A Stress Singularity Parameter Approach for Evaluating Adhesive Strength*

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Since the stress and displacement fields near a bonding edge show singularity behaviors, the adhesive strength evaluation method, using maximum stresses calculated by numerical stress analysis such as the finite element method, is generally not valid. In this paper, a new method, which uses two stress singularity parameters, is presented for evaluating adhesive strength. This method is applied to several kinds of molded models, composed of epoxy base resin and Fe-Ni alloy sheets. Predictions about the initiation and extension of delamination are compared with the results of observations made by scanning acoustic tomography on molded models.

Key Words: Adhesion, Fracture, Adhesive Strength, Delamination, Stress Singularity, Scanning Acoustic Tomography, Plastic Encapsulation

1. Introduction

Recently, the use of adhesives has become increasingly important in the production of electronic or optoelectronic devices, and in accordance with this trend, the necessity of developing more accurate strength evaluation methods for an adhesively bonded interface is increasing. For instance, in the case of plastic encapsulated LSI devices, the thermal expansion mismatch of utilized materials causes thermal stresses on the adhering interface in the cooling process from the molding temperature. These thermal stresses could cause serious device reliability problems, such as interface debonding, resin cracking, and reduction of environmental durability. Thus, the development of more accurate bonding strength evaluation methods is an important subject for evaluation

of LSI device reliability. The most difficult problem in the strength evaluation of adhesively bonded structures is that the stress and displacement fields near the bonding edge, where the delamination starts, show singularity behavior⁽¹⁾⁻⁽⁴⁾, and accurate strength evaluation can't be made using stress values alone. Concerning this point, a new adhesive strength evaluation method using two singularity parameters which express stress fields near a bonding edge, is presented.

2. Calculation of Stress Singularity Parameters

A typical model of plastic encapsulated LSI devices is shown in Fig. 1. Adhering interfaces in these LSI devices have various bonding edges, as shown by the circles in this figure, and the stress fields near these bonding edges show singularity behaviors. Since in these regions, the maximum stresses calculated by numerical stress analysis, such as the finite element method, depend on the size of the element meshes, overall strength evaluation can't be made using only these calculated maximum stress values. Therefore, a new adhesion strength evaluation method using two stress singularity parameters, K , λ , is presented, which can express stress distributions near a bonding

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edge as follows:

$$\tau(r) = K/r^\lambda \quad (1)$$

$\tau(r)$: shearing stress (MPa)

r : distance from singularity point (mm)

K : intensity of stress singularity

λ : order of stress singularity

Since shearing and normal stresses exist on the adhering interface, the stress singularity parameters concerning the two stresses must be used for a strict evaluation. But, in this paper, parameters referring only to shearing stress, which mainly dominates delaminating, are used, and calculation methods of parameters λ and K are explained.

The order of stress singularity λ for the two-material wedge-bonded models, with wedge angles θ_1 , θ_2 , Young's modulus E_1 , E_2 and Poisson's ratio ν_1 , ν_2 , can be calculated by solving the characteristic equation (Eq. 2), which is derived by elastic analysis under adequate boundary conditions⁽¹⁾⁽⁴⁾, as follows:

$$\begin{aligned} Q(\theta_1, \theta_2, \alpha, \beta; P) = & A(\theta_1, \theta_2; P)\beta^2 \\ & + 2B(\theta_1, \theta_2; P)\alpha\beta + C(\theta_1, \theta_2; P)\alpha^2 \\ & + 2D(\theta_1, \theta_2; P)\beta + 2E(\theta_1, \theta_2; P)\alpha \\ & + F(\theta_1, \theta_2; P) = 0 \end{aligned} \quad (2)$$

In this equation, α and β can be written using elastic parameters, as follows:

$$G_i = \frac{E_i}{2(1+\nu_i)} \quad (i=1,2) \quad (3)$$

$$m_i = \begin{cases} 4(1-\nu_i): \text{plane strain} \\ 4(1+\nu_i): \text{plane stress} \end{cases} \quad (i=1,2) \quad (4)$$

$$\alpha = \frac{G_1 m_2 - G_2 m_1}{G_1 m_2 + G_2 m_1} \quad (5)$$

$$\beta = \frac{G_1(m_2-2) - G_2(m_1-2)}{G_1 m_2 + G_2 m_1} \quad (6)$$

A, B, C, D can be written using the following auxiliary function $H(P, \theta)$

$$H(P, \theta) = \sin^2(P, \theta) - P^2 \sin^2(\theta) \quad (7)$$

as follows:

$$A(\theta_1, \theta_2; P) = 4H(P, \theta_1) \cdot H(P, \theta_2)$$

$$B(\theta_1, \theta_2; P) = 2P^2 \cdot \sin^2(\theta_1) \cdot H(P, \theta_2) + 2P^2 \sin^2(\theta_2) \cdot H(P, \theta_1)$$

$$C(\theta_1, \theta_2; P) = 4P^2 \cdot (P^2 - 1) \cdot \sin^2(\theta_1) \sin^2(\theta_2) + H\{P, (\theta_2 - \theta_1)\}$$

$$D(\theta_1, \theta_2; P) = 2P^2 \cdot \{\sin^2(\theta_2) \cdot \sin^2(P\theta_1) - \sin^2(\theta_1) \cdot \sin^2(P\theta_2)\}$$

$$E(\theta_1, \theta_2; P) = -D(\theta_1, \theta_2; P) + H(P, \theta_2)$$

$$F(\theta_1, \theta_2; P) = H\{P, (\theta_1 + \theta_2)\} \quad (8)$$

Finally, the order of stress singularity λ can be obtained using the root of Eq. (2), P , as follows:

$$\lambda = 1 - P \quad (9)$$

Calculation results of Eq. (2) for the case $\theta_1 = \theta_2 = 90^\circ$, $E_1/E_2 = 0.1$, and $\nu_1 = \nu_2 = 0.3$ are shown in Fig. 3. In this case, λ can be obtained as 0.159. Calculation results of λ as a function of the ratio E_1/E_2 in two cases of $\theta_1 =$

Fig. 1 General view of plastic encapsulated LSI devices and various kinds of bonding edges

Fig. 2 Geometry of bonded edge

Fig. 3 Calculated results of characteristic equation ($\theta_1 = \theta_2 = 90^\circ$, E_1/E_2)

Fig. 4 Calculated results of the order of stress singularity λ ($\theta_1 = \theta_2 = 90^\circ$)

$\theta_2=90^\circ$ and $\theta_1=90^\circ$, $\theta_2=180^\circ$ are shown in Fig. 4 and Fig. 5 respectively. Sometimes Eq. (2) has a complex root or double roots; in these cases the largest real parts of Eq. (9) are used as the order of stress singularity since these dominate the stress state near the singularity point⁽³⁾. The order of stress singularity λ for other adhering models, such as a three-material wedge, can be calculated by the same method⁽³⁾.

Intensities of stress singularity K are calculated by fitting Eq. (1) to the stress distributions near a bonding edge calculated by numerical stress analysis, such as the finite element method or the boundary element method.

3. Experimental Measurement of Delamination Criteria

Two-material bonding specimens composed of epoxy base resin and Fe-Ni alloy sheets were used (See Fig. 6), to obtain the relation between the critical intensity value of stress singularity, K_{crit} , where delamination starts from the bonding edges and order of stress singularity λ . Material constants of these

Table 1 Material constants of compositions

Material	Young's modulus E (GPa)	Poisson's ratio ν	Coefficient of thermal expansion α ($10^{-6}/^\circ\text{C}$)
Resin (epoxy base)	14.7	0.25	19
Metal (Fe-Ni alloy)	148	0.3	5

Fig. 5 Calculated results of the order of stress singularity λ ($\theta_1=90^\circ$, $\theta_2=180^\circ$)

Fig. 6 Shapes of two-material bonding specimens

compositions are shown in Table 1. These two materials were bonded at 170°C and after-cured in a furnace at the same temperature for 5 hours. Delamination in cooling processes were measured using two strain gauges mounted on both surfaces, as shown in Fig. 7(5).

During the cooling process, the specimens were first warped by thermal stresses. Then, accompanying the delamination, these thermal stresses were released, as shown in Fig. 7. The released stresses coincided well with the calculated results of the finite element method. Thus, using the obtained delamination temperature and the calculated results of thermal stresses, critical intensity values of the stress singularity K_{crit} were obtained. The values of K_{crit} for various orders of stress singularity λ are shown in Fig. 8. The delamination occurrence can be estimated on this criterion curve.

Fig. 7 Measured result of delamination in the cooling process

Fig. 8 Delamination criteria using stress singularity-parameters K and λ

4. Application of Delamination Criteria on the Molded Model

The above-mentioned delamination criteria were applied to three types of resin molded models, the shapes of which are shown in Fig. 9. The delamination occurrence and its propagation behaviors in the cooling process from the molding and curing temperature (170°C) were estimated. Element mesh and shearing stress distributions on the quarter-cut section of the model (C) are shown in Fig. 10. Intense stress concentration can be seen near the bonding edge. The same shearing stress distribution of the model (C) is shown in Fig. 11, in this case there is a delamination of 0.5

Fig. 9 Shape of molded models

Fig. 10 Element mesh and shearing stress distribution of model (C) (complete adhesion)

Fig. 11 Element mesh and shearing stress distribution of model (C) (0.5 mm delamination)

mm from the bonding edge. Shift of the stress singularity point from the bonding edge to the delamination tip is evident.

Shearing stress distributions near the singularity point (bonding edge) are shown in Figs. 12 and 13. Shearing stress on the adhering interface ($y=0$) increases as the distance from the singularity point decreases. The shearing stress distribution on the adhering interface on a log scale is shown in Fig. 14. Bold lines in these figures show Eq. (1) to be fitted to the calculated stress distributions with λ calculated from Eq. (9). The obtained K for each model is shown in Fig. 15. In this figure, the hollow circle, square and triangle show the calculated results of K

Fig. 12 Shearing stress distribution near the singularity point (model (C), complete adhesion)

Fig. 13 Shearing stress distribution near the singularity point (model (C), 0.1 mm delamination)

for the case of complete adhesion; the solid circle, square and triangle show the case of 0.01 mm delamination.

These figures show that in all cases, delamination occurs at the bonding edge, but in the case of model (A) this delamination stops instantaneously. To estimate the propagation behavior of delamination for each model, the relations between delamination length a and stress singularity intensity K at the delamination tips are calculated, as shown in Fig. 16. In the cases of model(A) and model(B), in which Fe-Ni alloy sheets are completely molded in the resin, stress singularity intensity K decreases as the delamination propagates. In the case of model(C), in which the bonding edge exists on the outer surface, K initially decreases, but in accordance with the extension of delamination length a , K increases gradually. In Fig. 16 the propagation limit of delamination (delamination criteria on $\lambda=0.5$) is shown by the hatched lines. It can be estimated that model(A) has almost complete adhesion, model(B) has a small quantity of delamination and model(C) has complete delamination.

Fig. 14 Shearing stress distributions on the adhering interface

To confirm the validity of this estimation method, the three types of models shown in Fig. 1 were molded, and delamination behaviors in the cooling process from molding temperature (170°C) to room tempera-

Fig. 15 Stress singularity parameters for each molded model

Fig. 16 The relations between delamination length a and intensity of stress singularity K at the delamination tips

Fig. 17 Delamination observation conditions by the scanning acoustic tomography

Fig. 18 Scanning acoustic tomography images of molded models

ture (20°C) were observed using scanning acoustic tomography. Delamination observation conditions by the scanning acoustic tomography are shown in Fig. 17. Molded models are put into the water and the focus of a 20 MHz transducer is placed at the adhering interface. The delaminations are detected by scanning this transducer in the x - y plane with 0.1 mm pitch, and measuring the reflected wave levels from the adhering interface.

The scanning acoustic tomography images for three types of molded models are shown in Fig. 18. The adhering and delaminated regions are denoted in the respective cases. In the case of model(A), delamination could not be observed; in the case of model(B), a small region of delamination could be observed, and in the case of model(C), almost all regions were delaminated. These observed results of delamination behaviors coincided well with the estimated results of those using stress singularity parameters.

5. Conclusions

Recently, the necessity of developing more accurate strength evaluation methods for adhesive bonded interfaces has increased in accordance with the demand for high reliability, adhesively bonded struc-

tures. A new adhesive strength evaluation method was developed which uses two stress singularity parameters, and the following conclusions were obtained.

(1) The calculation method of the order of stress singularity λ using the elastic properties of adhesives and adherends and the geometry of the bond edge, and the stress intensity singularity K calculation method using the calculated results of the finite element stress analyses were derived. These were applied to two-material bonding specimens and molded models.

(2) Delamination criteria using two stress singularity parameters could be obtained from delamination tests using two-material bonding specimens.

(3) The above-mentioned calculation method of stress singularity parameters and delamination criteria were applied to three types of molded models; the occurrence and propagation behavior of the delaminations were estimated.

(4) Delamination occurrence and delamination propagation behaviors of molded models were observed with scanning acoustic tomography. These results coincided well with the estimated results.

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