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Debonding of the interface between a thin film and an orthotropic substrate

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ABSTRACT

Interface debonding in an orthotropic bilayer consisting of a thin film and a half-plane substrate is investigated. Three crack patterns including a plane–strain interface crack, a delamination channeling crack, and a channeling crack with film cracking and interface debonding are considered. Based on the modified Stroh formalism and the orthotropic rescaling technique, the energy release rate for the three cracks and mode mixity for the plane–strain interface crack are derived in the closed form for each numerically determined dimensionless function. Special attention is paid to the effect of orthotropic material constants on the energy release rate and mode mixity. Stable or unstable plane strain delamination and crack channeling are discussed according to fracture criteria based on the energy release rate.

1. Introduction

Film cracking and interface debonding in film bilayers as a result of residual stresses or applied loads represent an important issue in fracture mechanics because they can reduce the reliability of layered structures. Hutchinson and Suo [1] reviewed a number of studies of various cracking patterns in film/substrate systems. Ye et al. [2] investigated film cracking and interface debonding in an isotropic film/substrate system and determined the critical film thickness for no cracking. Zhao et al. [3] examined crack channeling and spalling in a homogeneous plate as a result of a thermal shock loading and constructed failure maps for various cracking patterns in terms of the critical temperature and Biot number. Yu and Hutchinson [4] analyzed the delamination of a thin film strip of finite width bonded to a substrate and explored full and partial delamination modes. The formula for energy release rate associated with full delamination mode was derived and the effects of strip/substrate geometry and crack length on the energy release rate were examined numerically. Mei et al. [5] investigated crack channeling with delamination in a thin film on an isotropic substrate and developed an interfacial delamination map to discuss the stable and unstable delamination through the channeling process. Chai and Fox [6] experimentally investigated delamination growth from channel cracks in layered structures with thin-film coatings and measured fracture resistance. Fan et al. [7] considered interface debonding in an isotropic thermal barrier coating system and investigated the effects of periodic surface cracks on the interface fracture by using the finite element method and the cohesive zone model. The fracture criterion for crack growth along the interface between dissimilar materials is well established based on the energy balance, and the dependence of interface toughness on inplane mode mixity has been recognized [1]. Tvergaard and Hutchinson [8] proposed a three-mode interface fracture criterion and paid special attention to the mode III effect on

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Nomenclature

a	crack length or channel width
C_1, C_2	dimensionless functions
$\widetilde{C}_1, \widetilde{C}_2$	dimensionless functions
$\mathbf{c}, \tilde{\mathbf{c}}$	dimensionless vector functions
$\mathbf{D}$	bimaterial matrix
d	bimaterial constant
G_i, G_f, G_{fi}	steady-state energy release rates
G_i^*, G_{fi}^*	normalized steady-state energy release rates
G_i^c, G_f^c, G_{fi}^c	fracture toughnesses
$\widetilde{G}_i^*, \widetilde{G}_f^*, \widetilde{G}_{fi}^*$	normalized steady-state energy release rates
h	film thickness
$\mathbf{I}$	identity matrix
J	energy release rate
$J^*, \tilde{J}^*$	normalized energy release rates
J^c, J_1^c	interface toughnesses
K_1, K_2	interface stress intensity factors
K_1^h, K_2^h	interface stress intensity factors
$\mathbf{k}$	vector of the interface stress intensity factor
$\mathbf{L}$	real matrix
S_{ij}, S_{ij}^e	elastic compliance
x_1, x_2, x_3	Cartesian coordinates axes
$\mathbf{Y}, \tilde{\mathbf{Y}}$	matrix functions
$\boldsymbol{\alpha}$	bimaterial matrix
$\alpha_0, \alpha_{11}, \alpha_{22}$	bimaterial parameters
β	bimaterial matrix
$\beta_0, \beta_{12}, \beta_{21}$	bimaterial parameters
γ	bimaterial parameter
δ	crack opening displacement
δ^*	normalized crack opening displacement
$\varepsilon, \varepsilon_0$	oscillatory indices
η	constant
$\boldsymbol{\Lambda}$	material matrix
$\lambda, \lambda_1, \lambda_2$	orthotropic parameters
ξ	geometric parameter
ρ, ρ_1, ρ_2	orthotropic parameters
σ_0, σ_{ij}	stresses
$\psi, \tilde{\psi}$	mode mixity
Ω, Ω_{fi}	dimensionless toughness functions

interface toughness. Veluri and Jensen [9] analyzed a three-dimensional interface corner crack between a thin film and an isotropic substrate under steady-state propagation conditions. They focused on modeling the shape of the interface crack front and calculating the critical stress for steady-state propagation of the crack. However, these studies have been limited mainly to cases of isotropic bilayers, and only a few studies have investigated channel cracking and interface debonding in orthotropic bilayer structures. Kotoul et al. [10] analyzed periodic edge cracks in a thin coating bonded to an orthotropic substrate under mechanical and residual stresses and examined the competition between the penetration and deflection of edge cracks. Charalambides and Zhang [11] investigated an interface crack bounded by two orthotropic dissimilar materials and developed an energy method and a crack surface displacement method to calculate the stress intensities at the crack tip. Beom et al. [12] analyzed steady-state interface cracking in an orthotropic bimaterial structure consisting of a thin film and a substrate. A complete expression of interface stress intensity factors was obtained based on the path independence of the J integral, apart from one dimensionless parameter undetermined. Recently, Beom and Jang [13] investigated crack channeling confined to an orthotropic film bonded to an orthotropic substrate under steady-state conditions. The influence of the material constants on the steady-state energy release rate was discussed.

This paper considers the debonding of an interface between a thin film and a half-plane substrate. The film and substrate consist of orthotropic materials, and special attention is paid to the effects of material constants on interface debonding. In addition, an interface crack between a thin film and a substrate under plane–strain conditions is analyzed. The interface crack with symmetric delamination originates from the tip of the vertical film crack terminating at the interface. Closed-form