition at IF2 provides a crack tip shielding effect; C_{inh2} is negative. The crack driving force J_{tip} for a specimen with a single interlayer can be determined from the relation, $J_{\text{tip}} = J_{\text{far}} + C_{\text{IL}}$ [4,5].

Fig. 1d shows, for a specimen with a single interlayer, schematically the variation of the crack driving force J_{tip} for a constant J_{far} and various crack tip positions: J_{tip} is plotted against the distance L_1 between crack tip and IF1. A crack far from the interlayer is not influenced by the material inhomogeneity, $C_{\text{IL}} \approx 0$ and $J_{\text{tip}} \approx J_{\text{far}}$ for $|L_1| > r_y^{\text{IL}}$. When the crack approaches the interlayer from the left, J_{tip} first increases, since IF1 is closer to the crack tip than IF2; therefore, crack growth is promoted. Subsequently, J_{tip} precipitously decreases due to the shielding effect of IF2. The minimum value of J_{tip} is reached immediately after the crack tip has crossed IF2. This position, referred to as the "crack arrest (CA-) position", is critical for the fracture toughness of the composite, since the crack must overcome this position for further crack growth. The crack is arrested, if the crack driving force for a crack tip located at the CA position, $J_{\text{tip}}^{\text{CA}}$, is smaller than the fracture initiation toughness of the matrix material, $J_{\text{tip}}^{\text{CA}} < J_{\text{c}}^{\text{M}}$; hereby it is assumed that the fracture initiation toughness of the matrix material in the multilayer equals that of the homogeneous matrix material. The arrested crack will start to grow again and the single-interlayer composite will fracture completely, if the load increases so that $J_{\text{tip}}^{\text{CA}} = J_{\text{c}}^{\text{M}}$.

The situation in the multilayer is similar: It will fracture, if the crack is able to overcome the CA-position of the first interlayer, IL1, in front of the crack tip, Fig. 1b. In the following, the fracture toughness of the multilayer, J_{c}^{ML}, shall be estimated.

2.3. Fracture toughness of multilayers

If the volume fraction of the interlayer material is low, i.e. for $t \ll \lambda$ (Fig. 1b), the far-field J-integral of the arrested crack in the multilayer, $J_{\text{far}}^{\text{CA}}$, can be approximated from Eq. (2), but with the crack length a_0 replaced by the length of the arrested crack, $a_{\text{CA}} = a_0 + \Delta a_{\text{CA}}$, yielding

$$J_{\text{far}}^{\text{CA}} = \frac{\sigma_{\text{appl}}^2(1-\nu^2)}{E}\pi a_{\text{CA}}\left[f_K\left(\frac{a_{\text{CA}}}{W}\right)\right]^2. \tag{4}$$

The crack driving force of the arrested crack, $J_{\text{tip}}^{\text{CA}}$, can be determined