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

X.-J. Fan, H. B. Wang, and T. B. Lim, *Member, IEEE*

***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 indissimilar 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 delamina-

TRESS 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]

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

V. Finite Element Modeling

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

	Order of singularity p
Before delamination	0.107
After delamination	0.582+0.012i

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)

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

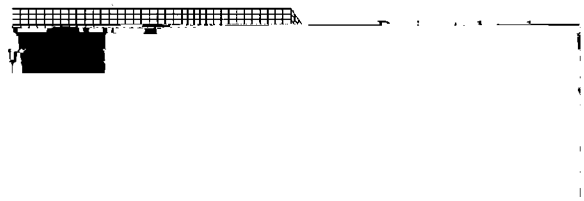

Fig. 5. Global finite element meshing.

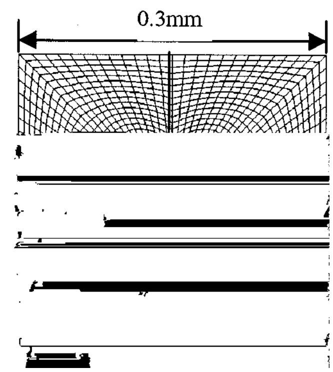

Fig. 6. Local finite element modeling.

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.

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H. B. Wang received the B.E. degree in mechanical engineering from Xi'an Jiaotong University, Xi'an, China and the M.E. degree in mechanical engineering from the Nanyang University of Technology, Singapore.

He is currently working as a Senior R&D Engineer (CAE) in Corporate Package Development, STMicroelectronics Corporation, Singapore, responsible for whole corporation wide activities of simulation and finite element analysis.

T. B. Lim (M'84) received the B.Sc. degree in production and the Ph.D. degree in mechanical engineering from the University of Aston, Birmingham, U.K., in 1980 and 1984, respectively.

He worked for Texas Instruments Singapore Pte., Ltd., from 1986 to 1993, as Senior Engineer and Elected Member of Technical Staff, R&D, Electronic Packaging Department. In 1993, he joined the Institute of Microelectronics, Singapore, to start up the Advanced Packaging Development Support Department to further his R&D interests in electronic packaging as well as to provide support for the packaging industry. He has about a dozen patents and publishes regularly in ecslerelectronic172pornftsHeIn