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Analytical model for adhesive die-attaching subjected to thermal loads using second-order beam theory

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ABSTRACT

In this work, an analytical model for adhesive die-attaching under thermal loads is proposed. The second-order beam theory is employed to model the die and substrate, so the shearing deformations can be evaluated more accurately comparing to models based on the Timoshenko beam theory and interface compliance. Then, governing equations are solved by Fourier series with the elastic foundation for the adhesive layer. As such, numerical calculations for eigenvalues are avoided, and explicit closed-form solutions are obtained. Based on the analytical model, effects of material properties and dimensions on the thermal deformation in the die are discussed. In the die, the longitudinal expansion and transverse warpage induced by thermal deformation both decrease with decreasing Young's modulus of adhesive. The longitudinal expansion decreases with increasing die thickness. However, the transverse warpage increases with increasing die thickness.

1. Introduction

Adhesive die-attaching (ADA) is the application of adhesively bonded bimaterial assemblies in the microelectronic and microelectromechanical system (MEMS) packaging [1]. An ADA typically consists of two layers of different materials bonded together through a thin adhesive layer, as shown Fig. 1. The mismatch of coefficients of thermal expansion (CTE) induces serious thermal deformation and interface stress. Because there usually exist mechanical elements in MEMS devices, the thermal deformation in the die results in serious temperature drifts [2–4]. In addition, the interface stress could lead to delamination related failures [5]. Thus, it is critical to develop a theoretical model for thermal deformations and interface stresses in ADA.

Analytical models for the interface stress in adhesively bonded bimaterial assemblies, subjected to mechanical or thermal loads, have been well developed by many researchers. Two typical analytical approaches, continuum method [6,7] and strength of material method [8–18], are employed. The continuum method results in more accurate solutions. However, it involves complicated calculations. The strength of material method is much simpler. Based on the strength of material method, Suhir proposed an analytical model with simple closed-form solutions obtained by computing eigenvalues [8,9]. However, the accuracy of the model is limited by the assumption that the normal stress in the adhesive layer is zero. In order to increase accuracy, shear and normal stresses must be both considered. Two-parameter [10–13], three-parameter [14–17], and even four-parameter [18] elastic foundations for the adhesive layer were employed. The differences of these elastic foundations are the simplification of stresses in the adhesive layer.

However, these analytical models based on the strength of material method still have drawbacks on the description of the thermal deformation and the solution for high order governing equations. In these models, the deformation inside the die or substrate is divided into four components, which are the longitudinal normal deformation induced by the thermal expansion, the longitudinal normal deformation induced by the shear stress, the transverse bending deformation, and the longitudinal shearing deformation, respectively, as shown in Fig. 1. The first, second and third components are evaluated through CTE, beam stretching theory and Timoshenko beam theory, respectively. For the fourth component, a coefficient called interface compliance directly gives the relationship between the shear stress and the displacement at the interface. However, the longitudinal shearing deformations inside the die and substrate can't be evaluated. Additionally, in order to solve high order governing equations in these analytical models, the numerical calculation of eigenvalues is required.

In this work, an analytical model for ADA subjected to thermal loads is proposed based on the second-order beam theory. Within the model, deformations at the interface and inside the die can both be evaluated

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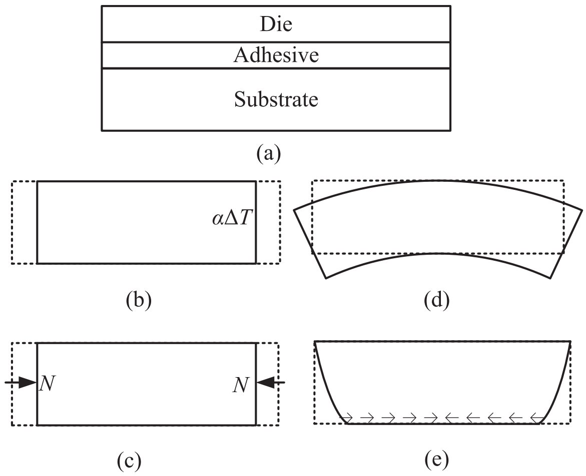

Fig. 1. Typical ADA structure and four components of the deformation in the die or substrate. (a) typical ADA structure; (b) longitudinal normal deformation induced by the thermal expansion; (c) longitudinal normal deformation induced by the shear stress; (d) transverse bending deformation; (e) longitudinal shearing deformation.

accurately. Additionally, high order governing equations are solved by Fourier series, so the numerical calculation of eigenvalues are avoided, and the explicit closed-form solutions are obtained.

2. Governing equations for the die and substrate

In this section, governing equations for the die and substrate are established by the second-order beam theory. Considering a typical ADA shown in Fig. 1**(a)**, the die is fully bonded to the substrate by the adhesive. Thus, the typical ADA forms an adhesively bonded bimaterial assembly. The die and substrate are the top and bottom adherends, respectively. For simplification, displacements, strains, and stresses in the die, adhesive layer, and substrate are distinguished by the subscripts of" t", "a", and " b". In addition, subscripts of "t" and " b" are also used to distinguished stresses at the two interfaces, as shown in Fig. 2. To describe the displacement field, the following coordinate systems are introduced. In the die and substrate, x-coordinates and z-coordinates are taken along the length and thickness, respectively. The x-coordinates in the die and substrate point in the same direction, while the z-coordinates point in the contrary direction, as shown in Fig. 2.

2.1. Displacements and strains

Due to the symmetry of the deformation of ADA, only half of an adherend is studied to derive the governing equations, as shown in

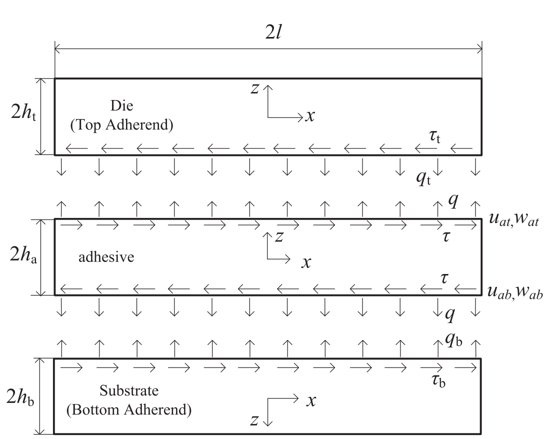

Fig. 2. Schematic diagram of the coordinate systems, geometric dimensions, and interface stresses.

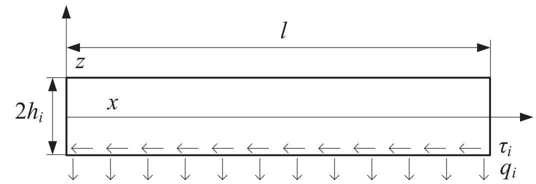

Fig. 3. Schematic diagram of the coordinate system, geometric dimensions and interface stresses for half of an adherend.

Fig. 3. The die bends due to the moment together induced by shear and normal interface stresses, so does the substrate. According to the beam theory, the longitudinal displacement induced by bending is an odd function of the z-coordinate. However, the shear interface stress also induces longitudinal expansion and shear. As such, the longitudinal displacement must include even terms. In this work, displacements are described by the second-order beam theory

$$u_i(x, z) = u_{i0}(x) + \phi_i(x)z + \psi_i(x)z^2$$
$$w_i(x, z) = w_{i0}(x) \tag{1}$$

where the subscript of "i" denotes" t" or " b", u_i and w_i denote the longitudinal and transverse displacements, respectively, u_{i0} and w_{i0} both denote displacements on the mid-surface, $\phi_{\rm i}$ and $\psi_{\rm i}$ together define the quadratic nature.

According to Eq. (1), the strain-displacement relations are given in

$$\varepsilon_{ixx} = \frac{\partial u_i}{\partial x} = \frac{\partial u_{i0}}{\partial x} + \frac{\partial \phi_i}{\partial x}z + \frac{\partial \psi_i}{\partial x}z^2$$
$$\gamma_{ixz} = \frac{\partial u_i}{\partial z} + \frac{\partial w_i}{\partial x} = \phi_i(x) + 2\psi_i(x)z + \frac{\partial w_{i0}}{\partial x} \tag{2}$$

There are four dependent unknown functions in the displacement field given in Eq. (1). According to the beam theory, the free conditions on the top or bottom boundary can be employed to reduce the number of unknown functions [19]. Because the top and bottom boundaries of ADA are free, the shear stresses on the two boundaries are zero, so as the shear strains. Based on Eq. (2), the shear strains on the top and bottom boundaries are expressed as

$$\gamma_{ixz}(x, h_i) = \phi_i + 2\psi_i h_i + \frac{\partial w_{i0}}{\partial x} = 0 \tag{3}$$

Combining Eqs. (1) and (3) leads to

$$u_i(x, z) = u_{i0} + \phi_i\left(z - \frac{z^2}{2h_i}\right) - \frac{1}{2h_i}\frac{\partial w_{i0}}{\partial x}z^2$$
$$w_i(x, z) = w_{i0} \tag{4}$$

Combining Eqs. (2) and (3) leads to

$$\varepsilon_{ixx} = \frac{\partial u_{i0}}{\partial x} + \frac{\partial \phi_i}{\partial x}\left(z - \frac{z^2}{2h_i}\right) - \frac{z^2}{2h_i}\frac{\partial^2 w_{i0}}{\partial x^2}$$
$$\gamma_{ixz} = \left(\phi_i + \frac{\partial w_{i0}}{\partial x}\right)\left(1 - \frac{z}{h_i}\right) \tag{5}$$

Eq. (4) shows that the quadratic longitudinal displacement accommodates the vanishing of shear stress on the free boundary. As such, the shear correction factor [19], which is necessary for the Timoshenko beam theory employed in most models based on strength of material method, is avoided.

2.2. Constitutive relations

ADA is usually treated as a plane strain problem. Using Hooke's law, the constitutive relations in the die and substrate are expressed as

$$\sigma_{ixx} = \widetilde{E}_i(\varepsilon_{ixx} - \alpha_i \Delta T)$$
$$\sigma_{ixz} = G_i\gamma_{ixz} \tag{6}$$