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Simulations of arbitrary crack path deflection at a material interface in layered structures

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ABSTRACT

The competition between crack deflection along the interface or penetration across the interface is numerically modeled in this paper using two novel, isogeometric, numerical approaches. In the first, cracks are modeled as discontinuous enrichments defined isoparametrically on lower dimensional geometrical entities and composed with underlying continuous behavioral approximation. In the second approach, the underlying material description is enriched with a cohesive damage description whose stiffness is evolved according to a prescribed damage law. An automatic crack propagation algorithm is developed for simulating fracture in layered structures, which is demonstrated on a practical, multilayered example problem derived from the semiconductor industry.

1. Introduction

Layered structures are common in nature as well as in engineering applications. Often, biological structures are hierarchically organized at different length scales to provide stiffness as well as fracture resistance (see for example the sponge spicule of Rosella, Fig. 1(a) [1]). In engineering applications, layered structures become necessary to provide specific performance objectives that are not achievable by a single material. For example, layered ceramics are used to replace monolithic ceramics due to their high fracture strength to weight ratio. In semiconductor chips, interconnect structures (see Fig. 1(b)) are typically used for signal distribution from semiconductor logic devices. In general, the interconnect structure is a three-dimensional network of copper lines embedded in a nano-porous, brittle dielectric matrix, fabricated on the silicon wafer surface. Thermal stresses arising during fabrication, testing or service due to large coefficient of thermal expansion (CTE) mismatch between these materials is often attributed as a main driving force for failure due to fracture of the dielectric layers [2–4]. The presence of flaws has a major impact on the reliability of such layered structures. The understanding of the failure mechanisms in layered structures is thus of practical importance. Specifically, understanding of the behavior of a crack close to an interface (impinging or adjacent) is of importance, for example, in the design of interface between material layers.

The mechanics of crack deflection of an oblique or perpendicular crack has been analytically, and thoroughly, investigated in prior literature. Zak and Williams [5] characterized the singularity in stress field corresponding to a crack normal to an interface and showed it to be of order $r^{-\lambda}$, where λ is real and a function of elastic properties of the two conjoined materials. Bogy [6] studied the stress singularity of an infinite crack terminated at the interface at an oblique angle. He and Hutchinson

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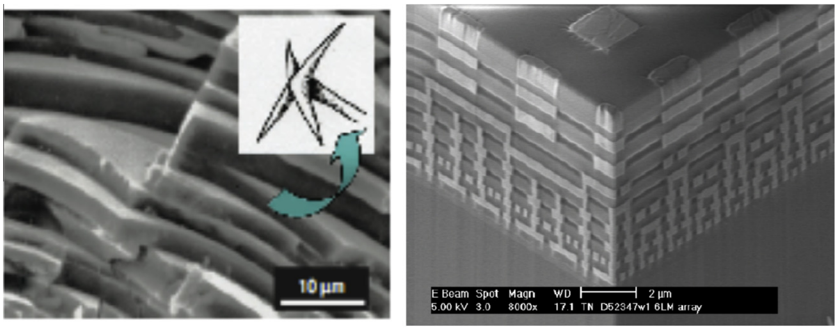
Nomenclature

α, β	Dundurs' parameters
μ_i	shear modulus of material i
ν_i	Poisson's ratio of material i
K_I	Mode I stress intensity factor for bulk material
K_{II}	Mode II stress intensity factor for bulk material
G, G_P	energy release rate for bulk material
Γ_c	fracture toughness of bulk material
$K_1 K_2$	mixed-mode stress intensity factors for interfacial fracture
ϵ	oscillation index
$G_{interface}$	interfacial energy release rate
$\Gamma_{interface}$	interfacial fracture toughness
f_Ω	underlying continuous approximation at a spatial location $\mathbf{x}$
f_e	enriching approximation at a spatial location $\mathbf{x}$
w_Ω	weight field corresponding to underlying continuous approximation at a spatial location $\mathbf{x}$
w_Ω^e	weight field corresponding to enriching approximation at a spatial location $\mathbf{x}$
N_I	parametric Non-Uniform Rational B-Spline (NURBS) basis function corresponding to control point I
$\mathbf{P}_I$	Ith control point coordinate vector
E_o	elastic modulus of the undamaged material
E	elastic modulus of the damaged material
D	damage $0 \leqslant D \leqslant I$
$D_{interface}$	damage along the interface
$D_{P_{max}}$	damage in material across the interface

[7] investigated the competition between crack penetration and deflection for cracks approaching the interface at arbitrary angles. Similar analyses have been utilized in references [8–14].

Attempts at numerical investigation of the spilt singularities for cracks terminated at the material interface have been few. Kaddouri et al. [15] computed strain energy release rates using the finite element method (FEM) at the crack tip of ceramic–metal bi-material as a function of elastic mismatch between the two materials. Marsavina and Sadowski [16] numerically investigated the effect of bi-axial loading on the asymptotic stress field for a crack terminating at bi-material interface. Kim et al. [17] studied the direction of crack propagation for a crack obliquely incident on the bi-material interface. Madani et al. [18] numerically investigated the competition for alumina-metal bi-material systems.

In general, crack propagation studies in multilayered structures appears to be largely missing in the literature. The apparent lack of crack propagation studies is possibly due to numerical challenges associated with simulations of crack propagation in heterogenous structures. The finite element method has been widely used to model structures with pre-specified crack locations and lengths. However, modeling crack propagation is challenging due to the fact that the finite element technique does not efficiently handle moving interfaces and discontinuities (such as cracks) because of the need for remeshing. Finite element models with damage at crack tip described using a Cohesive Zone Model (CZM) has been used to simulate fracture propagation in layered structures by inserting cohesive elements along potential crack paths [19]. Thus, if the crack path is assumed to be known *a priori*, the problem of remeshing may be avoided, but in general, remeshing remains a challenge.



(a) (b)

Fig. 1. Layered structures in nature and engineering systems (a) Sponge spicule of Rosella made of layered silica [1] (b) 9 level dual damascene Cu/Low k interconnects [31].