Investigation of the Underfill Delamination and Cracking in Flip-Chip Modules under Temperature Cyclic Loading

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***Abstract*—In this paper, stress singularity in electronic packaging is described and three general cases are summarized. The characteristics of each stress singularity are briefed. In order to predict the likelihood of delamination at a bimaterial wedge, where two interfaces are involved, a criterion is proposed and the corresponding parameters are defined. The propagation of a crack inside a homogeneous material with the effects of delamination and stress singularity is predicted by the maximum hoop stress criterion. The proposed criteria are adopted in the analysis of a flip-chip with underfill under thermal cyclic loading. A finite Eelement (FE) model for the package is built and the proper procedures in processing FE data are described. The proposed criterion can correctly predict the interface where delamination is more likely to occur. It can be seen that the opening stress intensity factor along the interface (or peeling stress) plays a very important role in causing interfacial failure. The analytical results are compared with experimental ones and good agreement is found. The effects of delamination and cracking inside the package on the solder balls are also mentioned. Further investigation into the fatigue model of the underfilled solder ball is discussed.**

***Index Terms*—Cracking, delamination, finite element, flip chip, fracture mechanics, singularity, solder joint fatigue, thermal cycling, underfill.**

I. Introduction

EXTENSIVE studies have shown that the delamination and cracking of the underfill not only reduce its ability to ensure good solder joint reliability, but also allow moisture to accumulate at these interfaces, prompting additional failure modes. Temperature cycling tests have shown that a number of delamination sites at underfill/chip, and solder/underfill interfaces were formed during the loading [1]. It has been generally believed that the shear stress is a major cause of the delamination, but it is now being recognized that the interfacial peeling stress plays a very important role in causing interfacial failures [2].

For structures containing either dissimilar materials, or cracking and delamination, the stresses are singular at the corners of geometric shape, the edge of the interface between dissimilar materials, and the tip of the interface crack (or delamination). The finite element stress analyses are inadequate to capture the stress singularity. Fracture mechanics approaches are needed to take the singular behaviors into consideration for the extraction of meaningful fracture parameters that can be used for design and testing. However, only standard type of crack or interface crack is considered in the context of classical fracture mechanics. The more complicated singular behaviors of stresses in various cases are present in different packages, and these problems can not be solved directly in using classical fracture mechanics. Therefore, several researchers have done the work to determine the dependence of the stress singularity on the geometry and material properties [3]–[5].

For a bimaterial wedge corner like chip/underfill in a flip-chip assembly, where two bonded interfaces are involved, it is important to know which interface is likely to delaminate. One of the objectives of this study is to establish a criterion for the delamination initiation under thermal cycling. To predict the cracking propagation inside a homogeneous material after the delamination, the maximum circumferential stress criterion is adopted in this paper. The impact of the underfill failures on the solder joint reliability is discussed.

II. Stress Singularity Analysis for Bimaterial Wedge

Examples of the stress singularity fields in flip-chip assemblies are shown in Fig. 1, such as chip/underfill, underfill/solder mask, and underfill/chip/solder ball. In spite of complexity of geometry and material combinations, all stress singularities arising in bimaterial wedge configurations in electronic packaging can be grouped into three categories, which will be detailed in the subsequent analysis. These are:

1) angular corner of a homogeneous material;
2) angular corner of bimaterial wedge;
3) bimaterial wedge with adhesion, as shown in Fig. 2(a)–(c), respectively.

For any bimaterial wedge system, in which the materials are considered as isotropic and linear elastic, four elastic constants, i.e., two Young's moduli and two Poisson's ratios are involved. However, it has been proven that under traction-specified boundary conditions the solution to plane problems of elasticity depends on only two-dimensional combinations of the elastic moduli, namely, Dundurs parameters defined by [6]

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

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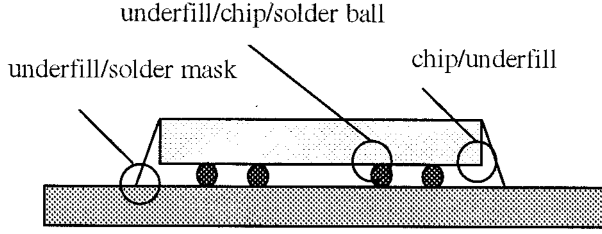

Fig. 1. Schematic structure of a flip chip module. The circle areas represent regions of local stress.

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

or by the connection

$$\varepsilon = \frac{1}{2\pi} \ln \frac{1-\beta}{1+\beta} \tag{3}$$

where

- ν Poisson's ratio;
- μ shear modulus;
- subscripts 1 and 2 materials across the interface.

The α measures the relative stiffness of the two materials. Material 1 is stiffer than material 2 if $\alpha > 0$. The so called oscillating index, β or ε, which is responsible for oscillating stress behaviors at wedge tip in some cases as to be discussed shortly, can hardly be interpreted intuitively.

The singular stress field is generally expressed as

$$\sigma_{ij} = r^{p-1} f_{ij}(\theta, p) \tag{4}$$

where r, θ are polar coordinates at wedge tip, and p the order of singularity. If $0 < p < 1$, the stress field is singular. The order of singularity p is not only dependent on the material properties (α and β or ε), but also dependent on the geometry, such as θ_0, or $\theta_{\rm I}$ and $\theta_{\rm II}$, or θ_W for three different cases in Fig. 2. It should be noted that (4) is valid only when p is a real value. In some cases, p appears to be complex value, which introduces oscillating stresses in the vicinity of wedge tip. The stress field in this case should be written in the form of $\sigma_{ij} = r^{\text{Re}p-1} f_{ij}(\theta, p, \text{Im}\, p \ln r)$ [8]. The term $\text{Im}p \ln r$ gives rise to the oscillating behavior of stresses, but the stress singularity still remains as $\text{Re}(p-1)$. In the following sections, the determination of the singularity order p is outlined for three cases, respectively.

A. Angular Corners of a Homogeneous Material

As shown in Fig. 2(a), the stresses may be singular at a wedge corner of a homogeneous material. A homogeneous wedge can be considered as a special case for a bimaterial wedge with complete delaminations along two interfaces. A crack in a homogeneous material can also be treated as a special case of this wedge with $\theta_0 = 0$. The order of the singularity is dependent on the angle θ_0, and can be determined by [7]

$$\frac{\sin p(2\pi - \theta_0)}{p(2\pi - \theta_0)} = \frac{\sin(2\pi - \theta_0)}{2\pi - \theta_0}. \tag{5}$$

It can be verified from this equation without difficulty that with $\theta_0 = 0$, $p = 1/2$ for a true crack, which is the solution for classical fracture. p increases when θ_0 increases. There is no stress singularity when $\theta_0 \geq \pi$.

B. Angular Corners of a Bimaterial System

Fig. 2(b) shows a general configuration for an angular corner of a bimaterial. The configuration is reduced to a standard interface crack, which refers to a crack lying along the interface in dissimilar material ($\theta_{\rm I} = \pi$, $\theta_{\rm II} = \pi$). A free edge of bimaterial corresponds to $\theta_{\rm I} = \pi/2$, $\theta_{\rm II} = \pi/2$. With $\theta_{\rm I} = \pi/2$, $\theta_{\rm II} = 3\pi/2$, the configuration corresponds to a corner (e.g., chip/underfill in Fig. 1) with delamination along one interface.

The general characteristic equation for determining the order of the singularity is

$$D(\theta_I, \theta_{\rm II}, \alpha, \beta, p) = 0 \tag{6}$$

(refer to the detailed equation in the Appendix). The solution can be obtained by solving this equation numerically by Newton–Raphson method. In the case of a standard interface crack, i.e., $\theta_{\rm I} = \pi$, $\theta_{\rm II} = \pi$, the well-known complex stress singularity is found, see Rice [8]

$$p = 1/2 + i\varepsilon. \tag{7}$$

The imaginary part of the stress singularity at above equation introduces oscillating stresses in the vicinity of the crack tip and a possible overlapping of both materials. Rice [8] has shown that in this situation tensile and shear stresses are inherently coupled. It has been found further [4] that the stress field around the tip always displays an oscillating singularity in the case of $\theta_{\rm I} + \theta_{\rm II} = 2\pi$, which implies a delamination is present in an arbitrary bimaterial wedge. However, in the case of $\theta_{\rm I} + \theta_{\rm II} < 2\pi$, stress field around the tip does not exhibit an oscillating singularity. For instance, at the free edge of bimaterial, the stress field is singular, but showing no oscillating behavior.

C. Bimaterial Wedges with Adhesion

Fig. 2(c) shows a bimaterial wedge in which two bonded interfaces are involved. The characteristic equation of the order of singularity for this situation is derived by Vroonhoven as [3]

$$D(\alpha, \beta, \theta_W) = 0 \tag{8}$$

where the detailed equation is listed in Appendix. It was found that the order of stress singularity is always considerably smaller than the same wedge system with one delaminated interface [obtained from (7), with $\theta_{\rm I} + \theta_{\rm II} = 2\pi$]. This implies that the stress is released when delamination is present at one interface for a bimaterial wedge. For most cases, the stress field does not have an oscillating singularity.

III. Delamination Criterion for Interfaces at Bimaterial Wedge

For a crack in homogeneous material, the well-known mode I, II and III stress intensity factors ($K_{\rm I}$, $K_{\rm II}$, and $K_{\rm III}$) were found to be the only parameters that characterize the magnitude of the singular stress field at the crack tip for each basic failure mode, respectively. For a standard interface crack in a dissimilar

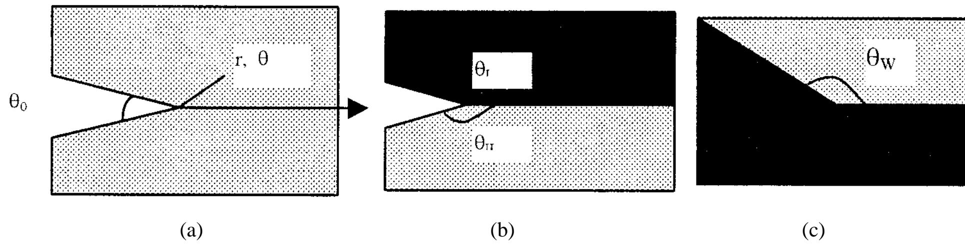

Fig. 2. Bimaterial system: (a) angular corner of a homogeneous material, (b) angular corner of bimaterial wedge, and (c) bimaterial wedge with adhesion.

material [i.e., $\theta_{\rm I} = \pi, \theta_{\rm II} = \pi$ in Fig. 2(b)], the total energy release rate or J-integral can be used as fracture parameters, while the separated mode fracture parameters like $K_{\rm I}$ and $K_{\rm II}$ do not exist except for special material combinations with $\beta = 0$ [8]. For a bimaterial wedge with two bonded interfaces, however, it is impossible to find a unique parameter (or a few) to represent the whole singular field of the wedge tip. In the following analysis, without lack of the generality, a bimaterial wedge with two bonded interfaces, which are placed horizontally and vertically, respectively, is considered [see Fig. 3(a)]. The singular stress field for this situation can be represented in the form of equation (4). The singularity shows no oscillating behavior and the order is much less than 1/2. With the introduction of the polar coordinate system, the hoop stress σ_θ and $\tau_{r\theta}$ at the tip along the different angular direction can be expressed as

$$\sigma_\theta = f(\theta)/r^{1-p}, \qquad \tau_{r\theta} = g(\theta)/r^{1-p}. \tag{9}$$

Unlike the stress field in a crack tip of a homogeneous material, where the stress intensity factors ($K_{\rm I}$, $K_{\rm II}$, and $K_{\rm III}$) are found to be only parameters governing the crack tip behaviors, (9) virtually gives no such kind of solution. However, the opening and shearing mode "stress intensity factors" can be defined as function of the angular position at the corner tip by

$$K_o = f(\theta), \qquad K_s = g(\theta). \tag{10}$$

The introduction of opening and shearing stress intensity factors in equation (10) is important, since in the mixed-mode crack propagation of homogeneous material, the cracking is present in the direction of $K_s = 0$ or maximum K_o [7]. For a bimaterial wedge considered here in Fig. 3(a), the opening and shearing stress intensity factors along the two bonded interfaces can thus be introduced as the parameters for delamination prediction as

$$K^h = [(K_s^h)^2 + (K_o^h)^2]^{1/2}, \qquad \varphi^h = \tan^{-1}(K_s^h/K_o^h) \tag{11}$$

$$K^v = [(K_s^v)^2 + (K_o^v)^2]^{1/2}, \qquad \varphi^v = \tan^{-1}(K_s^v/K_o^v) \tag{12}$$

where K^h, φ^h, and K^v, φ^v are the combined stress intensity factors and phase angle, and the superscript h and v represent the horizontal and vertical interfaces, respectively. The delamination behavior along the interface can be characterized by these two parameters completely. The delamination initiates when the stress intensity factor reaches its critical value, i.e., $K(\varphi) = K_{ad}(\varphi)$, where $K_{ad}(\varphi)$ is considered to be a material property as function of phase angle and is termed as the interface adhesion strength for this wedge configuration. Since two bonded

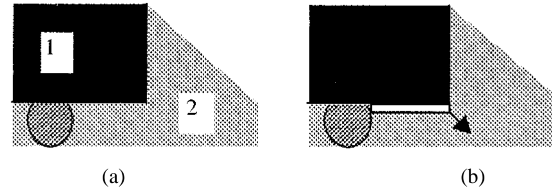

Fig. 3. Bimaterial wedge: (a) without delamination and (b) with delamination.

interfaces are involved, the delamination will be along the horizontal interface when

$$\frac{K^h(\varphi^h)}{K_{ad}^h(\varphi^h)} > \frac{K^v(\varphi^v)}{K_{ad}^v(\varphi^v)} \tag{13}$$

is satisfied. Delamination will occur along the vertical interface if the inequality is reversed.

IV. Prediction of Cracking Propagation in Homogeneous Material

The delamination of the interface in a bimaterial wedge will give rise to a potential possibility for the cracking from the tip of edge through the underfill bulk. For example, if the interface delamination is present along the horizontal interface, as shown in Fig. 3(b), it is likely to be followed by the bulk cracking developed in material 2. After delamination, the order of stress singularity for the wedge is more severe than that the same wedge without delamination. In addition, the delamination will result in a complex oscillating singular stress distribution at the wedge tip, as analyzed in Section II. Since the oscillating singularity occurs only in the immediate vicinity of the wedge tip, the contribution of the imaginary part of the singularity is ignored when the distance from tip, r, is chosen far from this region [5]. The maximum circumferential stress criterion, which was originally used for the mixed-mode crack propagation in homogeneous material, is extended here to predict the cracking direction. The cracking is assumed to occur in opening mode perpendicular to the direction of maximum stress intensity factor or maximum circumferential stress. The circumferential stress σ_θ at the tip is given as

$$\sigma_\theta = f(\theta)/r^{1-p} \tag{14}$$

where the order of the singularity can be taken on its real part as approximation. The cracking direction is where maximum $f(\theta)$ (or σ_θ) takes place.

V. Finite Element Modeling

In order to investigate the delamination behaviors of underfill at the edge of chip in a flip-chip assembly under thermal loading, it is necessary to perform a finite element analysis to extract the fracture or delamination parameters defined above. The most important region in a fracture (delamination) model in a finite element analysis is the region with stress singularity. The traditional singular element is commonly applied to obtain the stress intensity factors accurately for a homogenous cracked structure (the element is quadratic, with the midside nodes placed at the quarter points to capture the $1/r^{1/2}$ singularity in strain). Such singular element, however, can not be applied for the bimaterial wedge configuration such as the edge of chip/underfill in flip chip, since the stress singularities at the wedge tip vary with the geometry and material properties. Therefore, the global/local finite element modeling techniques are employed in this paper. The local modeling (or submodeling) is known as the cut-boundary displacement method, in which, the cut boundary is the boundary of the submodel that represents a cut through the global model with coarse mesh [9].

In the present study, the flip-chip structure considered here is shown in Fig. 4. A two-dimensional (2-D) plane strain deformation model was used, based on the cross-section of the flip chip assembly perpendicular to the plane of the silicon chip face and parallel to the chip edge. Eight-node axisymmetric elements were used in the symmetric half-model. In the model, the silicon chip, underfill, solder mask, BT substrate and eutectic solder bump were considered, with the material properties in Table I. The structure is subject to a temperature change from $T_1 = 25\,°\mathrm{C}$ to $T_2 = 150\,°\mathrm{C}$. The stress free temperature is at room temperature because it is assumed that the residual stress inside the package after assembly will be relaxed after the storage for a period of time. In addition, since the linear elastic analysis is applied here, it is necessary to select the most typical temperature range for this elastic analysis to represent the true deformation situation during the thermal cycling. It is known that the temperature inside the underfill during heat-up to $150\,°\mathrm{C}$ is near or above its Tg temperature. The underfill becomes very soft and the adhesion is the weakest. Furthermore, the interface at this temperature is under shear and tensile normal stresses, which is more crucial than it is at low temperature during cooling down, which is under shear and compressive normal stresses. Therefore, this temperature loading is considered to represent the true deformation of the package during thermal cycling.

The procedures for the extraction of fracture parameters and for the prediction of delamination and cracking are summarized as follows.

1) Calculate the Dundurs parameters α and β or ε, based on (1)–(3).
2) Calculate the order of stress singularity, p, based on (8) for a bimaterial edge with adhesion;
3) Perform a global finite element analysis and extract the displacements at the cut boundary for the local finite element modeling.

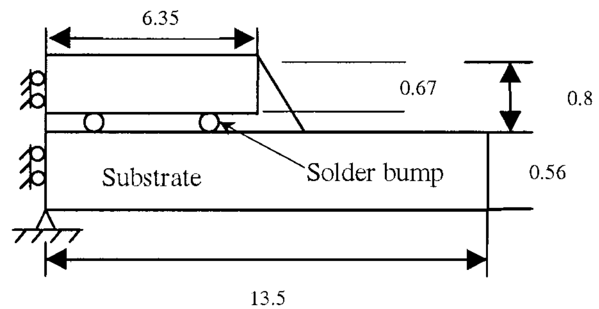

Fig. 4. Flip-chip assembly geometry (unit: mm).

TABLE I
Material Properties

Material	E (Gpa)	CTE (ppm/°C)	Poisson Ratio
Si chip	155.	2.6	0.25
Solder Pb/Sn 37/63	31.7	29.8	0.4
Cu	120.	17.	0.3
BT	21.	15.	0.35
SR	2.9	40.	0.35
Underfill	9.	60.	0.35

4) Apply the boundary condition obtained from global modeling and perform a local finite element modeling at the chip/underfill corner.
5) Extract the normal and shear stresses along two interfaces, respectively.
6) Plot the opening stress intensity factors and shearing stress intensity factors at different points of tip by using (9) and (10), and select the range where the relation between K and r is monotonic.
7) Extrapolate to $r = 0$ based on the plot above and obtain the actual values of opening and shearing stress intensity factors along two interfaces, respectively.
8) Calculate the combined stress intensity factors and the phase angle based on (10) and (11).
9) Predict at which interface the delamination occurs by the criterion defined in (13).
10) Calculate the order of stress singularity after delamination by (6).
11) Use the maximum hoop stress criterion equation (14) to predict the cracking direction of the underfill.

For the flip chip package studied here, the orders of the singularity can be determined from equations (7) and (8), respectively based on the material properties in Table I. The results are shown in Table II. It can be seen that the singularity of stress with delamination is more severe than that without delamination. Fig. 5 showed the enlarged portion of the finite element mesh near the chip/underfill corner for a global finite element model. From this global model with a relative coarse mesh, the displacement of the cut boundary that is used for the submodel can be extracted. A sub-modeling is then performed at the chip/underfill region to obtain the more accurate information on the stresses

TABLE II
THE ORDER OF STRESS SINGULARITY AT CHIP/UNDERFILL CORNER

	Order of singularity p
Before delamination	0.107
After delamination	0.582+0.012*I*

at the edge of chip. The finite element mesh for this sub-model is shown in Fig. 6.

Since the finite element results are very inaccurate at a very small distance from the wedge tip even with global/local modeling, due to the inability of the elements used, the results for points very close to the tip should be discarded. On the other hand, the singular solutions are valid only in an area close to the crack tip, thus the procedure should be limited to elements in the vicinity of the crack tip. According to (9) and (10), the stress intensity factor, e.g., the opening stress intensity factor K_o, can be obtained when r approaches to zero, as follows

$$K_o = \lim_{r \to 0} \sigma_\theta r^{1-p}. \tag{15}$$

When the regular element is applied, a series of points can be picked up at corner to extract the stress intensity factors (e.g., see Figs. 7 and 8). The stress intensity factors are dependent on the distance due to the errors caused by finite element results at tip area. The actual value of the stress intensity factor has to be obtained by the extrapolation of these data to $r = 0$. In the following example, the range to pick up the stress at the tip is from 0.05 mm to 0.10 mm, by which the stress intensity factors at different points vary monotonically.

VI. RESULTS AND DISCUSSIONS

A. Prediction of Delamination

The purpose here is to assess that at the chip/underfill corner, along which interfaces, i.e., the underfill/polyimid, or underfill-fillet/chip-edge, the susceptibility to delamination is high. Figs. 7 and 8 plotted the opening and shearing stress intensity factors as function of the distance from tip for the vertical and horizontal interfaces, respectively. In the region of r from 0.05 mm to 0.1 mm as shown in Figs. 7 and 8, the stress intensity factors computed by (9) and (10) at different points vary monotonically with r. Therefore the actual values of the stress intensity factors can be obtained by the extrapolation to $r = 0$ based on (15) (the x coordinate in the figures starts at $r = 0.05$ mm). The results read

$$K_s^h = 17.3\ \text{MPamm}^{1-p} \qquad K_o^h = 31.4\ \text{MPamm}^{1-p}$$
$$K_s^v = 17.3\ \text{MPamm}^{1-p} \qquad K_o^v = 26.5\ \text{MPamm}^{1-p}$$

where $p = 0.107$ (refer to Table II). Therefore, the combined stress intensity factor and phase angle along the horizontal interface are, by (11) and (12)

$$K^h = [(K_s^h)^2 + (K_o^h)^2]^{1/2} = 35.9\ \text{MPamm}^{1-p}$$
$$\varphi^h = 28.9^\circ$$

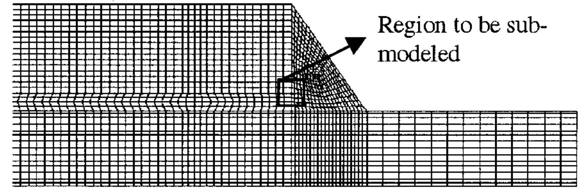

Fig. 5. Global finite element meshing.

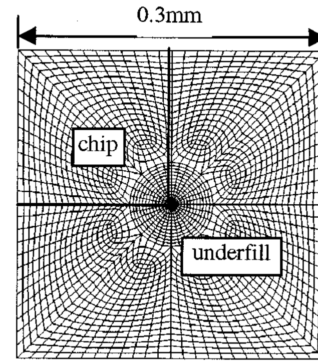

Fig. 6. Local finite element modeling.

and along vertical interface

$$K^v = [(K_s^v)^2 + (K_o^v)^2]^{1/2} = 31.65\ \text{MPamm}^{1-p}$$
$$\varphi^v = 33.1^\circ.$$

It is shown by experiments that the adhesion strength is a function of the phase angle φ. When the phase angle is increasing from 0° to 90°, that is, the cracking mode changes from pure tensile to pure shearing, the adhesion strength increases. Therefore, following relationship can be obtained:

$$K_{ad}^v(\varphi^v) > K_{ad}^v(\varphi^h). \tag{16}$$

It is also known that the adhesion between polyimide and underfill is lower than that between silicon and underfill, that is

$$K_{ad}^h(\varphi^h) < K_{ad}^v(\varphi^h). \tag{17}$$

With (16) and (17), it can be obtained that

$$K_{ad}^h(\varphi^h) < K_{ad}^v(\varphi^v). \tag{18}$$

Since the horizontal stress intense factor K^h is greater than vertical one K^v, these values can ensure that the validity of (13). Therefore, it can be concluded that the delamination will occur first along the horizontal interface between polyimide and underfill. This conclusion is confirmed by the experimental results shown in Fig. 9.

It is very important to note that the peeling stress (or opening stress intensity factors) is in the same range or even higher than that of the shearing stress. Thus it must be pointed out that opening stress intensity factor plays a very important role in causing interfacial delamination. It is also noted that the opening stress intensity factor along the horizontal interface is bigger than that along the vertical interface, while the difference of the shearing stress is insignificant. This implies that the delamina-

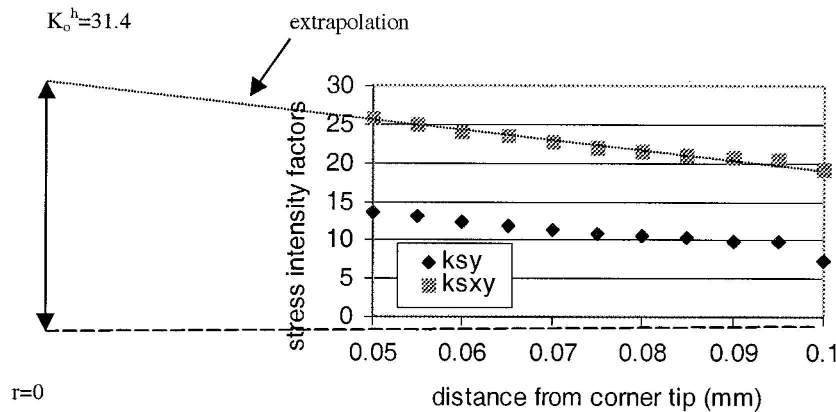

Fig. 7. Peeling and shearing stress intensity factors along the interface between underfill and chip edge (horizontal).

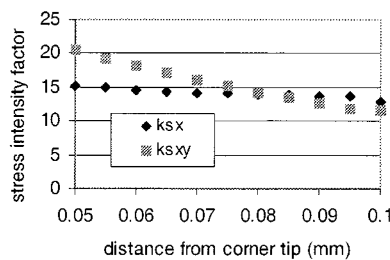

Fig. 8. Peeling and shearing stress intensity factors along the interface between underfill and chip edge (vertical).

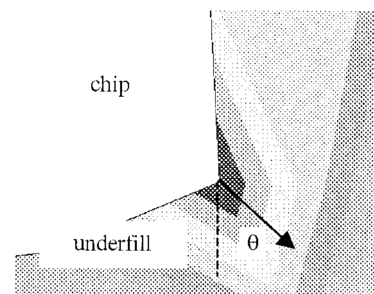

Fig. 10. Contour of hoop stress in underfill by FE simulation.

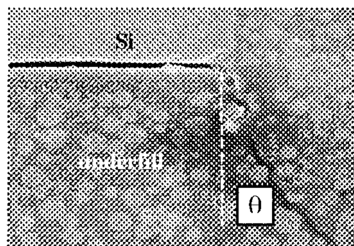

Fig. 9. Experimental results of failures of underfill.

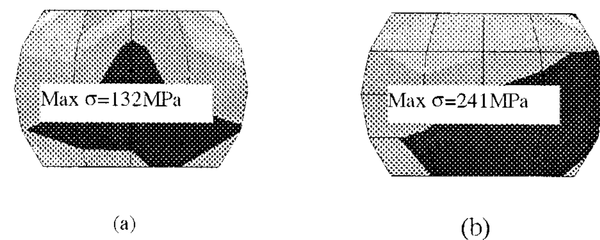

Fig. 11. Von Mises stress distribution in the outermost bump (a) without underfill delamination and cracking and (b) with underfill delamination and cracking.

tion is likely to occur along the horizontal interface if the interface adhesion strength for both interfaces are assumed to be same. Such a result shows good agreement with experimental result.

B. Propagation of Underfill Cracking

The underfill cracking after the delamination between the chip and underfill was also investigated. The singular stress field after the delamination is different from that for a standard interface crack, and the order of the singularity is given in Table II. The complex stress singularity implies that the shearing and opening stresses are inherently coupled with each other. In order to determine the cracking angle, the maximum hoop stress criterion was applied. It is found from simulation that the maximum hoop stress is along the direction of 32°. Fig. 10 showed the contour of circumferential stress along the wedge by local modeling. Such results were verified by the actual test results shown in Fig. 9, which shows the cracking is along the direction of 26°–34°.

C. Impact of Delamination on Solder Reliability

It has been known that the use of the underfill could significantly improve the solder joint reliability of the flip chip assembly. On the other hand, the delamination and cracking of the underfill will reduce its ability to ensure good solder joint reliability. When delamination and cracking are present in the underfill, the stress on the solder ball is redistributed as compared to that without failures. The effects of delamination between chip/underfill on the outermost solder bump is shown in Fig. 11. From the figure, it can seen that the maximum Von Mises stress increased almost 83%. This is an indication that the failure of the underfill will lead a significant change in solder stress.

In the first level of the interconnect, between the chip and the organic substrate, the solder ball will fail within a few or dozen cycles during thermal cycling if the underfill is not applied. Under such circumstance, the Coffin–Manson model can be adopted to predict accurately the fatigue life of solder ball. However, when there is underfill, the Coffin–Manson model al-

ways over-estimates the fatigue life [1]. One of the reasons is that this model assumes the underfill is in perfect condition before the failure of the solder ball. Extensive experimental results have shown that there are a lot of delamination and cracking in underfill before the solder fails during thermal cycling. The horizontal delamination between the chip and the underfill investigated in this paper is the most typical one. Beside this, there are delamination along the interfaces such as underfill/solder ball and underfill/solder mask. It must be emphasized that the stress/strain in the solder change as the failures inside the underfill develop. This implies that in predicting the solder joint fatigue life, the interaction between the solder and underfill failures must be fully accounted for. To fulfill this, one of the possible approaches is to modify the Coffin–Monson model so that there is a factor in the model, which reflects the effect of each underfill failure mode. Further investigation will be conducted in the future.

VII. Conclusion

Stress singularity problems in electronic packaging are categorized into three groups. The characteristics of each stress singularity group are described briefly. A criterion for prediction of delamination is proposed for bimaterial wedge, which can be readily used in the reliability analysis of electronic packaging. To evaluate the effects of delamination on the cracking inside homogenous materials, the maximum hoop stress criterion is adopted to determine the crack direction.

The proper procedures to apply bimaterial fracture mechanics in finite element analysis are detailed. A flip-chip assembly with underfill under thermal cyclic loading is analyzed using the criterion and procedures proposed in this paper. It is found that the criterion for delamination initiation can correctly predict the interface which is prone to such defect. It can be seen that the opening stress intensity factor along the interface (or peeling stress) plays a very important role in causing interfacial failure. The cracking development inside the underfill using the maximum hoop stress criterion is also in good agreement with the cracking failure of the underfill when the packaging goes through thermal cycling.

Finally, the possible effects of delamination and cracking of the underfill on the solder reliability is also highlighted. The fatigue model for solder under the effects of underfill failures is suggested for further study.

Appendix

Characteristic equation for angular corners of a bimaterial system

$$
\begin{aligned}
&16[\sin^2(\theta^I p)-p^2\sin^2\theta^I][\sin^2\theta^{II}p)-p^2\sin^2\theta^{II}]\beta^2\\
&\quad+16p^2\{\sin^2\theta^I[\sin^2(\theta^{II}p)-p^2\sin^2\theta^{II}]\\
&\qquad\quad+\sin^2\theta^{II}[\sin^2(\theta^I p)-p^2\sin^2\theta^I]\}\alpha\beta\\
&\quad+\{16p^2(p^2-1)\sin^2\theta^I\sin^2\theta^{II}\\
&\qquad-4[p^2\sin^2(\theta^{II}+\theta^I)-\sin^2 p(\theta^{II}+\theta^I)]\}\alpha^2\\
&\quad+16p^2[\sin^2\theta^I\sin^2(\theta^{II}p)-\sin^2\theta^{II}\sin^2(\theta^I p)]\beta\\
&\quad+8\{-2p^2[\sin^2\theta^I\sin^2(\theta^{II}p)-\sin^2\theta^{II}\sin^2(\theta^I p)]\\
&\qquad+[\sin^2(\theta^{II}p)-p^2\sin^2\theta^{II}]-[\sin^2(\theta^I p)-p^2\sin^2\theta^I]\}\alpha\\
&\quad-4p^2\sin^2(\theta^I-\theta^{II})+4\sin^2 p(\theta^I-\theta^{II})=0.
\end{aligned}
$$

Characteristic equation for bimaterial wedge with adhesion

$$
\begin{aligned}
&p^4(1-\Gamma)^4\sin^4\theta-\lambda^2(1-\Gamma)^2\sin^2\theta\{(1+\Gamma\kappa_1)^2\sin^2(p\theta)\\
&\quad+(\Gamma+\kappa_2)^2\sin^2(p(\theta-2\pi))-2\Gamma(1+\kappa_2)\sin^2(p(\theta-\pi)))\\
&\quad+\{(1+\Gamma\kappa_1)(\Gamma+\kappa_2)\sin(p\theta)\sin(p(\theta-2\pi))\\
&\qquad-\Gamma(1+\kappa_1)(1+\kappa_2)\sin^2(p(\theta-\pi))\}^2=0
\end{aligned}
$$

where

$$
\kappa_1=\begin{cases}3-4\nu_1, & \text{plane strain}\\ (3-\nu_1)/(1+\nu_1), & \text{plane stress}\end{cases}
$$

$$
\kappa_2=\begin{cases}3-4\nu_2, & \text{plane strain}\\ (3-\nu_2)/(1+\nu_2), & \text{plane stress}\end{cases}
$$

$$
\Gamma=\mu_2/\mu_1.
$$

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