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Interfacial fracture analysis of bonded dissimilar strips with a functionally graded interlayer under antiplane deformation

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ABSTRACT

This paper provides the solution to the problem of dissimilar, homogeneous semi-infinite strips bonded through a functionally graded interlayer and weakened by an embedded or edge interfacial crack. The bonded system is assumed to be under antiplane deformation, subjected to either traction-free or clamped boundary conditions along its bounding planes. Based on the Fourier integral transform, the problem is formulated in terms of a singular integral equation which has a simple Cauchy kernel for the embedded crack and a generalized Cauchy kernel for the edge crack. In the numerical results, the effects of geometric and material parameters of the bonded system on the crack-tip stress intensity factors are presented in order to quantify the interfacial fracture behavior in the presence of the graded interlayer.

1. Introduction

The significant advances have been made in the development of functionally graded materials over the last few decades, owing to their tailoring capability to produce spatial and gradual variations of physical properties, coping with a variety of technological problems in engineering practice. In particular, the deliberate incorporation of graded, nonhomogeneous media as a transitional interlayer to join dissimilar bulk materials such as ceramics and metals was found to be one of the viable methods of alleviating various limitations frequently encountered in the use of conventional bonded materials and structures [1]. These drawbacks may include high stress concentrations, poor bonding strength and consequent vulnerability to failure around the interfacial zone that are likely to be caused by the property mismatch apparent at the junction between two piecewise different phases in such composite bodies.

From the fracture mechanics viewpoint, even though the existence of graded interphase possibly enhances the resistance against failure, considerable research efforts have focused on the characterization of singular stress field induced by crack-like defects. In this context, a series of solutions to a variety of benchmark crack problems entailing the graded properties has been obtained by Erdogan and his coworkers [2–8], where a crack was assumed to be aligned parallel to, perpendicular to or along the kink line of spatial distributions of elastic moduli between homogeneous and nonhomogeneous constituents. The most noteworthy was the near-tip stress field with the square-root singularity and angular distributions around the crack that are identical to those in homogeneous materials, with the effect of material gradation manifesting itself through the values of stress intensity factors.

A number of additional contributions toward the fracture analysis of bonded media that takes the presence of a graded interlayer into account have subsequently been reported in the literature. Among them are, for example, the influence of coating architectures on the interfacial fracture behavior in a functionally graded coating/substrate structure under antiplane shear [9]; the plane problem of an interface crack for a graded strip between homogeneous layers of finite thickness [10]; the antiplane analysis of periodic interface cracks in a graded coating/substrate system [11]; the interfacial cracking in a graded coating loaded by a frictional flat punch [12]; the two parallel interface cracks in bonded dissimilar orthotropic half-planes with a nonhomogeneous interlayer [13]; and the multilayered approach applied to some interface crack problems for graded media with arbitrary distributions of material properties [14,15]. Meanwhile, the problems of a crack at an arbitrary angle to the graded interfacial zone in bonded materials were considered under various loading conditions [16–20], whereas the mixed-mode behavior of an arbitrarily oriented crack crossing the interface in a functionally graded layered structure was dealt with in [21] and that of an inclined crack in the functionally graded plane under impact was investigated in [22]. In recent years, the antiplane and mixed-mode interactions of two offset interfacial

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cracks in bonded materials with a functionally graded interlayer were also examined in [23–26].

As can be inferred from the foregoing, although a great deal of attempts made to date have resolved various issues and provided insightful results for the interfacial crack problems entailing the graded constituents, these prior studies appear to have mainly been concerned with such cases as containing a crack embedded deep inside the bonded system. It should be reminded that most interfaces intersect a free surface and in consideration of the interfacial failure that often initiates near or from the free surface, the problems of particular technical importance would be that of an embedded interfacial crack interacting with the neighboring free surface and that of an edge interfacial crack breaking the free surface, accounting for both the boundary and size effects. The present paper is, therefore, aimed at further quantifying the interfacial fracture behavior by solving the problem of an embedded or edge interfacial crack in bonded dissimilar semi-infinite strips with a functionally graded interlayer. The state of antiplane deformation is assumed, because it has the practical significance of its own when the third fracture mode is separable and it may also form the informative basis for understanding the more involved inplane counterpart. Both the traction-free and clamped boundary conditions are considered along the bounding planes of the bonded system. The Fourier integral transform method is employed and a singular integral equation is derived with a simple Cauchy kernel for the embedded crack and with a generalized Cauchy kernel for the edge crack, which is solved by the expansion-collocation technique. The mode III stress intensity factors are evaluated, addressing the effects of geometric parameters of the bonded system, in conjunction with that of the material stiffness.

2. Problem statement and formulation

The problem configuration under consideration is shown in Fig. 1, where two dissimilar, homogeneous strips of semi-infinite length are bonded through a functionally graded interlayer. The

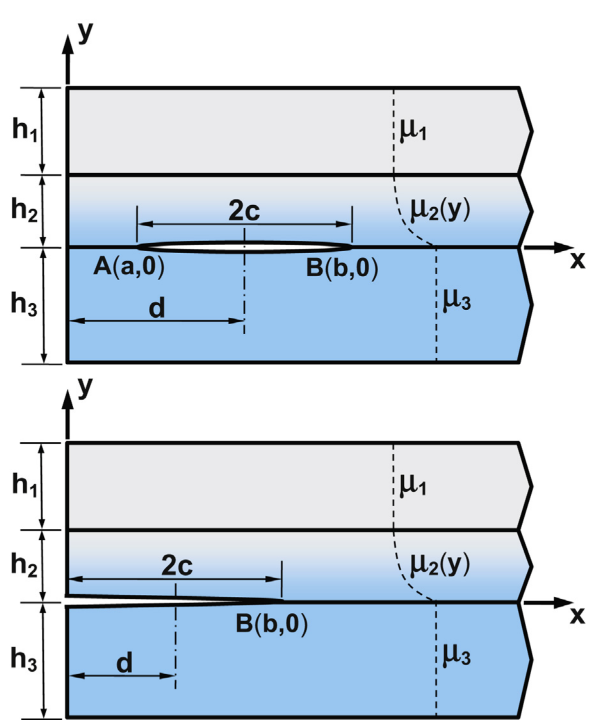

Fig. 1. Bonded dissimilar strips with a functionally graded interlayer containing (a) an embedded interfacial crack; (b) an edge interfacial crack.

constituents of this bonded system are distinguished in order from the top with the thickness $h_j, j = 1, 2, 3$, respectively, and an interfacial crack of length $2c = b - a$ is located along $A(a,0) < (x,y) < B(b,0)$, where $a > 0$ is for the embedded crack and $a = 0$ for the edge crack. The shear modulus of the graded, nonhomogeneous interlayer, $\mu_2(y)$, is represented in terms of an exponential function [2]

$$\mu_2(y) = \mu_3 e^{\beta y}, \quad \beta = \frac{1}{h_2}\ln\left(\frac{\mu_1}{\mu_3}\right); \quad 0 < y < h_2 \tag{1}$$

which renders the continuous transition of elastic moduli across the nominal interfaces with the top and bottom strips of shear moduli $\mu_j, j = 1, 3$, respectively.

Under the state of antiplane deformation, there exist only out-of-plane displacement components, $w_j(x,y)$, $j = 1, 2, 3$, with the stress components and governing equations given by

$$\tau_{jxz} = \mu_j \frac{\partial w_j}{\partial x}, \quad \tau_{jyz} = \mu_j \frac{\partial w_j}{\partial y}; \quad j = 1, 2, 3 \tag{2}$$

$$\nabla^2 w_j + \beta \frac{\partial w_j}{\partial y} = 0; \quad j = 1, 2, 3 \tag{3}$$

where $\beta = 0$ for the homogeneous constituents ($j = 1, 3$) and $\beta \neq 0$ for the interlayer ($j = 2$).

It is assumed that the bonded system is subjected to antiplane shear traction applied solely on the crack surfaces and that the left-hand side flank edges at $x = 0$ are traction-free. A set of boundary and interface conditions is thus prescribed as

$$\tau_{1xz}(0, y) = 0; \quad h_2 < y < h_1 + h_2 \tag{4}$$

$$\tau_{2xz}(0, y) = 0; \quad 0 < y < h_2 \tag{5}$$

$$\tau_{3xz}(0, y) = 0; \quad -h_3 < y < 0 \tag{6}$$

$$\tau_{1yz}(x, h_2) = \tau_{2yz}(x, h_2), \quad \tau_{2yz}(x, 0) = \tau_{3yz}(x, 0); \quad x > 0 \tag{7}$$

$$w_1(x, h_2) = w_2(x, h_2); \quad x > 0 \tag{8}$$

$$w_2(x, 0) = w_3(x, 0); \quad 0 < x < a, \quad x > b \tag{9}$$

$$\tau_{3yz}(x, 0) = f(x); \quad a < x < b \tag{10}$$

where the function $f(x)$ denotes the crack surface traction, with the bounding planes being either traction-free

$$\tau_{1yz}(x, h_1 + h_2) = 0, \quad \tau_{3yz}(x, -h_3) = 0; \quad x > 0 \tag{11}$$

or rigidly clamped such that

$$w_1(x, h_1 + h_2) = 0, \quad w_3(x, -h_3) = 0; \quad x > 0 \tag{12}$$

Based on the Fourier integral transformation, the general solutions for the displacements that satisfy the conditions at the flank edges in Eqs. (4)–(6) are readily obtained as

$$w_j(x, y) = \frac{2}{\pi}\int_0^\infty (A_{j1} e^{sy} + A_{j2} e^{-sy}) \cos sx \, ds; \quad j = 1, 3 \tag{13}$$

$$w_2(x, y) = \frac{2}{\pi}\int_0^\infty \sum_{k=1}^{2} A_{2k} e^{\lambda_k y} \cos sx \, ds \tag{14}$$

where s is the transform variable, $A_{jk}(s)$, $j = 1, 2, 3$, $k = 1, 2$, are arbitrary unknowns and $\lambda_k(s)$, $k = 1, 2$, are written as

$$\lambda_1 = -\frac{\beta}{2} + \sqrt{\frac{\beta^2}{4} + s^2}, \quad \lambda_2 = -\frac{\beta}{2} - \sqrt{\frac{\beta^2}{4} + s^2} \tag{15}$$

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