CRACK-TIP SHIELDING AND ANTI-SHIELDING BY A BIMATERIAL INTERFACE

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Abstract

Spacial variations of the mechanical properties have a shielding or anti-shielding effect on the crack tip by inducing an additional crack driving force term, the material inhomogeneity term, C_{inh}. This paper explores this effect by studying the influence of a sharp bimaterial interface on the effective crack driving force in a fracture mechanics specimen. Linear elastic or elastic – ideally plastic materials are assumed with a mismatch in the elastic modulus and/or yield stress at the interface. Following a numerical stress analysis, the material inhomogeneity term, C_{inh}, is obtained by post-processing. This parametric study is especially focused on the effect of the distance between the crack tip and the interface.

Introduction

In inhomogeneous materials, the effective crack driving force becomes different from the applied far-field crack driving force. This well known effect has been treated mainly by classical fracture mechanics papers which have restrictions to elastic materials and special geometries, or by numerical investigations which give only specific explanations that cannot be easily generalized (see [1] for a literature review). The inhomogeneity effect is important for understanding the fracture behavior of multiphase or composite materials, brazed or welded components and materials with special surface treatments, such as nitrided or case-hardened steels and any coated material. Also, the effect provides a basis for the design of materials and structural components where variations in material properties are intentionally introduced to increase the fracture resistance.

By using the concept of material forces [2,3], Simha et al. [1] have shown that a material inhomogeneity can have a shielding or anti-shielding effect on a crack tip, since it induces an additional crack driving force term, called the material inhomogeneity term, C_{inh}. The effective, near-tip crack driving force, J_{tip}, is given by the sum of the nominally applied far-field crack driving force, J_{far}, and the material inhomogeneity term,

$$J_{tip} = J_{far} + C_{inh} \ . \quad (1)$$

Post-processing methods have been developed to evaluate the material inhomogeneity term both for a continuous variation of the material properties [1] and for a discrete jump at a sharp interface [4]. Results from selected examples show that C_{inh} is positive and J_{tip} becomes larger than J_{far} if a crack is in the stiffer and/or higher strength material. In contrast, if the crack is in the more compliant and/or lower strength material C_{inh} is negative, and J_{tip} becomes smaller than J_{far}.

In this paper, we concentrate on the distance between the crack tip and a sharp bimaterial interface, and thereby explore the influence of a sharp bimaterial interface on crack growth.

The evaluation of the material inhomogeneity term

Consider a two-dimensional body containing a crack and a sharp interface Σ. The materials on the left and right of the interface are homogeneous, but there is a jump in the material properties at the interface. Then the material inhomogeneity term is given by [4]

$$C_{inh} = -\int_{\Sigma} \left([[\phi]] - \langle \sigma_{ik} \rangle [[\varepsilon_{ik}]] \right) n_j \, e_j \; ds \quad . \quad (2)$$

Here, ϕ is the stored elastic energy density, σ_{ij} denotes the Cauchy stress, ε_{ij} the linear strain, e_i the unit vector in the direction of crack growth, and n_i the unit normal to the interface Σ pointing from the left side to the right (Fig. 1). [[ ]] denotes the jump and < > the average at the interface. Simha et al. [4] show that the material inhomogeneity term (Eq. 2) can be deduced from the standard J-integral concept, see [5], by calculating the J-integral around the interface, J_{int}:

$$C_{inh} = -J_{\mathrm{int}} \quad (3)$$

We consider a compact tension specimen made of two homogeneous isotropic materials, separated by a sharp interface which is perpendicular to the crack plane and at a distance L in front of the crack tip. The specimen width is $W = 50$ mm, height from the crack plane to the upper surface is $h = 30$ mm, and the crack length $a = 29$ mm. We use a finite element program, ABAQUS (http//www.hks.com), to perform the stress analysis. Figure 1 shows the mesh of the specimen, consisting of two-dimensional 8-node elements. The minimum mesh dimension is 0.013 mm at the crack tip and 0.05 mm at the interface. The materials on either side of the interface are assumed to be perfectly bonded. Linear elastic and non-hardening elastic-plastic materials are considered. Elastic-plastic materials are modeled using the incremental plasticity model provided by ABAQUS. The computations are performed under plane strain conditions, using small strain formulations. The loading is controlled by prescribing the load-line displacement. The J-integrals, J_{tip}, J_{far}, and J_{int}, are evaluated using the virtual crack extension method of ABAQUS; the corresponding contours are shown in Fig. 1.

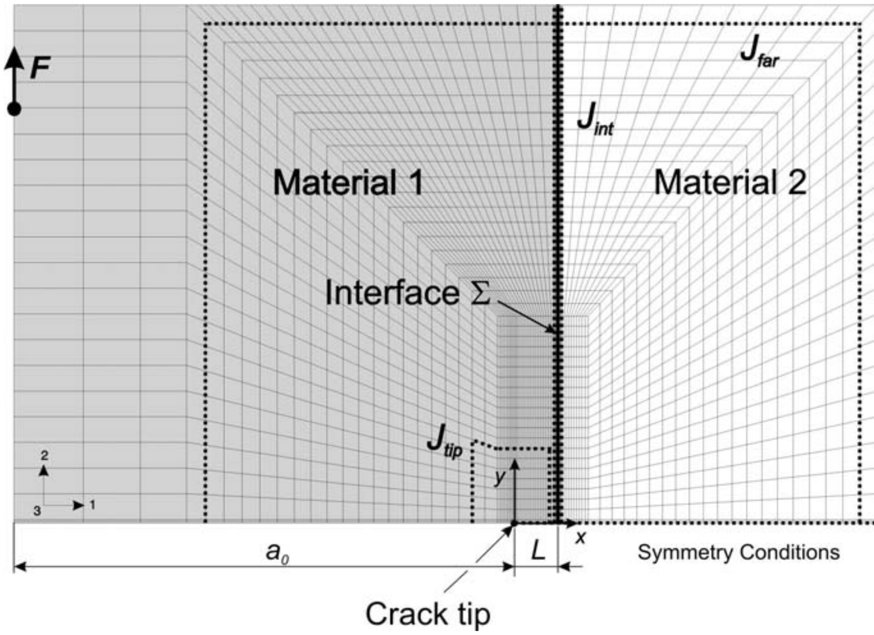

FIGURE 1. Finite-element mesh of the CT-specimen with a bimaterial interface.

The computations are performed for a stationary crack, but the distance between crack tip and interface is varied, -2.5 mm $\leq L \leq 2.5$ mm. Material 1 is to the left of the interface, while Material 2 is on the right. The following cases are examined: (1) linear elastic materials with modulus inhomogeneity at the interface, (2) linear elastic – ideally plastic materials with modulus inhomogeneity, but same yield stress, (3) linear elastic – ideally plastic materials with yield stress inhomogeneity, but same modulus. Both materials always have the same Poisson's ratio: $\nu = 0.3$ for the elastic regime and $\nu = 0.5$ for the plastic regime. For elastic-plastic materials, the stress analysis is performed using the incremental plasticity model provided by ABAQUS. For calculating C_{inh} by Eq. 2, ϕ is taken as the total strain energy density and ε_{ik} as the components of the total strain. Thus, the material is treated in the post-processing procedure as if it were non-linear elastic.

Results

Linear elastic materials – modulus inhomogeneity

In Fig. 2, the material inhomogeneity term, C_{inh}, is plotted against the far-field crack driving force, J_{far}. The upper curves belong to a stiff/compliant transition, for $E_1 = 210$ GPa, $E_2 = 70$ GPa: C_{inh} is positive and enhances the effective crack driving force, J_{tip} (Eq. 1). The lower curves in Fig. 3 belong to the compliant/stiff transition ($E_1 = 70$ GPa, $E_2 = 210$ GPa): C_{inh} is negative and diminishes J_{tip}. Notice that for all cases, the material inhomogeneity depends linearly on J_{far}.

An estimate for the slope, $k = C_{inh}/ J_{far}$, has been presented in [6],

$$k = \frac{1}{4\pi(1-\nu)} \frac{E_1 - E_2}{E_1 + E_2} \left[(3-4\nu) \ln\left(\frac{\sqrt{h^2+L^2}+h}{\sqrt{h^2+L^2}-h} \right) + 4(1-2\nu) \arctan\left(\frac{h}{L} \right) - \frac{2h}{\sqrt{h^2+L^2}} \right] . \quad (4)$$

Thus, the slope C_{inh}/J_{far} depends primarily on the Dundurs parameter, $(E_1\text{-}E_2)/(E_1\text{+}E_2)$ [7], and on the non-dimensional distance between the interface and crack tip (L/h).

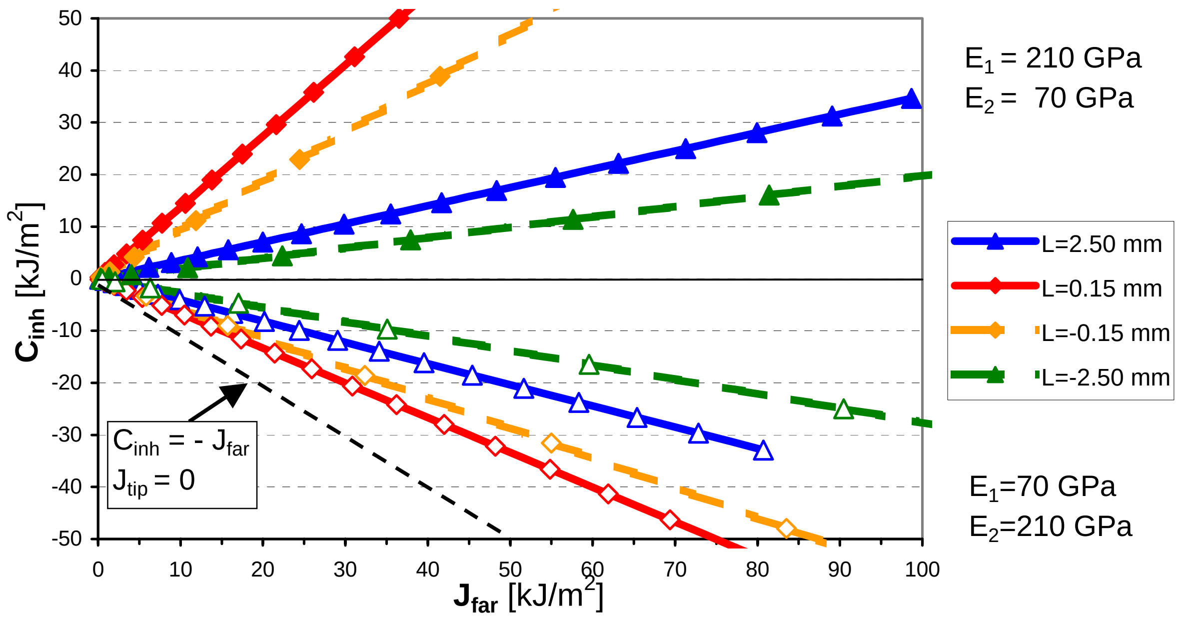

FIGURE 2. Modulus inhomogeneity for linear elastic materials.

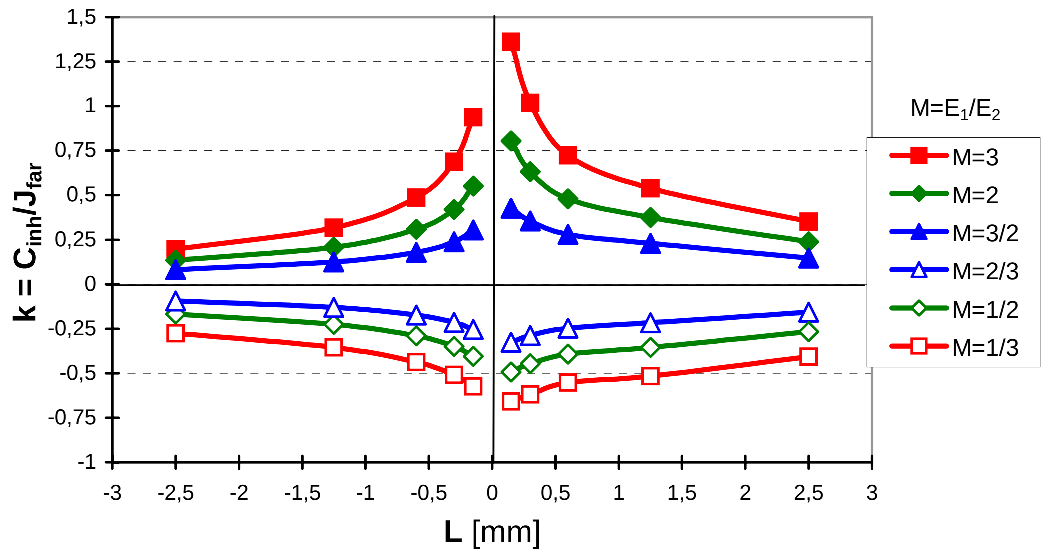

FIGURE 3. Effect of the distance between interface and crack tip on the ratio of the material inhomogeneity term to the far-field crack driving force for linear elastic materials.

In Fig. 3, the slope $k = C_{inh}/ J_{far}$, is shown as a function of the distance between interface and crack tip, L, and the ratio of the Young's modulus, $M = E_1/E_2$. When a crack approaches the interface, the absolute size of the material inhomogeneity term, $|C_{inh}|$, increases sharply. For the stiff/compliant transition, k seems to approach infinity for $L \rightarrow 0$; for the compliant/stiff transition, the data seem to approach $C_{inh} = -J_{far}$, or $J_{tip} = 0$, i.e., the effective crack driving force cannot become smaller than zero. This explains the asymmetry between the stiff/compliant and the compliant/stiff transition which is not reflected by Eq. 4. When the crack has penetrated the interface, $L < 0$, the k vs. L curves decrease in an almost symmetrical manner.

Elastic-ideally plastic – modulus inhomogeneity

Next, results are presented for bimaterial specimens consisting of two linear elastic – ideally plastic materials (strain hardening coefficient, $N = 0$) with constant yield stress, $\sigma_y = 500$ MPa but a misfit in the elastic modulus, $E = 70$ and 210 GPa. At small values of J_{far}, the slope of the C_{inh} vs. J_{far} curves is close but not identical to that of the corresponding linear elastic case. However, as J_{far} increases the slope continues to decrease and eventually the material inhomogeneity term approaches a saturation value, $\hat{C}_{inh}$, at high J_{far} (see [7] for details). In Fig. 4, C_{inh} is plotted against the distance L for different values of J_{far} between 40 and 240 kJ/m^2. When a crack approaches the interface to a more compliant material, C_{inh} first increases (at constant J_{far}) with decreasing L, reaches a maximum value at a distance between $L = 0.6$ mm (for $J_{far} = 40$ kJ/m^2) and $L = 1.3$ mm (for $J_{far} = 240$ kJ/m^2), and then decreases. The asymmetry between the stiff/compliant and the compliant/stiff transition appears weaker than for the purely elastic bimaterials. When the crack has penetrated the interface, the decrease of C_{inh} slows down. It should be also noted that at a loading of $J_{far} = 240$ kJ/m^2, the material inhomogeneity term has reached its saturation value, $\hat{C}_{inh}$, for all values of L. Thus,

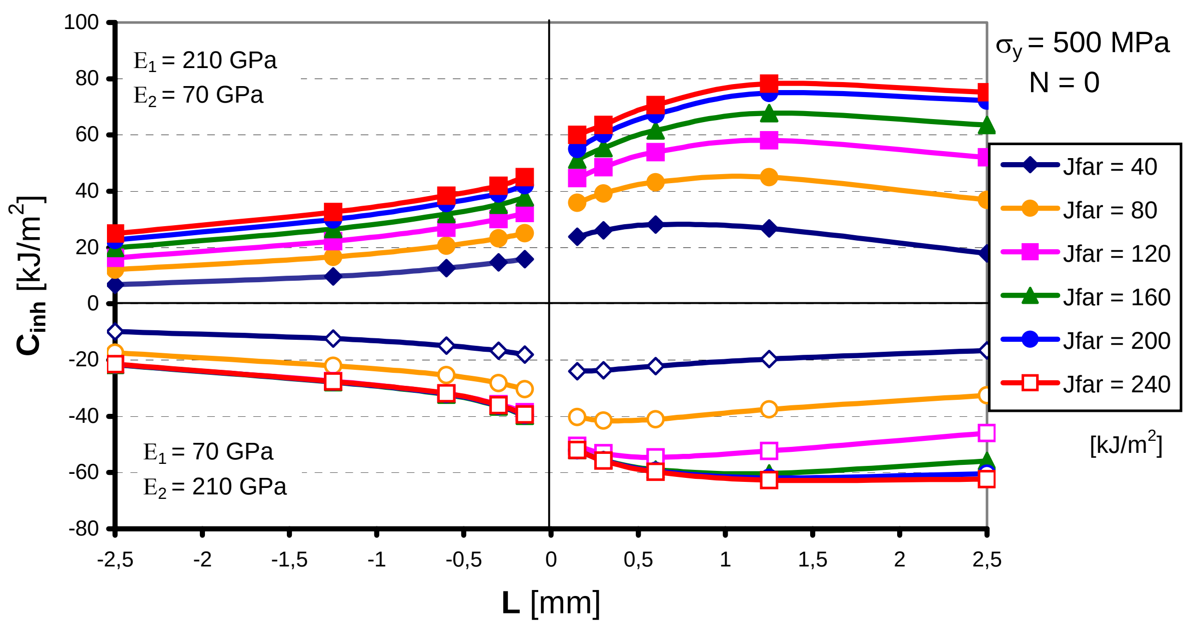

FIGURE 4. Modulus inhomogeneity for elastic – ideally plastic materials.

the maximum $\hat{C}_{inh}$-values for this material combination and geometry are *78* kJ/m^2 for the stiff/compliant transition and *63* kJ/m^2 for the compliant/stiff transition. The maximum value depends on the square of the constant yield stress value and difference in the elastic moduli (for a fixed specimen) and can be estimated using

$$\max\left(\hat{C}_{inh}\right) \approx \sigma_y^{\ 2} \frac{E_1 - E_2}{E_1 E_2} h \quad . \tag{5}$$

For a strain hardening material, the C_{inh} vs. J_{far} curves do not saturate and the C_{inh}-values may increase appreciably above the maximum $\hat{C}_{inh}$-values of the non-hardening material [7].

Elastic-ideally plastic – yield stress inhomogeneity

The third case considered is that of linear elastic – ideally plastic bimaterials with constant elastic modulus, $E = 210$ GPa, but a mismatch in the yield stress, $\sigma_y = 900$ and 300 MPa. Figures 5 and 6 show the influence of the distance between crack tip and interface, L, on the material inhomogeneity term. For small loading, C_{inh} is negligible, since the crack tip plastic zones do not interact with the interface (see [8]). With increasing J_{far} and for $L > 0$, the inhomogeneity effect increases in an exponential manner and converts to a line with constant slope; this means that the magnitude of C_{inh} can become comparable to that of J_{far}. A strong asymmetry appears between the hard/soft transition with large, positive C_{inh} and the soft/hard transition where C_{inh} is appreciably smaller in size and negative. For the crack approaching the interface, C_{inh} seems to approach infinity for the hard/soft transition; for the soft/hard transition, the data seem to approach $C_{inh} = -J_{far}$, or $J_{tip} = 0$, compare Figs 3 and 6.

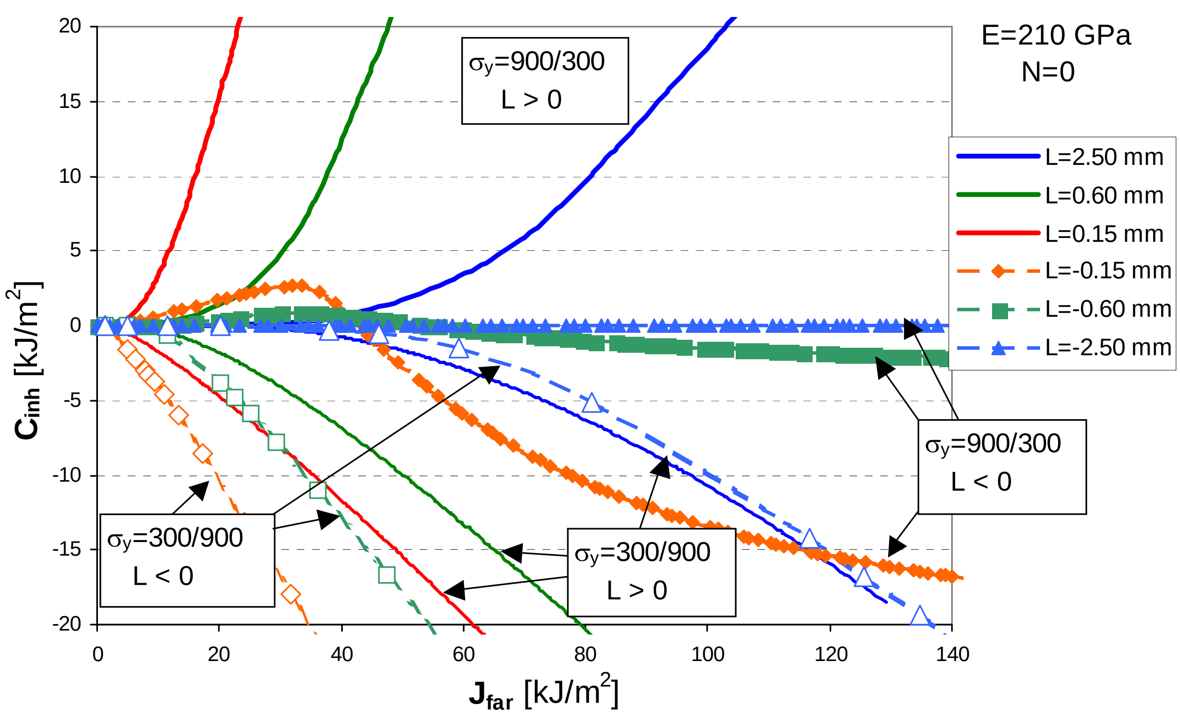

FIGURE 5. Yield stress inhomogeneity for elastic – ideally plastic materials.

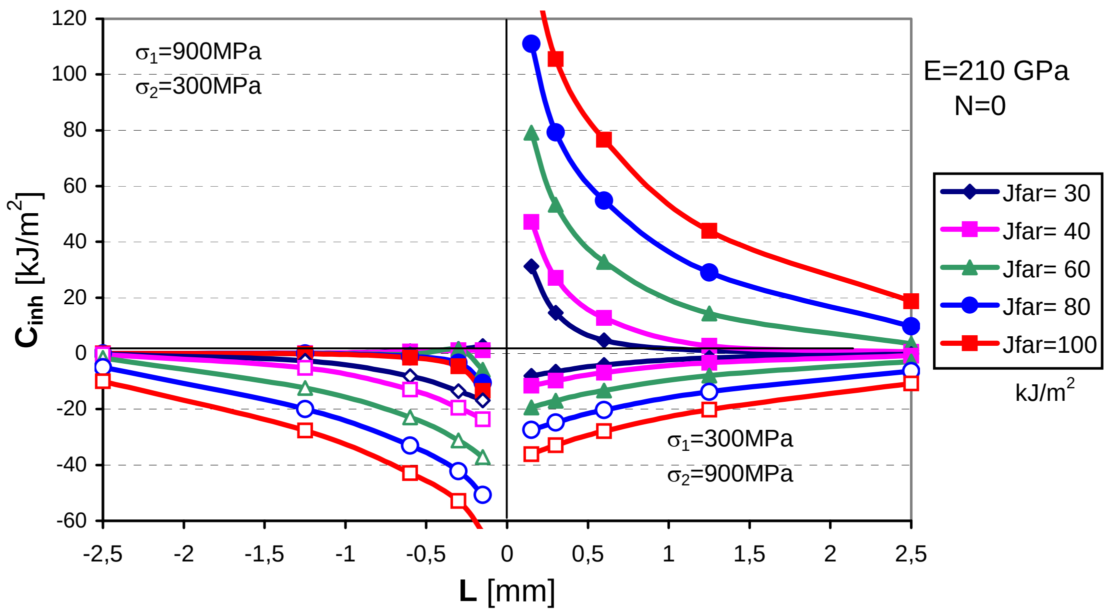

FIGURE 6. Effect of the distance between interface and crack tip on the material inhomogeneity term for a bimaterial with a yield stress inhomogeneity.

Figure 6 shows very interesting results for $L < 0$: For the hard/soft transition, C_{inh} drops immediately to a very small value after the crack has penetrated the interface. For the soft/hard transition, the C_{inh}-values are appreciably larger compared to the corresponding value for the same J_{far} and positive L. The reasons for these trends are currently being explored and more details will be presented in a forthcoming publication [9].

Conclusions

The effective crack driving force, J_{tip}, can be determined as the sum of the material inhomogeneity term, C_{inh} and the nominally applied far-field crack driving force, J_{far}. In a computational setting, C_{inh}, is evaluated by a post-processing procedure. Numerical studies of a fracture mechanics specimen containing a sharp interface separating two homogeneous materials, show that the inhomogeneity due to the interface can significantly influence the effective crack driving force. Specific results include

- Linear elastic bimaterials – modulus inhomogeneity: C_{inh} scales linearly with J_{far}, and the constant slope $k = C_{inh}/J_{far}$ depends on the Dundurs parameter and on the distance between the distance between the crack tip and interface. As the crack tip approaches the interface, C_{inh} and hence J_{tip} approach infinity for the stiff/compliant transition, whereas J_{tip} approaches zero for the compliant/stiff transition.
- Linear elastic-ideally plastic bimaterials – modulus inhomogeneity: C_{inh} saturates at large J_{far}, The magnitude of C_{inh} reaches a maximum value when the crack tip is at some distance from the interface. This maximum value scales as the square of the constant yield stress and linearly with the difference in elastic modulus.

- Linear elastic-ideally plastic bimaterials – yield stress inhomogeneity: C_{inh} is comparable to J_{far} at large values of J_{far}. As the crack tip approaches the interface, J_{tip} approaches infinity for the hard/soft transition, whereas J_{tip} approaches zero for the soft/hard transition.

The combined effects of modulus + yield stress + hardening inhomogeneity will be treated in a forthcoming paper [9]. The application of the material inhomogeneity effect for welded joints is studied in [10]. Such parametric studies identify the material combinations that provide either a large or negligible influence on the fracture behavior and offer possibilities for optimizing composite materials and structural components.

Acknowledgments

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