Evaluation of Joining Strength of Silicon-Resin Interface at a Vertex in a Three-Dimensional Joint Structure

Hideo Koguchi
Department of Mechanical Engineering,
Nagaoka University of Technology,
Nagaoka, Niigata 940-2188, Japan
e-mail: koguchi@mech.nagaokauniv.ac.jp

Kazuhsa Hoshi
Department of Mechanical Engineering,
Graduate School of Nagaoka,
University of Technology,
Nagaoka, Niigata 940-2188, Japan
e-mail: hoshikazu@stn.nagaokauniv.ac.jp

Portable electric devices such as mobile phones and portable music players have become compact and improved their performance. High-density packaging technology such as chip size package (CSP) and stacked-CSP is used for improving the performance of devices. CSP has a bonded structure composed of materials with different properties. A mismatch of material properties may cause a stress singularity, which leads to the failure of the bonding part in structures. In the present paper, stress analysis using the boundary element method and an eigenvalue analysis using the finite element method are used for evaluating the intensity of a singularity at a vertex in three-dimensional joints. A three-dimensional boundary element program based on the fundamental solution for two-phase isotropic materials is used for calculating the stress distribution in a three-dimensional joint. Angular function in the singular stress field at the vertex in the three-dimensional joint is calculated using an eigenvector determined from the eigenvalue analysis. The joining strength of interface in several kinds of silicon-resin specimen with different triangular bonding areas is investigated analytically and experimentally. An experiment for delaminating the interface in the joints is firstly carried out. Stress singularity analysis for the three-dimensional joints subjected to an external force for delaminating the joints is secondly conducted. Combining results of the experiment and the analysis yields a final stress distribution for evaluating the strength of interface. Finally, a relationship of force for delamination in joints with different bonding areas is derived, and a critical value of the 3D intensity of the singularity is determined. [DOI: 10.1115/1.4006139]

Introduction

CSP is used in recent electronic devices for improving their functionality and performance. CSP is consisted of an IC chip, resin, and metals, and delamination occurs frequently at a vertex of interface between the IC and resin. A lot of studies on the joints have been carried out theoretically and experimentally [1–3]. In the previous study, two-dimensional joints are extensively investigated; however, few studies on three-dimensional joint structures have been carried out until now [4]. Real CSP has a three-dimensional shape and an interface. Therefore, it is necessary to evaluate the strength of interface at the vertex in three-dimensional joints.

Generally, singular stress fields at the edge of interface in joints can be described as $\sigma_{ij} = \Sigma_{\alpha} K_{ij}^\alpha f_{ij}^\alpha (\theta, \phi) r^{-\alpha m}$, where $r$ represents the distance from the origin of the singular stress field, $\alpha_m$ is the order of stress singularity, $K_{ij}^\alpha$ is the intensity of singularity for stresses $\sigma_{ij}$, and $f_{ij}^\alpha (\theta, \phi)$ are angular functions. In the case of $0 < \alpha_m < 1$, it can be said that the stress field has a stress singularity [5–9].

In the present paper, a simple specimen is used for investigating the strength of interface at the vertex in a Si-resin joint constituting CSP. Firstly, the order of stress singularity is derived from eigenvalue analysis based on FEM, and an angular function for the singular stress field at the vertex in three-dimensional joints is calculated using an eigenvector determined from the eigen analysis. Secondly, a stress analysis is performed using BEM under mechanical and thermal loadings. It will be shown that residual thermal stress in the specimen is very small. Finally, the bonding strength of the interface is estimated experimentally and theoretically. A relationship between the bonding strength in joints and the bonding areas is derived. The critical intensity of the stress singularity on the interface in three-dimensional joints is determined to estimate the strength of interface.

Analysis Methods for Singular Stress Field

Three-Dimensional Boundary Element Method. The boundary integral equation can be expressed as follows:

$$c_{ij}(P) u_i(p) \rightarrow c_{ij}(P) u_i(P) \quad (1)$$

where $c_{ij}(P)$ represents a constant depending on the shape of the boundary, $P$ and $Q$ are an observation point and a source point located on the boundary $\Gamma$, and $U_{ij}$ and $T_{ij}$ represent the fundamental solutions for displacement and traction. Here, Rongved’s solution, which is the Green function for two-phase isotropic materials, is used as the fundamental solution for calculating the stress fields at the vertex in three-dimensional joints. Stress distribution in the domain for analysis is evaluated using Hooke’s law and the following equation:

$$\{U_{ij}\\!(P, Q) T_{ij}(Q) - T_{ij}\!(P, Q) U_{ij}(Q)\} \rightarrow \{U_{ij}\!(p, Q) T_{ij}(Q) - T_{ij}\!(p, Q) U_{ij}(Q)\} \quad (2)$$

where $U_{ij}$ and $T_{ij}$ are the derivatives of fundamental solutions of displacement and traction with respect to $p$.

The boundary element method does not require as much data as the finite element method does. Using the fundamental solutions...
for two-phase materials, mesh division on the interface is not, therefore, needed. Hence, stress distribution on the interface near the vertex can be calculated precisely.

Eigen Analysis. The order of the stress singularity \( \lambda \), which characterizes stress field, is determined using an eigenequation, which is formulated on the basis of the finite element method as follows (see Pageau and Bigger [10]):

\[
\langle p^2[A] + p[B] + [C]\rangle (u) = 0
\]

where \( \lambda = 1 - \text{Re}(p) \), \( p \) is a root of Eq. (3), \([A]\), \([B]\), and \([C]\) are matrices consisted of elastic moduli and the geometry of joints, and \( \{u\} \) represents a nodal displacement vector. When \( 0 < \lambda < 1 \), the stress field has a stress singularity, and when \( 1 > \lambda \), the stress singularity disappears.

Delamination Experiments

Materials and Methods. In the present study, specimens in which two IC (silicon) square plates are bonded using an underfill resin are prepared as shown in Fig. 1. This type of specimen was developed for investigating the strength of interface at the 3D vertex in multilayered thin films by Shibutani et al. [11]. The silicon plate is a square of 6 mm \( \times \) 6 mm and 0.63 mm in thickness. The resin is a square of 3 mm \( \times \) 6 mm and 0.05 mm in thickness. The specimens have a triangular bonding area. An experiment for delamination is carried out under conditions that the bonding area \( A \) varied about from 0.50 mm\(^2\) to 2.0 mm\(^2\). In a bonding process, the specimen is heated up to 453 K and two silicon plates are bonded to each other with resin. After that, it is naturally cooled to room temperature. The specimen is kept in a desiccator until the delamination test.

A schematic view of the experimental apparatus is shown in Fig. 2(a), and a portion encircled in this figure is enlarged in Fig. 2(b). A tensile load testing machine is used for the delamination test. A load cell is attached at one end of the machine for measuring the force of delamination in the specimens, which are glued at Jig 2 as shown in Fig. 2(b). The delamination test is carried out in the way that a specimen is pushed with a small steel ball of 2 mm in diameter glued to Jig 1 attached to a rod of the load cell in the arrow direction.

Results. A crack ran brittlely along an interface from the three-dimensional corner. The delamination surface was the interface between silicon and resin. The delamination occurred at the interface between the upper silicon and the resin. Through the precise observation of the fracture surface, it was found that the delamination initiated at the vertex of the joint. Hence, we perform stress analyses at the vertex of the upper interface bonding silicon and resin.

The results of the delamination test for each condition are shown in Fig. 3. Delamination forces are shown in Fig. 3(a), and delamination stresses, which are divided each load by each bonding area, are shown in Fig. 3(b). Average forces for the bonding area of 0.5 mm\(^2\), 1.0 mm\(^2\), and 2.0 mm\(^2\) are 0.59 N, 1.27 N, and 3.34 N, respectively. The average of the delamination stress is 1.20 MPa, 1.27 MPa, and 1.68 MPa, respectively. Hence, it is found that delamination force decreased with decreasing the bonding area. These experimental results are shown in Table 1.

Thermal Deformation Experiments

In the bonding process of two silicon specimens by resin, the specimens are heated up to 435 K and naturally cooled down to room temperature. Hence, residual thermal stress may occur in the specimen. Here, warpage in the specimen before and after bonding is measured using a laser measurement system whether residual thermal stress exists or not. A schematic view of the laser measurement system is shown in Fig. 4. The specimen put on XY-stage moves under the laser measurement system, and the warpage of the specimens is measured. The specimen with a bonding area of \( A = 1.0 \text{ mm}^2 \) was measured. The warpage along Line \( ST \) passing through the vertex of the upper silicon shown in Fig. 5 was measured.

Figure 6 represents the result of the measurement and the warpage along Line \( ST \) calculated from thermal residual stress analysis using the boundary element method. It is found that the specimen did not deform before and after heating. We suppose that residual thermal stress released after bonding. Hence, thermal residual stress has little influence on the delamination force.
Analysis of Stress Singularity

Eigen Analysis. In the experiment, delamination occurs at the vertex of the upper interface between silicon and resin, so eigen analysis at the vertex is performed. A model for eigen analysis is shown in Fig. 7, where angles around the stress singularity point O are \( \phi_1 = 90 \text{ deg} \), \( \phi_2 = 360 \text{ deg} \), and angles around the stress singularity line are \( \phi_1 = 180 \text{ deg} \), \( \phi_2 = 360 \text{ deg} \).

Firstly, the order of the stress singularity is determined using Eq. (3). The mesh division for eigen analysis is shown in Fig. 8. This figure represents a developed mesh on the \( \theta-\phi \) plane of the sphere surface shown in Fig. 5. In this analysis, mesh size of \( \theta \) and \( \phi \) coordinates is \( \theta \times \phi = 15 \text{ deg} \times 15 \text{ deg} \) and a mesh involving an interface and stress singularity lines is equally divided by five \( \theta \times \phi = 3 \text{ deg} \times 3 \text{ deg} \). Material properties used in the analysis are shown in Table 2.

### Table 1 Experimental results

<table>
<thead>
<tr>
<th>Bonding area, mm²</th>
<th>Delamination force force ( F ), N</th>
<th>Delamination stress, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower</td>
<td>Average</td>
</tr>
<tr>
<td>0.49</td>
<td>0.42</td>
<td>0.59</td>
</tr>
<tr>
<td>1.0</td>
<td>1.10</td>
<td>1.27</td>
</tr>
<tr>
<td>1.99</td>
<td>2.66</td>
<td>3.34</td>
</tr>
</tbody>
</table>

Fig. 3 The comparison of experimental results. (a) Delamination forces and (b) delamination stresses.

Fig. 4 Schematic view of a measurement

Fig. 5 Scan line for a measurement

Fig. 6 Measurements and analysis results for the thermal deformation

Fig. 7 Spherical coordinate system with an origin at a vertex
Results of eigen analysis are shown in Table 3. It is found that several eigen values yielding stress singularity exist for each pair of the angles, $\phi_1$ and $\phi_2$, of the vertex. In the previous study on the three-dimensional stress singularity [12], when a triple root of $p=1$ exists, logarithmic singularity occurs at the stress field. Then, the stress field at the vertex in three-dimensional joints can be expressed as follows:

$$
\sigma_{ij}(r, \theta, \phi) = K_{ij}f_{ij}(\theta, \phi)L^{-\lambda_{\text{vertex}}}_{ij} + K_{L}f_{L}(\theta, \phi)
+ \sum_{k=3}^{M} K_{L}f_{L}(\theta, \phi)(\ln r)^{k-2}
$$

(4)

where $M=4$ (with a triple root of $p=1$) and 5 (with a quadruple root of $p=1.0$). $\lambda_{\text{vertex}}$ represents the order of stress singularity at the vertex. Here, angular function $f_{ij}(\theta, \phi)$ can be obtained from the eigenvector ($\{a^j\}$ on Eq. (3)) corresponding to eigenvalue $p$.

Angular functions at the interface for each eigenvalue of $p_{\text{vertex}}$ = 0.280 and 0.350 in the joint angle $\phi_1 = 90$ deg, $\phi_2 = 360$ deg is shown in Fig. 9. In particular, the distribution of $f_{10}(\pi/2, \phi)$ relating to delamination at the interface is investigated. Here, $f_{10}(\pi/2, \phi)$ is expressed as $f_{10}^{\phi_1}(\phi)$.

The angular functions are normalized by the value of $f_{10}^{\phi_1}(\phi)$ at $\phi = 45$ deg. Here, the value of $\lambda_{\text{vertex}}$ for which $f_{10}^{\phi_1}(\phi)$ is similar to that of $\sigma_{ij}(r, \theta, \phi)$ on the interface against the angle $\phi$ obtained by boundary element method is selected. Then, the order of stress singularity of $\lambda_{\text{vertex}} = 0.65$ at the vertex with angles of $\phi_1 = 90$ deg, $\phi_2 = 360$ deg is selected. The result for boundary element analysis will be shown in the next chapter.

For the order of stress singularity at a point on the singular stress line of $\phi_1 = 180$ deg and $\phi_2 = 360$ deg, $\lambda_{\text{line}} = 0.49$ is selected from a comparison of $f_{10}^{\phi_1}(\phi)$ with $\sigma_{ij}(r, \theta, \phi)$.

Angular function $f_{10}(\theta, \phi)$ in the singular stress field can be expressed as follows [13]:

$$
f_{10}(\frac{\pi}{2}, \phi) = L_{100}r^{-\lambda_{\text{line}}} + L_{200} + \sum_{k=3}^{6} L_{4k}^{\phi_1}(\ln r)^{k-2}
$$

(5)

where $\rho_3$ is the distances from the singular stress line, and it is expressed as $\rho_{3} = \sin \phi$. Here, $\rho$ is taken to be 1.

Three-Dimensional Boundary Element Method. Stress analysis using BEM is conducted to determine the intensity of singularity at the vertex in the specimen shown in Fig. 1. The domain method is employed in the BEM analysis. The boundary condition is set as the same as the delamination test, and a unit normal force
to the specimen is applied to a point (see Fig. 1). Eight nodes quadrilateral serendipity element is used, and the minimum length of a side in an element near the vertex is about $10^{−6}$ mm. Material properties used in the analysis are shown in Table 2.

All stress components are transformed from a Cartesian coordinate system to a spherical coordinate system. Here, the results of analysis for mechanical loading will be presented for the joints with bonding areas of $A = 0.49, 1.0, 1.99, 2.99$ mm$^2$.

Only $\sigma_{00}$ of stress components, which influence delamination of the interface, will be shown. Distribution of stress $\sigma_{00}$ on the interface against distance from origin $r$ at $\phi = 45$ deg is shown in Fig. 10. It is found that the stress $\sigma_{00}$ decreases with increasing the bonding area. The expression of stress distribution, Eq. (4), can be rewritten as follows:

$$\sigma_{00}(r, \frac{\pi}{2}, \phi) = K_{100} f_{100} \phi \frac{\pi}{2}, \phi) + K_{200} f_{200} (\frac{\pi}{2}, \phi)$$

(6)

Here, the logarithmic terms are neglected for simplicity. Because it was shown in Ref. [14] that the logarithmic terms affect on the stress distribution far from the vertex, and the power law singularity represented by a line in the double logarithmic plot was dominant in this analysis. The coefficients determined by a least square method using Eq. (6) are shown in Table 4. Where the angular function is normalized to $f_{100}(\frac{\pi}{2}, 0) = 1$ at the angle $\phi = 45$ deg. $K_{100}$ is the intensity of the singularity with respect to the radial direction from the vertex. It is found that the value of intensity of the singularity $K_{100}$ decreases with increasing bonding area.

Distribution of stress $\sigma_{00}$ at $r = 0.0001$ mm on the interface ($\theta = 90$ deg) against $\phi$ is shown in Fig. 11. It is found that the stress $\sigma_{00}$ decreases with increasing the bonding area. Figure 12 shows a stress distribution normalized by the value of $\sigma_{00}$ at the angle $\phi = 45$ deg. It is found that all distributions are overlapped with each other. Omitting the logarithmic term, the expression of stress distribution can be expressed as follows:

$$f_{100}^\phi(\phi) = L_{100} f_{100}^\phi + L_{200}$$

(7)

The coefficients, $L_{100}$ and $L_{200}$, determined by a least square method using Eq. (7), are shown in Table 5. $L_{100}$ is the intensity

![Figure 10](image1.png)  
Fig. 10 Distributions of stress $\sigma_{00}$ at $\phi = 45$ deg on the interface against $r$ and fitted curve

![Figure 11](image2.png)  
Fig. 11 Distributions of stress $\sigma_{00}$ at $r = 0.0001$ mm on the interface against $\phi$

![Figure 12](image3.png)  
Fig. 12 Normalized stress $\sigma_{Mech}/\sigma_{Mech} \phi = 45$ deg at $r = 0.0001$ mm on the interface and fitted curves

### Table 4 Coefficients in Eq. (6)

<table>
<thead>
<tr>
<th>Bonding area $A$, mm$^2$</th>
<th>$K_{100}$, MPa-mm$^{0.65}$</th>
<th>$K_{200}$, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.49</td>
<td>13.8</td>
<td>−41.6</td>
</tr>
<tr>
<td>1.0</td>
<td>4.82</td>
<td>−24.1</td>
</tr>
<tr>
<td>1.99</td>
<td>1.53</td>
<td>−4.67</td>
</tr>
<tr>
<td>2.99</td>
<td>0.554</td>
<td>−1.22</td>
</tr>
</tbody>
</table>

### Table 5 Coefficients in Eq. (7)

<table>
<thead>
<tr>
<th>Bonding area $A$, mm$^2$</th>
<th>$L_{100}$</th>
<th>$L_{200}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.49</td>
<td>0.535</td>
<td>0.309</td>
</tr>
<tr>
<td>1.0</td>
<td>0.532</td>
<td>0.318</td>
</tr>
<tr>
<td>1.99</td>
<td>0.511</td>
<td>0.347</td>
</tr>
<tr>
<td>2.99</td>
<td>0.503</td>
<td>0.360</td>
</tr>
</tbody>
</table>
The stress distribution, \( F \), of a unit load by the delamination force can be expressed by multiplying the stress distributions for the critical status can be expressed by multiplying the stress distributions for the critical status.

The critical stress \( \sigma_{\theta0\text{critical}} \) is expressed as follows:

\[
\sigma_{\theta0\text{critical}}(r, \frac{\pi}{2}, \phi) = \sigma_{00}(r, \frac{\pi}{2}, \phi) F
\]  

(8)

The stress distribution, \( \sigma_{\theta0\text{critical}} \), for the critical status is shown in Fig. 13. It is found that all plots for different bonding areas are almost overlapped.

Substituting the equation, which \( f_{1\theta0} \) in Eq. (6) is replaced by Eq. (7), into Eq. (8) yields the following equation:

\[
\sigma_{\theta0\text{critical}}(r, \frac{\pi}{2}, \phi) = \left\{ K_{100}(\rho_{\theta0}(\phi)) r^{-\lambda_{\text{line}}} + K_{200}(\rho_{\theta0}(\phi)) \right\} F
\]

\[
= \left\{ K_{100}(L_{100} \rho_{A} j_{\text{line}} + L_{200}) r^{-\lambda_{\text{line}}}
+ K_{200}(L_{200} \rho_{A} j_{\text{line}}) \right\} F
\]

(9)

Equation (9) is factorized by a coefficient of power law term.

Thus,

\[
\sigma_{\theta0\text{critical}}(r, \frac{\pi}{2}, \phi) = K_{100} L_{100} F \left( 1 + \frac{L_{200}}{L_{100} \rho_{A} j_{\text{line}}} \right) r^{-\lambda_{\text{line}}}
+ \frac{K_{200}(\rho_{\theta0}(\phi))}{K_{100}(L_{100} \rho_{A} j_{\text{line}})} \rho_{A} j_{\text{line}} r^{-\lambda_{\text{line}}}
\]

(10)

Here,

\[
\phi \to 0 \text{ deg then } \frac{1}{\rho_{A} j_{\text{line}}} (\sin \phi) j_{\text{line}} \to 0
\]

\[
r \to 0 \text{ then } r^{-\lambda_{\text{line}}} \to 0
\]

Therefore,

\[
\sigma_{\theta0\text{critical}}(r, \frac{\pi}{2}, \phi) = K_{100} L_{100} F \rho_{A} r^{-\lambda_{\text{line}}} r^{-\lambda_{\text{line}}}
\]

(11)

Here, \( \rho_{A} = \sin \theta, \lambda_{\text{line}} = 0.49, \lambda_{\text{vertex}} = 0.65 \); therefore,

\[
\sigma_{\theta0\text{critical}}(r, \frac{\pi}{2}, \phi) = K_{100} L_{100} F \sin \phi r^{-0.49} r^{-0.65}
\]

(12)

Coefficients in Eq. (12) are used to evaluate the strength of interface in a delamination test. Hence, a critical intensity of singularity is expressed as follows:

\[
K_{100}^{3D\text{critical}} = K_{100}^{3D} F
\]

(13)

Where \( K_{100}^{3D} = K_{100} L_{100} F \), and \( F \) is the force for delamination shown in Table 1. \( K_{100}^{3D\text{critical}} \) is defined as the three-dimensional critical intensity of the singularity at the vertex. The values of \( K_{100}^{3D} \) and \( K_{100}^{3D\text{critical}} \) are shown in Table 6. It is found that the \( K_{100}^{3D\text{critical}} \) decreases a little with increasing the bonding area. Considering a variation in the result of the delamination experiment, a critical value can be determined as the value of \( K_{100}^{3D\text{critical}} \). The value of \( K_{100}^{3D\text{critical}} \) for the bonding joints in the present study is between 2.61 and 4.35 MPa·mm\(^{0.65}\).

### Conclusion

In the present paper, the strength of the interface in three-dimensional joints with several values of the bonding area was evaluated by experiment, BEM, and eigen analysis. The critical strength of the interface was evaluated from singular stress fields. As a result, the following items were obtained:

1. Warpage of the specimen used in the experiment after bonding could be ignored. So, residual thermal stress was not taken into account in evaluating the strength of the joint.
2. Angular functions for several values of the order of stress singularity were derived from eigen analysis, and the expressions for stress distribution were determined comparing the angular functions and the stress distribution obtained by BEM.
3. An expression for the critical strength of the interface was derived for mechanical loading. The critical strength of the interface obtained in the present study was about \( K_{100}^{3D\text{critical}} \) = 2.61 ~ 4.35 MPa·mm\(^{0.65}\).

### References
