COMPOSITE TOUGHENING BY LAYERING

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Summary The mode I crack growth resistance of 3-layer, 5-layer and multi-layer elastic-plastic composites containing a semi-infinite crack is computed under plane strain conditions. In all cases, the central cracked layer is elastic, while the outer layers can be elastic or elastic-plastic. The degree of toughening due to non-proportional straining in the elastic-plastic layers is assessed for both the isotropic case and for the anisotropic solid (Hill model). Anisotropy can lead to much enhanced toughening.

INTRODUCTION

Multi-layered ceramic-metal composites are finding increasing application in electronic components and in structural parts; likewise, multi-layered ceramic-polymeric composites are ubiquitous in Nature, such as in shells, bone and horn. Remarkable levels of macroscopic toughness are achievable, and micromechanical reasons for this are explored in the current study. We investigate the mode I crack growth resistance of multi-layered metal-ceramic composites via finite element numerical simulations under plane strain, small-scale yielding conditions. A remote mode I K-field is applied to the outer periphery of a finite element mesh, and crack growth within a central ceramic layer is simulated using the bilinear hardening-softening cohesive zone model of ABAQUS Standard, as characterised by a peak tensile traction of σ_{coh}, a crack opening displacement of δ_{coh}, and consequently a tip toughness of $G_c=0.5\sigma_{coh}\delta_{coh}$. An initial study on the toughness of an elastic layer, sandwiched between two elastic-ideally plastic half-spaces, has been performed by Suo *et al.* [1], see Fig. 1a. Their study reveals that the degree of toughening is sensitive to the height h_c of the elastic layer; as h_c tends to zero, the toughness is a maximum, and recovers that of Tvergaard and Hutchinson [2]. Suo *et al.* [1] show that the steady-state toughness K_{ss} is sensitive to the non-dimensional parameter $h_c\sigma_y\varepsilon_y/G_c$, where σ_y and ε_y are the yield strength and the yield strain, respectively, of the isotropic, elastic-ideally plastic solid. We shall extend the Suo *et al.* [1] analysis, in several directions, as follows.

EFFECT OF A METAL LAYER OF FINITE HEIGHT UPON TOUGHNESS

We begin by modifying the analysis of Suo *et al.* [1] to the case of a finite elastic-plastic layer, of height h_m, see Fig. 1b. It is anticipated that the extent of toughening is reduced from that analysed by Suo *et al.* [1] due to the fact that the plastic zone is constrained in magnitude: the practical question is how large a strip of elastic, ideally-plastic solid is needed in order to obtain a toughened composite?
A series of finite element simulations have been performed using ABAQUS Standard 6.10, with $h_c\sigma_y\varepsilon_y/G_c$ = 0.032, σ_{coh}/σ_y=4.0 and the ratio h_m/h_c varied from zero to infinity. We report the R-curves as the series of solid lines in Fig. 2: in each case, the ratio K/K_c is plotted as a function of $\Delta a/R_0$, where a reference material length has been introduced as $R_0=K_c^2/(3\pi\sigma_y^2)$ and $K_c=[G_cE/(1-\nu^2)]^{1/2}$. It is noted that the steady state fracture toughness K_{ss}/K_c increases from 1.0 to 3.6 as h_m/h_c is increased from zero to infinity. Significant toughening is achieved provided h_m/h_c exceeds about 10.0, for the assumed values of $h_c\sigma_y\varepsilon_y/G_c$ = 0.032, σ_{coh}/σ_y=4.0.

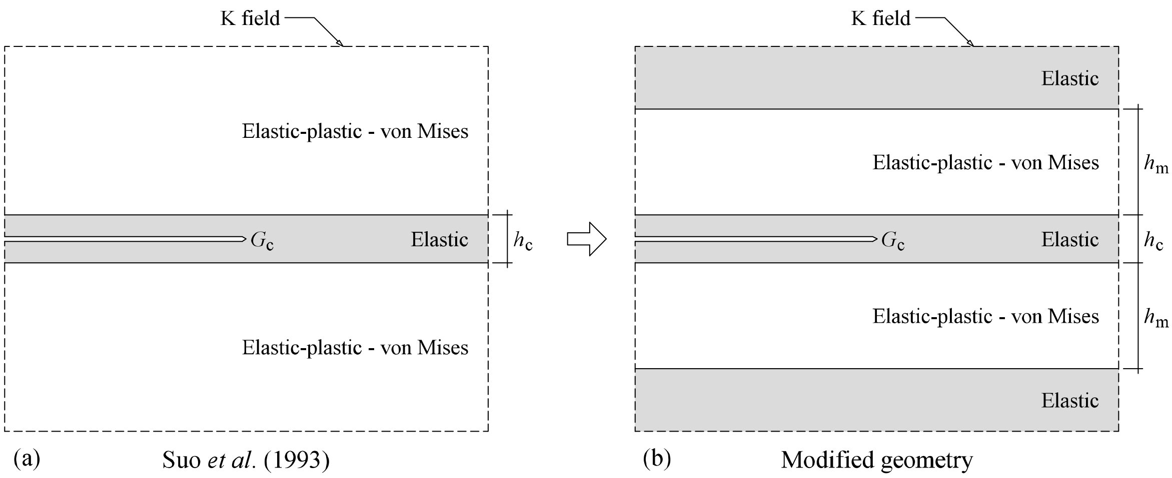

Fig. 1 (a) a sketch of the geometry as analysed by Suo *et al.* [1] for cleavage cracking in an elastic strip, sandwiched between elastic-plastic half-planes; (b) the modified geometry, in which the elastic-plastic half-planes are replaced by elastic half-planes and an elastic-plastic strip of finite height h_m.

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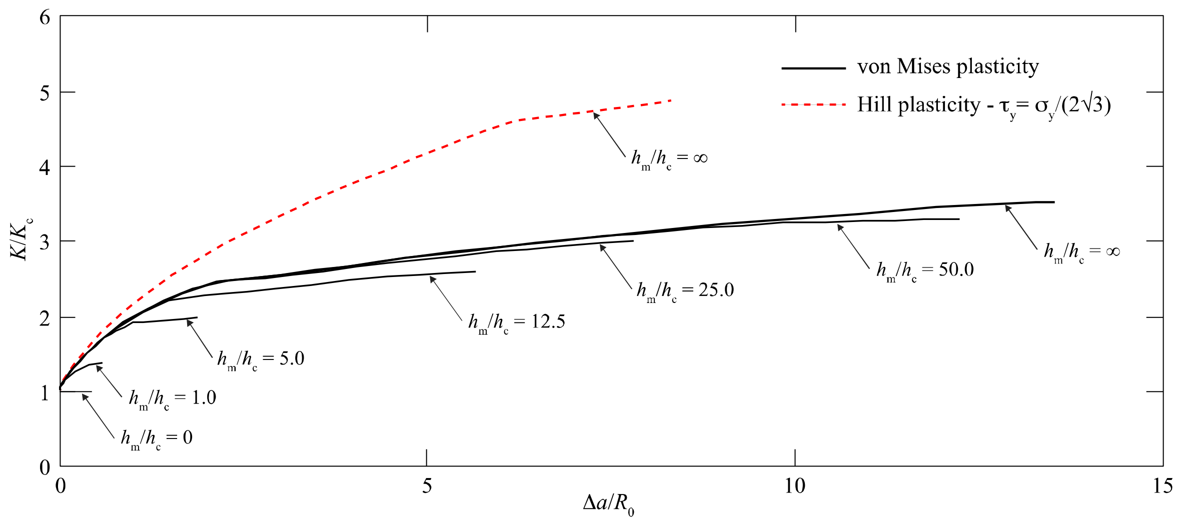

Fig. 2 Resistance curves for selected values of the ratio h_m/h_c. Results are shown for a finite elastic-plastic strip of height h_m (see Fig. 1b) which yields according to isotropic von Mises theory, and for the case of an elastic-plastic half-plane (see Fig. 3b) which yields according to the Hill model with $\tau_y=\sigma_y/(2\sqrt{3})$. All the numerical results have been obtained with $h_c\sigma_y\varepsilon_y/G_c$=0.032.

EFFECT OF PLASTIC ANISOTROPY UPON TOUGHNESS

Second, consider the toughness of a multi-layer stack, with a semi-infinite crack in the central, elastic layer. The geometry as sketched in Fig. 3a can be idealized to that given in Fig. 3b: shear yielding of the aligned microstructure occurs at a significantly reduced stress compared to that of normal yielding. To analyse this, we consider the reduced, idealised problem as sketched in Fig. 3b. The layered microstructure is replaced by an equivalent elastic-plastic material as characterized by the Hill yield surface. Strain hardening is neglected, and plastic anisotropy is accounted for by means of the ratio shear yield strength to direct strength, in axes aligned with that of the microstructure. Our initial results for R-curves have been obtained for $\tau_y=\sigma_y/(2\sqrt{3})$, and are shown as dashed line in Fig. 2. This compares with the isotropic von Mises results for which $\tau_y=\sigma_y/\sqrt{3}$, also shown in Fig. 2. We find that a reduced shear yield strength enhances the degree of toughening.

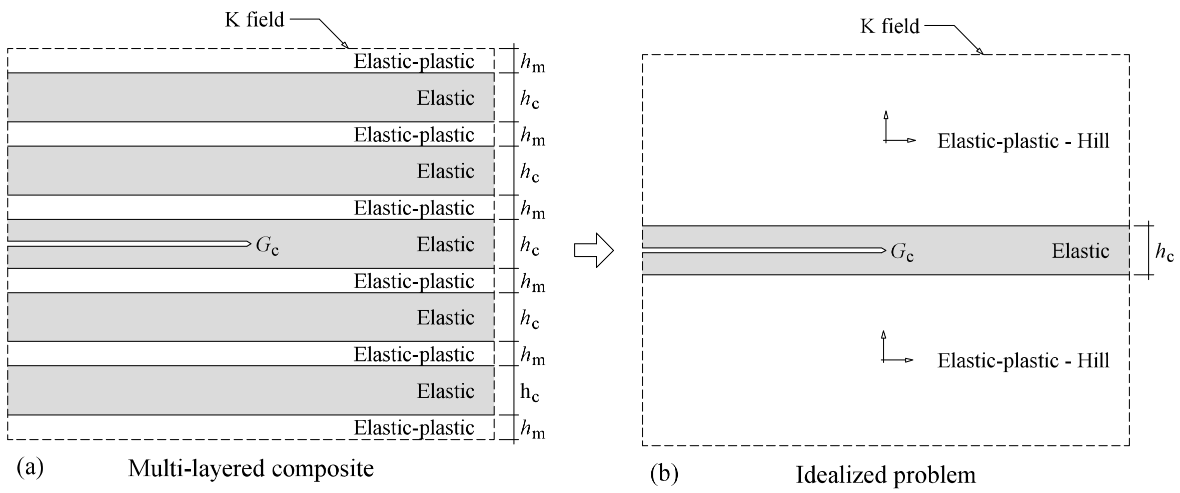

Fig. 3 (a) a sketch of the multi-layered composite under consideration; (b) the idealized problem, in which the layered microstructure has been replaced with an equivalent elastic-plastic material of the Hill type. Note the axes of anisotropy.

CONCLUSIONS

The mode I crack growth resistance of multi-layered composites has been analysed via finite element simulations. The role of topology and anisotropy has been explored, and the sensitivity of toughness to layer thickness and degree of anisotropy has been probed.

References

[1] Suo Z., Shih C. and Varias A.G.: A theory for cleavage cracking in the presence of plastic flow. *Acta Metall. Mater.*, **41**, 1551-1557, 1993.
[2] Tvergaard V. and Hutchinson J.W.: The relation between crack growth resistance and fracture process parameters in elastic-plastic solids. *J. Mech. Phys. Solids*, **40**, 1377-1397, 1992.