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# Improving strength and toughness of materials by utilizing spatial variations of the yield stress

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The introduction of thin interlayers with low yield stress can greatly improve the strength and the fracture toughness of inherently brittle materials. The reason is that the spatial yield stress variation affects the crack driving force, which strongly decreases when the crack tip is located in the interlayer region, near the boundary to the hard matrix material. This can lead to crack arrest. The material inhomogeneity effect appears without previous delamination of the interlayer. The decisive parameters influencing the effect are the interlayer spacing (the wavelength of the yield stress variation), the interlayer thickness and the yield stress ratio between interlayer and matrix. Based on numerical simulations with the configurational forces concept, it is demonstrated how the architectural parameters of the multilayer must be chosen in order to enhance the fracture stress and the fracture toughness of the material. An iterative procedure is proposed to find the optimum configuration. It is found that the optimum wavelength is inversely proportional to the square of the applied stress. A similar relation is given for composites with spatial variations in Young's modulus.



## 1. Introduction

The design of stronger and tougher materials has been in the focus of researchers throughout the last decades. In particular, the introduction of layered structures has been proposed as a promising way for the material improvement. The most relevant mechanisms behind the improvements are

- Interface delamination: In structures with weak interfaces, the hydrostatic stress state strongly decreases due to the opening of the interface, which leads to a reduction of the crack driving force. In addition, the sharpness of the crack tip is lost when the crack grows into the delaminated interface. The increase in fracture toughness is especially high for a crack arrester configuration, i.e. when the interfaces are perpendicular to the nominal crack plane [1–5].
- Crack deflection: The interface delamination can result in crack deflection which significantly reduces the Mode I component of the local stress intensity factor and enhances the fracture toughness [3,6–8].
- Compressive residual stresses: In multilayered structures with tailored residual stress variations, layers under compressive residual stresses act as barriers to crack propagation due to the reduction of the crack driving force [9–14].
- Reduction of defect probability: Based on Weibull's theory [15], the average fracture stress of intrinsically brittle materials increases with decreasing specimen volume, since the probability for the presence of a defect with critical size decreases. Therefore, the strength of a material increases when replacing a compact material by a layered structure [16,17].

There exist numerous literature where the strength or the fracture toughness of layered composites is investigated as a function of the layer geometry and the material properties. However, in most of these studies, e.g. Refs. [1–5,9–13], interface delamination and/or residual stresses are utilized in order to increase the fracture resistance. The current paper concentrates on an alternative method for designing new fracture-resistant and flaw-tolerant materials: the utilization of the material inhomogeneity effect. The effect is based on the fact that a spatial variation of material properties in the direction of crack extension leads to a

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spatial variation of the crack driving force and, thus, affects the fracture toughness [17–25]. For example, the crack driving force decreases, if a crack grows from a material with lower elastic modulus towards a material with higher elastic modulus. Due to the lower crack driving force, a higher load is required for crack propagation compared to the situation in a homogeneous material. In other words, a compliant/stiff transition provides a crack tip shielding effect. In contrast, a stiff/compliant transition provides anti-shielding effect. For the quantification of the material inhomogeneity effect, the concept of configurational forces has been applied [21–23,26–29]. Note that the material inhomogeneity effect does not require interface opening; it even occurs, if the Young's modulus exhibits a smooth variation [20,27]. Therefore, it is fundamentally different from the above mentioned effects of interface delamination.

Especially interesting for materials design is the introduction of thin, *compliant* interlayers in high-strength matrix materials with low intrinsic toughness [17,21,25,30]. Anti-shielding and shielding appear pairwise at the two interfaces of the interlayer, compare Fig. 1. If the material properties, the thickness and the spacing of the interlayers are appropriately chosen, the strong decrease of the crack driving force at the second interface of the interlayer leads to crack arrest, and fracture toughness and strength of the composite become much higher than the values of the homogeneous matrix material [17,21]. Since the interlayers are thin, the stiffness of the composite almost equals that of the matrix.

It is worth noting that the material inhomogeneity effect can be also utilized to improve the toughness of materials against interfacial cracking. Theoretical studies and tape peeling experiments by Kendall [31], discussed in Ref. [32], showed that a crack tip shielding effect occurs when an interface crack propagates from a more compliant (or thinner) tape to a stiffer (or thicker) tape. This idea can be applied for the design of tough surface coating composites where failure occurs by peeling [31].

It was shown that a *soft* interlayer, i.e. an interlayer with the same Young's modulus but a lower yield stress than the matrix material, also works as effective crack arrester, provided that the difference in yield stress and the thickness of the interlayer are appropriately chosen [23]. The reason is that a soft/hard transition also delivers a crack tip shielding effect, and vice versa [20,26,28,33]. The yield stress inhomogeneity effect opens additional possibilities for the design of tough, strong and damage-tolerant composites by inserting soft interlayers in high-strength, brittle matrix materials. Therefore, in the current paper the anti-shielding and shielding effects in a material with soft interlayers shall be investigated and a procedure shall be introduced how to find, for a given matrix material, the architectural parameters of the composite, i.e. yield strength, thickness and spacing of the soft interlayers (compare Fig. 4a), so that the properties improve.

The following section presents a short review of the influence of a single soft interlayer on the crack driving force. Then the effects of a single-interlayer specimen and a multilayer configuration are studied. Fracture mechanical considerations are then used to derive a criterion for finding the optimum spacing of the interlayers. The criterion is applied for various types of composite materials and loading scenarios; examples are presented.

## 2. Influence of a single, soft interlayer on the crack driving force

Sistaninia and Kolednik [23] examined the influence of a single soft interlayer on the crack driving force. Their findings are briefly presented in this section.

Fig. 1a shows a fracture mechanics specimen that contains a single interlayer with two sharp interfaces, IF1 and IF2. The interlayer material has equal elastic properties as the matrix material, but a lower yield stress, $\sigma_y^{IL} < \sigma_y^{M}$. Both materials are homogeneous and behave elastic–ideally plastic, i.e. do not exhibit hardening. The interfaces are assumed as being perfect, i.e. no interface decohesion can occur. A straight crack is assumed lying perpendicular to the interlayer; $L_1$ and $L_2$ are the distances between the crack tip and IF1 and IF2, respectively. When the crack tip is situated left of an interface, $L$ is negative. The distances $L_1$ and $L_2$ are related by

$$L_2 = L_1 - t, \tag{1}$$

where $t$ is the interlayer thickness.

The crack driving force, expressed in terms of the near-tip $J$-integral $J_{tip}$, can be determined from the relation,

$$J_{tip} = J_{far} + C_{inh1} + C_{inh2} = J_{far} + C_{IL}. \tag{2}$$

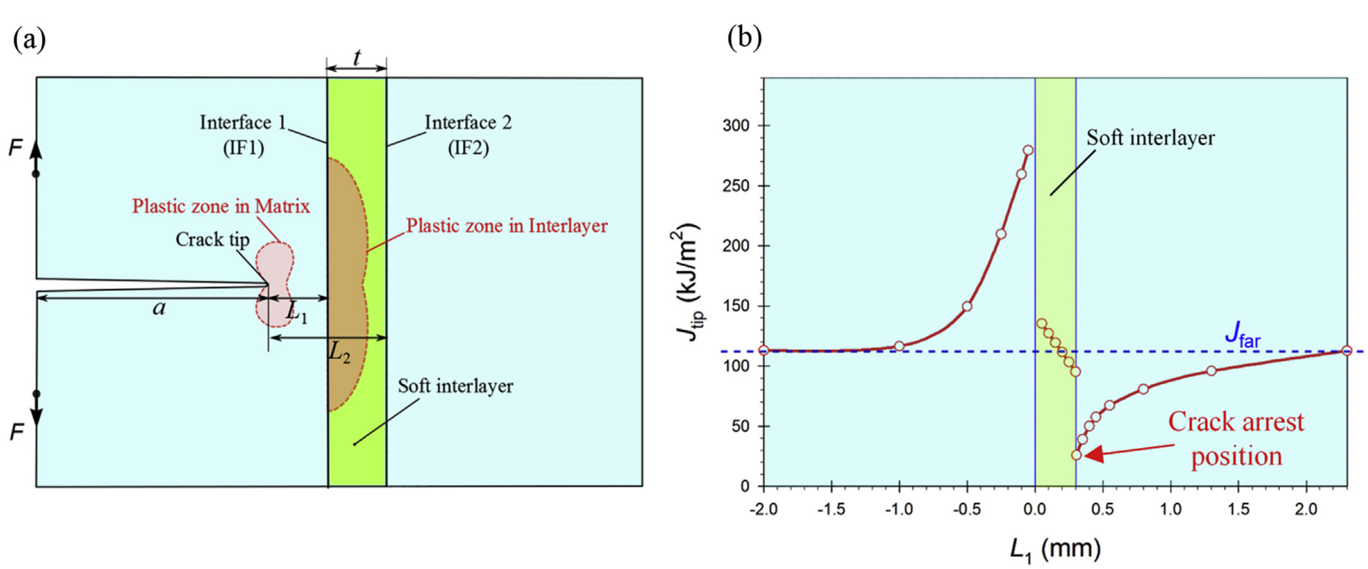


**Fig. 1.** (a) Fracture mechanics specimen with a long crack and a single, soft interlayer with interfaces, IF1 and IF2, perpendicular to the crack plane. (b) The crack driving force $J_{tip}$ reaches a minimum value immediately after the crack tip has crossed IF2.