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Determination of interface fracture toughness of adhesive joint subjected to mixed-mode loading using finite element method

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Abstract

In this study, a compact mixed-mode (CMM) specimen, which comprises an adhesive joint and a loading fixture, is employed to determine interface fracture toughness of an adhesively sandwiched joint with an interface edge crack subjected to global mixed-mode loading. An interface mechanics-based finite element (FE) method is developed to simulate the stress and displacement distributions around the tip of an interface edge crack situated in the sandwiched joint. A small region crack-tip opening displacement (CTOD)-based linear extrapolation method is developed to determine stress intensity factors (SIFs) at the crack-tip. Effect of pre-crack length on the SIFs is studied and a length range of pre-crack is proposed for the determination of SIFs. Furthermore, these methodologies are applied to characterize the critical interface fracture toughness of the sandwiched joint. Three types of fracture criteria, i.e., modes I and II critical fracture toughness-based failure assessment diagram (FAD), effective critical fracture toughness-based failure assessment criterion (FAC), and strain energy release rate-based FAC, are established for the reliability design and failure assessment of the adhesively bonded sandwich joint.

Keywords: Interfaces; Delamination; Fracture mechanics; Finite element stress analysis

1. Introduction

Adhesive bonding is a key method enabling packaging technology for the integration of electronic devices. However, the use of adhesives brings in discontinuous interfaces and structures in electronic packages. When the packages are subjected to various environmental loadings (e.g., thermal, mechanical, moisture, and electrical), several failures (e.g., delamination, cracking, etc.) will appear at the interface and/or in the adhesive layer, causing the damage of solder joint and the loss of function and further leading to the failure of whole electronic device [1].

Failure in adhesive layer can be cohesive or adhesive in nature [2,3]. However, since electronic packages are multilayered material systems and often suffer from complex environmental loadings, the interfacial fracture mode mixity of adhesive joint is governed by both local material mismatch and global complex loading. It is therefore necessary to develop a characterization methodology, which can measure the fracture toughness of adhesive joint over a wide range of mixed-mode (modes I and II) loading conditions.

Considerable research efforts have been made in trying to develop different theoretical, numerical, and experimental methodologies to investigate the interface problem [4–6]. Based on the bimaterial system with an interfacial crack [7,8], as shown in Fig. 1(a), many theoretical models and numerical approaches were developed. On the other hand, sandwiched structure, as shown in Fig. 1(b), was often employed to establish the fracture toughness characterization method for adhesively bonded system. The structure includes

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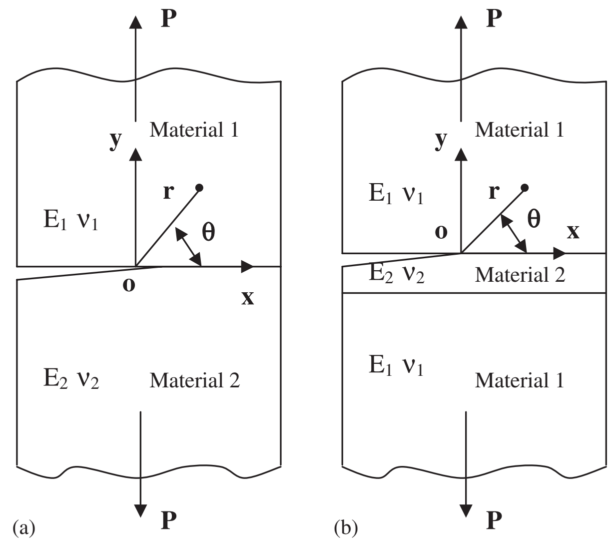

Fig. 1. Schematic diagrams show the interfacial crack problems in (a) bimaterial system and (b) sandwiched structure.

double cantilever beam [2], compact mixed-mode (CMM) specimen [9,10], Brazil nut [11,12], modified Brazil nut [13], compact tension shear joint [14], and scarf joint specimen [15]. Although there is no essential distinction between the bimaterial system and sandwiched structure, since the sandwiched structure is distinct in the constraint from the bimaterial system, the stress and displacement distributions around the crack-tip of sandwiched structure are different from those around the crack-tip of bimaterial system. Therefore, when the stress and displacement fields are employed to determine fracture toughness, more attention has to be paid to the constraint of adhesively bonded joint. Several analytical methods were proposed for the estimation of complex stress intensity factor (SIF) for interfacial crack [8,11,16]. Among these methods, the extrapolation approach is widely used because of its simplicity. Based on the stress distribution determined by boundary element method (BEM), Yukki et al. [17] used the approach to obtain the SIF of sandwiched Brazil nut specimen.

In this study, with a CMM sandwich specimen containing an interfacial edge crack, finite element (FE) method was used to study the interfacial crack problem in an adhesively bonded joint. An interface mechanics-based FE method was established to predict both stress and displacement distribution around the crack-tip. The stress field around the crack-tip was found to be unsuitable for the determination of SIF at the crack-tip. The displacement-based extrapolation method was then developed to determine the SIF at the crack-tip. As a result, three types of fracture criteria, i.e., modes I and II critical fracture toughness-based failure assessment diagram (FAD), effective critical fracture toughness-based failure assessment criterion (FAC), and strain energy release rate-based FAC, were established for the optimal design and fracture assessment of adhesively bonded joint involved in electronic devices.

2. Interface mechanics methodology

As shown in Fig. 1, the interface crack-tip experiences both normal and shear stress due to material elasticity mismatch in the bimaterial system or sandwiched structure. For plane strain condition, the elasticity mismatch between the two materials is governed by the Dundurs' [4] parameters and given by

$$\alpha = \frac{(1-\nu_2)/\mu_2-(1-\nu_1)/\mu_1}{(1-\nu_2)/\mu_2+(1-\nu_1)/\mu_1},\quad \beta = \frac{1}{2}\,\frac{(1-2\nu_2)/\mu_2-(1-2\nu_1)/\mu_1}{(1-2\nu_2)/\mu_2+(1-2\nu_1)/\mu_1}, \tag{1}$$

where ν_i and μ_i are the Poisson's ratio and shear modulus of the two materials, respectively; $i = 1, 2$, the subscripts 1 and 2 refer to materials across the interface. Assuming that an interface crack is situated in between two dissimilar isotropic materials, the William asymptotic stress field near the crack-tip can be described by [5,11]

$$\sigma_{ij}(r,\theta) = \frac{1}{\sqrt{2\pi r}}\left\{\mathrm{Re}[Kr^{\mathrm{i}\varepsilon}]\tilde{\sigma}^{I}_{ij}(\theta) + \mathrm{Im}[Kr^{\mathrm{i}\varepsilon}]\tilde{\sigma}^{II}_{ij}(\theta)\right\}, \tag{2}$$

where r and θ are the polar coordinates with local Cartesian x along the material interface; $\tilde{\sigma}^{\mathrm{I}}_{ij}$ and $\tilde{\sigma}^{\mathrm{II}}_{ij}$are the dimensionless angular distributions which correspond to tractions across the interface [12]; K is the complex SIF defined as

$$K = K_\mathrm{I} + \mathrm{i}K_\mathrm{II}, \tag{3}$$

where $\mathrm{i} = \sqrt{-1}$; K_I and K_II are the SIFs related to mode I and mode II loading configurations, respectively, and ε is the oscillatory index

$$\varepsilon = \frac{1}{2\pi}\ln\frac{1-\beta}{1+\beta}. \tag{4}$$

By introducing a characteristic length parameter ℓ into Eq. (3), the complex SIF can be expressed as

$$K\ell^{\mathrm{i}\varepsilon} = |K|e^{\mathrm{i}\psi} \tag{5}$$

where ψ is the phase angle of the complex quantity $K\ell^{\mathrm{i}\varepsilon}$, representing the mixity of mode II SIF to mode I SIF at the crack-tip. Thus, the local stress field ahead of the interfacial crack ($\theta = 0$) can be obtained by

$$\sigma_y + \mathrm{i}\tau_{xy} = \frac{K}{\sqrt{(2\pi r)}}\left(\frac{r}{\ell}\right)^{\mathrm{i}\varepsilon}, \tag{6}$$

where σ_y and τ_{xy} are the normal stress and shear stress at the crack-tip, respectively. The displacement field along