Die attach interface property characterization as function of temperature using cohesive zone modeling method

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Figure 2(d) shows the specimen of Double Cantilever Beam (DCB) for Mode I. The data analysis is based on the Irwin-Kies equation [1]. This equation is then modified by Williams and JIS (Japanese Industrial Standards) respectively [2, 3]. They are referred to as CBT (corrected beam theory) and modified compliance calibration (MCC) by Hojo [4]. The mode II test, see Fig. 2(a), (b), (c) remains controversial for practical reasons, such as unstable propagation in the ENF specimen, friction effects and difficulty in defining a starter defect. The specimen for mixed mode bending (MMB), Fig. 2(e) as introduced by Reeder, Crews and Reeder [5, 6] has become the most widely used specimen for the determination of mixed mode envelopes. These types of specimen are suitable for bi-material samples. For the tri-materials samples, some modifications are needed to ensure that the delamination occurs at the required interface. Based on Charalambides [7], a four point bending Mode I tool was designed and constructed. This test method shows stable delamination and reproducible results.

2. Experimental samples and equipment

2.1. Tri-material sample

In order to obtain the similar interface toughness as in the actual package, samples are made according to the packaging processes. The test samples are tri-material strips consisting of copper layer (0.2mm in thickness), epoxy molding compound layer [EMC] (0.6mm in thickness) and a die attach adhesive (60 μ m) layer in between. The sample dimension is 60x10x0.85 mm³.

A thin layer of adhesive glue is dispensed on the surface of the copper lead frame by using the flexible foil stencil, which is fixed in a frame. The thickness of the adhesive glue on the surface of the lead frame is controlled by the thickness of the stencil foil.

After dispensing adhesive glue, samples are placed in a pre-heated oven at 180°C for 15 minutes for curing. And then the leadframe is placed in the mold. EMC molding is finished in a pre-heated mold at 180°C within 60 seconds and post cured in the mold for 90 seconds. The final map mold is shown in Fig. 3(a). Before cutting off the sample, the map mold is post cured at 175°C for 4 hours to ensure that the epoxy molding compound is fully cured. Then the map molds are cut into 60x9mm² strips, see Fig. 3(b).

Fig.3(a) Map mold

Fig.3(b) Cut samples

To trigger the interface delamination, a pre-defined notch (0.5mm wide and 80% depth of EMC) is created in the epoxy

molding compound materials by sawing. The geometry and dimensions of the sample are shown in Fig.4.

Fig. 4 Geometry and dimensions of the sample

2.2 Setup of Four Point Bending

A special four point bending tool is designed and manufactured to investigate the interface toughness. Fig.5 schematically shows the test setup while the actual four point bending tool, which consists three parts, is shown in Fig.6. The first part is the four point bending frame which is used to support the two rollers. The second part consists of two rollers which are used to support the test sample. For decreasing friction between the rollers and the molding compound layer of the test sample, two rollers are allowed to rotate freely. Silicon lubricant grease is used in bearings for withstanding the high temperature effects. The third part is the loading head which applies displacement or loading to the sample.

Fig.5 Schematic overview of four point bending test setup

Fig.6 Four bending tool setup

2.3 Loading system and optical system

Fig. 7 shows the universal tester Zwick/Roell Z005. Loading head moves downwards in 100 μ m/min and reaction force of the loading head is measured by the force sensor when loading head touches the sample. A Keyence optical camera system is mounted at the back of the bending tool, see Fig. 6. The optical camera focuses on the notch and monitors the deformation and delamination between die attach and copper.

Fig.7 Displacement/loading and optical system

3. Four Point Bending Test Results

3.1. Four point bending test crack and delamination processes

In order to obtain more reliable interface toughness properties, four point bending tests are performed at different temperatures. Fig.8 to Fig.11 visualizes the typical procedures of four point bending tests, from start of the delamination to delamination propagation. Fig. 12 shows the relation between displacement and loading. Loading speed is 0.1mm/min and it appears that the loading speed has no effects on the “allowable load” according to our tests at room temperature.

The initial state of the three layers before loading is shown in Fig. 8. The three layers are leadframe, glue and EMC from top to bottom layers respectively. The thickness of glue layer, approximately 58 μ m in thickness, is uniformly distributed between copper and molding compound layer using controlled stencil foil.

Fig.8 Initial state of the notch

When the load head touches the test sample, the test sample deforms and the response is elastic (see Fig. 12). The applied load increases with the displacement and the load gradually reaches the highest point. At some critical displacement, the load suddenly drops. The EMC notch cracks and penetrates through the molding compound towards the interface, as shown in Fig.9.

Fig. 9 Initial molding compound crack

Fig. 10 initial delamination

After that, the crack penetrates through the glue layer very quickly and reaches the interface between glue and copper, (see Fig. 10). The load will continue to increase until interface delamination starts on both sides see Fig. 11. Finally the load begins to decrease, see Fig. 12.

Fig.11 Delamination propagation

When this load starts to decrease, the delamination starts. After the delaminations at both sides have started, the crack propagation load “stabilizes” around a constant value. From this constant allowable load, the interface fracture toughness value is derived with the aid of the results of numerical simulations (see 3.3).

Fig. 12 Relation between displacement and load

3.1. Test result at different temperatures of dry samples

Fig.13 shows response for four repetitive tests at room temperature. The stable crack propagation force is reproducible within error about 0.1N. Other tests were performed at 40, 60, 85 and 150°C respectively. Detail test results at 150°C are shown in Fig.14. Fig. 15 shows the response of four point bending at different temperatures and these results show that temperature has a great effects on the critical crack propagation load. This means that the interface toughness decreases with increasing temperature.

3.2. Four Point Bending Test results of PRECON Samples

In order to investigate moisture effects on interface toughness, test samples are put in humidity oven at 85°C/85%RH for at least 48 hours in order to reach moisture

saturation. Four point bending tests are performed at room temperature and 85°C respectively after this pre conditioning.

Fig 13. Response of four point bending at room temperature

Fig 14. Response of four point bending at 150°C

Fig 15. Response of four point bending at different temperatures

Table 1 shows the average crack propagation load for both dry and pre-conditioned samples. Test results show that the average crack propagate load of the pre conditioned sample at

room temperature is almost the same as that of the dry sample tested at room temperature. The average crack propagate load of the pre-conditioning sample tested at 85°C is also almost the same as that of the dry sample tested at 85 °C. This means that moisture has no effects on the interface toughness between the die attach and copper leadframe.

3.3. Calculation of interface toughness

3.3.1 Analytical model

The critical interface fracture toughness, G_c can be deduced analytically by recognizing that it is simply the difference in the strain energy in the uncracked and cracked beam. Since there is negligible strain energy in the beam above the crack, G_c can be deduced from the consideration of energies in the uncracked section, and the lower section below the crack. Using the Euler-Bernoulli theory and plane strain conditions, these energies can be expressed in terms of the applied moment M as [7]

$$U = (1 - \nu^2) M^2 / 2EI \quad (1)$$

where U is the strain energy per unit cross-section and I is the second moment of area per unit width, G_c can then derived into (2)

$$G_c = \frac{M^2 (1 - \nu_2^2)}{2E_2} \left(\frac{1}{I_2} - \frac{\lambda}{I_c} \right) \quad (2)$$

where I_2 and I_c are second moment of inertia per unit cross-sectional area for the bottom layer and the composite beam, respectively, and

$$\lambda = E_2 (1 - \nu_1^2) / E_1 (1 - \nu_2^2) \quad (3)$$

$$I_2 = \frac{1}{12} h_2^3 \quad (4)$$

$$I_c = \frac{1}{12} h_1^3 + \frac{\lambda}{12} h_2^3 + \frac{\lambda h_1 h_2 (h_1 + h_2)^2}{4(h_1 + \lambda h_2)} \quad (5)$$

The subscript 1 indicates quantities relevant to the top layer, whereas the subscript 2 denotes the corresponding quantities for the bottom layer. Subscript c refers to the composite beam. Note that the moment per unit width $M = PI/2B$, with P being the constant load and I the spacing between inner and outer span. According to Eq. (2) analytical G_c can be obtained. This G_c value can be used initially to estimate crack propagation load in the simulation model, (see Table 1), temperature effects on young's modules are roughly considered in analytical equation (2).

3.3.2 Numerical model

In addition to the analytical model, the interface toughness G_c can be obtained by changing the G_c value until crack propagation load equals the experimental propagation load.

A four point bending model is constructed in the finite element package Marc and its graphical user interface Mentat (see Fig.16). Due to the symmetry of the model, only half a

specimen is modeled. Top layer is copper and bottom layer is EMC. Vertical displacements fixed at the bottom support (see arrow bottom supports) is the boundary condition. Top load applies a loading in downwards direction. Symmetry_dx fixes displacement of all symmetric nodes in horizontal direction. Thermal deformation is considered here. Symmetry_4PB fixes displacement of only symmetric nodes of copper layer in horizontal direction see Fig. 16. An initial crack is made in the model at the center of the EMC and die attach.

Four stages are prescribed in the simulation model including initial thermal stresses. The first stage is cooling down from the initial condition 175°C. Temperature is cooled from 175°C to room temperature using boundary conditions at bottom support and symmetry_dx. The second stage is the heating up. Temperature is increased from room temperature to the test temperature using boundary conditions bottom support and symmetry_dx. The third stage is the relaxation. Temperature is kept at the test temperature using the boundary conditions of bottom support and symmetry_dx. The last one is four point bending stage. Temperature is kept at test temperature and other boundary conditions are bottom support, top load and symmetry_4PB. Top load is the downwards displacement applied to the sample. Symmetry_dx fixes all nodes in x direction at the symmetry line while symmetry_4PB fixes only nodes on copper in x direction as shown in Fig. 16.

Fig. 16 2D four point bending FE model

3.3.3 Cohesive zone element

Marc has a library of interface elements, which can be used to simulate the onset and propagation of delamination. The constitutive behavior of these elements is expressed in the terms of tractions versus relative displacements between the top and bottom edge/surface of the elements, as shown in the Fig.17.

Fig. 17 2D Interface element

The traction t is introduced as function of effective opening displacement and is characterized by an initial reversible response, followed by an irreversible response once the critical effective opening displacement v_c has been reached. An exponential function is used in the simulation.

$$t = G_c \frac{v}{v_c^2} e^{\frac{-v}{v_c}} \quad (6)$$

in which G_c is the interface toughness and $e = 2.718$ [8].

It can easily be verified that the maximum effective traction t_c , corresponding to the critical effective opening displacement v_c is given by [8, 9]:

$$t_c = \frac{G_c}{ev_c} \quad (7)$$

If the maximum effective traction is known, the critical or effective opening displacement can be determined by:

$$v_c = \frac{G_c}{et_c} \quad (8)$$

Damage is defined as:

$$D = \frac{\int_{v_c}^{v_s} t dv}{\int_{v_c}^{\infty} t dv} \quad (9)$$

$$v_c \leq v_s$$

If $D=1$, the element is fully damaged.

G_c is obtained from 4 point bending tests combined with simulation of the fitted crack propagation load. G_c values from analytical equation is input as initial value. By adjusting the G_c value until simulation load equals to measured load, the actual G_c can be found (see simulation results in Fig. 18).

Fig. 18 shows some typical four point bending simulation results at different temperatures. In this simulation, the relationship between applied displacement and load are shown in this figure. The mesh size is chosen such that convergence of the results is obtained.

Fig. 18 Fitted load by changing G_c

Table 1 G_c value of Equation and Simulation

Temp (°C)	Load (N)		G_c (J/m ²)	
	Dry	PRECON 85°C/85%RH	Eq. (2)	Dry Simulation
23	4.1	4.0	27.2	26.5
40	2.75		12.2	13
60	2.1		7.1	8
85	1.7	1.76	4.7	5.6
150	0.71		3.0	1.9

Table 1 shows the crack propagation load, G_c values of equation (2) and simulation. From Fig. 19, it can be seen that these two curves fit well. It can be seen that G_c value decreases rapidly with increasing temperature. As already discussed, tests results show that in our case, moisture has no effects on G_c value.

Fig.19 Temperature and moisture effects on G_c value

3.3. Determination of the interface critical opening

Interface toughness and critical opening are two important material properties for simulation. In order to extract critical opening from sample delamination, a special optical camera system is installed combined with universal tester Zwick.

Fig. 20 Delamination test with camera setup

The Keyence optical camera system is placed at the back of the four point bending tool frame and focuses on the notch, especially the range of the interface delamination. Camera can be manually adjusted vertically in order to follow the movement of the sample due to the loading applied to the sample, see the C direction in Fig. 20. Focus can be performed by the rough and fine adjustment provided by the Keyence optical camera system, see B and A knobs respectively. Knob D can be used to adjust the angle around its shaft to ensure that the delamination front is in the center of the image. A series of particular pictures were taken, especially when the delamination was visible and delamination propagated.

In [10], critical opening is determined by the local deformation around the crack tip in the samples. This will provide a guide for conducting experiment and deduce the parameters needed to be measured.

Fig. 21 shows simulation result of delamination length, (indicated by length E), which is dependent on the values of critical opening. When damage value reaches 1 at interface nodes, delamination occurs.

Fig. 21 Simulation result of delamination; contour bands denote the damage value D

Fig. 22 is an enlargement of Fig. 21, which shows another delamination parameter, the interface opening at the symmetry line. This length between M and N in vertical direction is independent of critical opening values according to simulations. Combining Fig. 21 and Fig. 22, curves with different critical value ranges can be determined.

Fig. 22 The interface opening at symmetry line

3.3.1 Test results of delamination measurements

The test procedures for this part of experiment is the same as in section 3.1 with the exception of the displacement speed of clamp head of four bending tool. This loading speed is decreased from 100 to 50 $\mu\text{m}/\text{min}$ in order to take more pictures. The displacement speed has no effect on measured critical delamination force applied to the specimen.

Fig. 23 shows one of the delamination pictures including the measured dimensions. If the delaminations lengths are not equal at both sides of the specimen, half of the total length measured is assumed to be the delamination length one side. And MN is measured at the centre of the total delamination length, see Fig. 24.

Fig. 23 Delamination measurements

Fig. 24 Non symmetric delamination measurement

Due to the higher interface toughness of the glue, about 5 times higher than that of interface toughness between copper leadframe and molding compound, it is sometimes difficult to obtain equal delamination length at both sides of the

specimen. The pre-crack location will sometimes result in unequal delamination length at both sides of samples. Therefore, a small v-shape pre-crack is made inside the larger U shape pre-crack in order to ensure better results. In Fig. 25, scattered dots with different shapes are results from different specimen. However, same shape dots at different locations are the results from the same specimen but from different delamination lengths as the delamination propagates.

The two curves are simulation results using different critical opening values. It is evident that the delamination length increases with increasing vertical delamination MN. All test results from the tests fall between the two simulation curves with critical opening values from 0.5 to 1.0 μm . From these fits between simulations and experiment, it turns out that critical opening value is between 0.5 and 1.0 μm at room temperature.

Fig.25 Comparison of results between tests and simulations

4. Conclusion

From a series of four points bending tests, it is found that temperature has a large effect on the interface toughness. G_c value greatly decreases with increasing temperature. In addition, moisture has no effects on interface toughness of copper and die attach in our samples.

Using results from both experiment tests and cohesive zone simulation method, critical opening is found between 0.5 to 1.0 μm at room temperature. Critical opening values will decrease with temperature increasing according to model [8].

These two important interface properties can be used in the future to predict the possibility of delamination in the microelectronic packages.

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References

- [1] Davies, P., Blackman, B.R.K., and Brunner, A.J., "Standard Test Methods for Delamination Resistance of

Composite Materials: Current Status," Applied Composite Materials, Vol. 5, No. 6 (1998), pp. 345-364.

- [2] Hashemi, S., Kinloch, A. J., and Williams, J. G., "Corrections needed in double-cantilever beam tests for assessing the interlaminar failure of fibre-composites," J. Mat. Sci. Letter 8 (1989), pp. 125-129.
- [3] Hashemi, S., Kinloch, A. J., and Williams, J. G., "The Analysis of Interlaminar Fracture in Uniaxial Fibre-Polymer," Proc. Royal Soc. A427 (1990), pp. 173-199.
- [4] Hojo, M., Kageyama, K. and Tanaka, K., "Pre-Standardization Study on Mode I Interlaminar Fracture Toughness Test for CFRP," Japan Composites, Vol. 26, No. 4 (1995), pp. 243-255.
- [5] Crews, J. H. and Reeder, J. R., "A Mixed-Mode Bending Apparatus for Delamination Testing," NASA TM 100662, 1988
- [6] Reeder, J. R. and Crew, J. H., "Nonlinear Analysis and Redesign of the Mixed-Mode Bending Delamination Test," NASA TM 102777, 1991
- [7] Charalambides, P.G., "A Test Specimen for Determining the Fracture Resistance of Bimaterial Interface," J. Appl. Mech., Vol. 56 (1989), pp. 77-82.
- [8] MSC.Marc/Mentat, value A, 2008 r1, 2008
- [9] M.Ortiz and A. Pandolfi, "Finite-Deformation irreversible cohesive elements for three dimensional crack-propagation analysis, International Journal for numerical methods in engineering," Vol. 44 (1999), pp.1267-1282.
- [10] O. van der Sluis, P.H.M. Timmermans, E.J.L. van der Zanden, J.P.M. Hoefnagels. Analysis of the three-dimensional delamination behavior of stretchable electronics applications. In M.H. Aliabadi, S. Abela, S. Baragetti, M. Guagliano, and H-S. Lee, editors, Key Engineering Materials, volume 417-418, pages 9-12. Trans Tech Publications, 2010. Special volume: Advances in Fracture and Damage Mechanics VIII, ISSN 1013-9826