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INTERFACE FRACTURE TOUGHNESS ASSESSMENT OF SOLDER JOINTS USING DOUBLE CANTILEVER BEAM TEST

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In the current work, a test scheme to evaluate solder joint interface fracture toughness using double cantilever beam (DCB) test has been successfully demonstrated. The obtained results, in terms of critical energy release rate, predict the joint failure based on the principle of fracture mechanics. The results can be used as a materials property in the reliability design of various types of solder-ball joined packages. DCB specimens made of 99.9 wt% copper were selected in the current work. Eutectic Sn-37Pb and lead-free Sn-3.5Ag-0.5Cu solders were used to join two pieces of the copper beams with controlled solder thickness. The test record showed steady propagation of the crack along the solder / copper interface, which verifies the viability of such a testing scheme. Interface fracture toughness for as-joined, extensively-reflowed and thermally aged samples has been measured. Both the reflow treatment and the thermal aging lead to degradation of the solder joint fracture resistance. Reflow treatment was more damaging as it induces much faster interface reaction. Fractographic analysis established that the fracture has a mixed micromechanism of dimple and cleavage. The dimples are formed as a result of the separation between the hard intermetallic compound (IMC) particles and the soft solder material, while the cleavage is formed by the brittle split of the IMCs. When the IMC thickness is increased due to extended interface reaction, the proportion of IMC cleavage failure increases, and this was reflected in the decrease of the critical energy release rate.

Keywords: Solder; interface fracture toughness; intermetallic compound (IMC); fractographic analysis.

1. Introduction

Solder joining has been increasingly used in microelectronic devices in the form of flipchip and ball grid arrays. The function of the joint is to provide both electrical and mechanical connections among different IC chips and packages. As the trend towards miniaturization continues, the integrity of the solder joints is becoming more critical for the device reliability. Mechanical loading of solder joints inevitably occurs during device processing and service and the joints may be subjected to different types of stresses. The stability and reliability of the joining is largely determined by the ability of the soldered layer structure to withstand these stresses. In particular, crack propagation is a main cause

of failure and therefore fracture toughness arises as an important factor in the design for solder joint reliability. The failure modes in the solder joints can be adhesive (interface failures between solder and metallization) or cohesive (failure through the solder joint) in nature. Bulk solders have been used for tensile test in dog bone configuration [1] in order to extract properties like yield strength, modulus from stress-strain curve, creep behaviour, etc. However, the properties of bulk solder specimens may not reflect the solder joint reliability in the actual devices as it is well known that thermal treatment and electromigration will cause the interface to be relatively weak than the bulk solder [2-4]. This is due to the extensive interface diffusion and the corresponding defect generation, typically indicated by the growth of intermetallic compound (IMC) at the interface [5-9]. Therefore, testing of the joints would ensure that the effect of the microscopic changes has been accounted for.

In practice, there are two main approaches to characterize interfacial fracture. Based on the conventional strength of materials approach, interfacial strength can be defined as the maximum stress that an interface can withstand. Expressing the strength in terms of the critical stress or strength, it could be measured by techniques such as tensile or shear test. The lap shear test is a rather straightforward method and is probably the easiest to prepare as no complicated fixtures or special equipment are required. While there are variations in the configuration of the specimen preparation and testing methodology [10-13], the fundamental concepts are the same. Another popular technique widely used is ball shear test [14-16], which can also be used to determine the bond strength between the solder ball and the substrate. Tensile tests of solder joints are also adopted to study the interfacial failures in the microstructures and the effect of reflow, ageing and surface finishes [2-4, 17-19]. Solder joint in the form of arrays or designed geometry could be employed to measure the joint strength. Such techniques are quick and easy to perform and give values of joint strength for comparative purpose. Fractographic analysis can be conducted after the test to examine the weakest link in the joint.

The other approach is based on fracture mechanics. Interfacial fracture toughness is measured by an interface's resistance to decohesion and is able to quantify and predict interface reliability. Interfacial fracture toughness predicts the stress (load) at which an existing crack advances. The crack tip deformation dissipates energy and this is a primary contributor to interfacial fracture toughness. The energy based failure criterion such as the critical energy release rate, G_c , is based on linear elastic fracture mechanics (LEFM) which is applicable only in cases where localized, small scale yielding at crack tip is observed. The plastic zone size is limited to a small area in front of the interface crack. Highly dependent on mode mixity, the stress field surrounding a crack tip can be characterized as mode-I (normal) or mode-II (shear), depending on the type of load applied to the crack and the stress fields surrounding the crack tip. For the fracture mechanics approach, sandwich test specimens have become popular as they are relatively easy to prepare. These sandwich structures exist in various forms such as four-point bend [20-22], double cantilever beam (DCB) [23, 24], and Brazil-nut specimens [25]. The

theoretical basis for using the sandwiched specimens to measure the interfacial fracture toughness was developed by Hutchinson and Suo [26].

While four point bend specimens have been widely used to characterize multi-layered thin film stacks in the semiconductor industry, the crack tends to propagate into the adherend(s) if the joint interface is too strong or the adherend is too weak (brittle). For these cases, such method becomes invalid. On the other hand, Brazil nut test is able to provide mixed mode G_c values but it requires complex mathematical calculations coupled with finite element analysis to obtain the necessary critical energy release rate [20, 25, 27]. The DCB technique allows the characterization of mode I fracture toughness, and is easy to implement as compared to the other two variants. Thus it was employed in the current work as a fracture mechanics based assessment scheme to study the interface reliability of solder joints as a function of processing conditions.

2. Experimental Details

The DCB specimens were fabricated from 99.9wt% copper plates. The nominal dimensions of one of the mating beam are shown in Figure 1. Pin holes were machined at one end of the DCB adherends from which tensile loading could be applied to the specimens.

Fig. 1. The DCB sandwich test specimen and its nominal dimension.

The mating surfaces were mechanically polished using 800 grit, followed by 1000 grit and 1200/2400 silica sandpapers. The aim was to create a smooth finish for reproducible testing results. This was followed by cleaning in acetone solution to remove any organic residues from the surfaces. Before solder joining, the surface was etched in a mild acid solution to remove the native copper oxide. Chemical etching was carried out

in acetic acid solution at 35°C for 5 – 10 minutes. Thermal tape was then applied to the joining surface to define the shape of the initial crack (Fig. 1). This tapered surface, after solder joining, serves the purpose of initiating a sharp natural crack to the full sample width without using the conventional fatigue crack initiation method.

Following this, the cantilever beam samples were coated with Cu/Au layers using a magnetron sputter. The sputtering parameter and layer thickness are given in Table 1. We found that the coatings improve the wetting performance in the subsequent preparation of the DCB test specimens.

Table 1. The sputtering conditions for each layer on the etched copper substrate.

	Cu	Au
Thickness	1.5µm	50nm
Time Taken	45min	0.5min
Power (DC)	250W	300W

Two DCB adherends with the mating surface facing each other were bonded together applying Alpha WS-709 water soluble solder paste. Both eutectic Sn-37Pb and lead-free Sn-3.5Ag-0.5Cu (SAC305) solders were used in the current work. The amount of the solid solder can be estimated from the paste loading. Spacers were used to control the thickness of the solder layer to be ~1 mm between the cantilever beams after reflow joining in an IR reflow oven. After the joining, some samples were further treated with extended reflow or aging in order to understand the effect on the crack propagation resistance. The details of the treatments are given in Table 2.

Table 2. Thermal process of the two types of solders used in the current experiment.

	Solder material	Thermal treatment history
Case 1	Sn-37Pb	Reflow at 210°C for 90s
Case 2	Sn-37Pb	Reflow at 210°C for 90s + second reflow at 210°C for 10mins
Case 3	Sn-37Pb	Reflow at 210°C for 90s + aging at 150°C for 100hrs
Case 4	SAC305	Reflow at 250°C for 90s
Case 5	SAC305	Reflow at 250°C for 90s + second reflow at 250°C for 5hrs

The specimens were loaded in tension on an Instron Universal Tensile Tester 5567 at room ambience. Constant crosshead speed of 1 mm/min was used till complete separation of the DCBs. For each test condition, three specimens were tested and the load-displacement curves were recorded for further analysis. A JEOL 6360 SEM was

subsequently used for surface and cross sectional analysis of the specimens. Energy dispersive X-ray (EDX) was also performed to analyze the chemical composition of the microstructure and also to determine and understand the crack path propagation in the DCB solder joint specimens.

3. Results and Discussion

3.1. Fracture toughness measurement

Figure 2 shows a typical load – displacement curve of the DCB fracture test. The presence of a load plateau before the subsequent increase to the peak load was caused by the propagation of the tapered initial crack to its full width. After reaching its full width, steady state crack propagation developed. For DCB test, the bending moment is constant through the whole process of crack propagation, therefore in theory many data points (load $\times$ crack length) can be taken for the calculation of the fracture toughness. In the current experiment we took the peak load, P_c , and the initial full width crack length, a_0 , for the calculation of the critical energy release rate:

$$G_c = \frac{12P_c^2 a_0^2}{b^2 h^3 E}, \quad (1)$$

where b is the width and h is the thickness of a single beam, and E is the modulus of the copper adherend, taken as 120 GPa. Equation (1) is a simplified version by ignoring the effect of finite ligament size and the elastic compliance from the sandwiched layer (elastic foundation). More precise expression is given by ref. [28] for single cantilever beam on rigid substrate, and the energy release rate expression for DCB should be multiplied by a factor of 2. For the current work, we expect that the effect from the finite ligament is negligible, and the one from the elastic foundation is quite limited too. Therefore equation (1) is used for the subsequent calculations.

Fig. 2. Typical load-displacement curves for the DCB test.

Table 3 lists the test results for eutectic solder joined specimens. The data scattering among each group is reasonable for this type of fracture experiment, and the average of the 3 individual G_c values was taken as the representative fracture toughness of the group. The data shows that both additional reflow treatment and ageing treatment have reduced the interface crack resistance. The results also clearly shown that the extended reflow (case 3) has much more detrimental effect compared to ageing treatment. This is probably not too surprising since it is well known that the interface reaction is much faster in liquid state reflow than in the solid state ageing [29].

Table 3. Test results for DCB specimens joined with eutectic Sn-37Pb solder.

	Spec. No.	P_c (N)	a_0 (m)	G_c (J/m ²)	Ave. G_c (J/m ²)
Case 1	1-1	132.75	0.0210	248.7	272.1
	1-2	152.70	0.0195	283.7	
	1-3	135.35	0.0220	283.8	
Case 2	2-1	109.95	0.0210	170.6	173.3
	2-2	107.28	0.0220	178.2	
	2-3	100.57	0.0230	171.2	
Case 3	3-1	137.18	0.0210	265.6	243.3
	3-2	143.97	0.0210	292.5	
	3-3	105.30	0.0220	171.7	

Table 4 shows the fracture test results for SAC305 joined DCB specimens. This series (cases 4 and 5) only investigates the effect of extended reflow after the initial joining. Again it was shown that long-time reflow (5hrs) had reduced the fracture toughness by more than 50%.

Table 4. Test results for DCB specimens joined with eutectic Sn-3.5Ag-0.5Cu lead-free solder.

	Spec. No.	P_c (N)	a_0 (m)	G_c (J/m ²)	Ave. G_c (J/m ²)
Case 4	4-1	264.46	0.0180	725.1	625.0
	4-2	195.3	0.0205	512.9	
	4-3	202.78	0.0220	636.9	
Case 5	5-1	155.34	0.0230	408.5	295.9
	5-2	113.42	0.0210	181.6	
	5-3	145.20	0.0210	297.5	

3.2. *Fractographic analysis*

Observed by naked eyes, the crack propagation paths of the sandwich solder joints were found to be at the interface between the copper adherend and the Sn-37Pb solder for all three cases. Under SEM (Fig. 3), it was found that the separation was generally between the IMCs and the bulk solder. Two types of microscopic features were found: dimple and cleavage, and they co-existed in all three cases. Combined with EDX analysis on both matching surfaces, it was clear that the dimples were caused by decohesion of the hard IMC particles from the soft bulk solder. The flat facets were cleavage fracture of the hard IMC particles.

(a)

(b)

(c)

Fig. 3. Fracture surfaces of the specimens joined by eutectic Sn-37Pb solder. (a) Case 1: reflow at 210°C for 90s; (b) Case 2: reflow at 210°C for 90s + second reflow at 210°C for 10mins; and (c) Case 3: reflow at 210°C for 90s + aging at 150°C for 100hrs

For tensile test of solder joint, bulk solder failure was the dominant failure mechanism for as-joined samples. Interface failure only occurred after extended reflow or aging treatment [2-4]. However in the current work, interface failure mechanisms dominated for all cases. This was because that the solder deformation was highly constrained by the copper beams in this type of specimen configuration. The triaxiality stress state has caused significant notch strengthening effect at the crack tip, which makes the interface the weakest link even in the as-joined samples.

Figure 4a displays the typical fracture surface feature for the as-joined SAC305 DCB specimens. Many small-sized dimples, with very few cleavage facets were observed. This indicates that for the as-joined samples, the separation was dominated by IMC/solder interface separation. With extended reflow for 5hrs, large cleavage facets were found on the fracture surfaces (Figure 4b). EDX analysis found that the composition at the flat cleavages was close to Cu:Sn = 6:5 (atomic), indicating brittle IMC Cu_6Sn_5 fracture. It was also noticed that there was ductile tearing between the cleavage facets.

(a)

(b)

Fig. 4. Typical fracture surfaces of the specimens joined by lead-free Sn-3.5Ag-0.5Cu solder. (a) Case 4: reflow at 250°C for 90s; (b) Case 5: reflow at 250°C for 90s + second reflow at 250°C for 5hrs.

3.3. Source of the fracture energy and its degradation

To explain the fracture toughness decrease after the extended reflow and aging, it is reasonable to analyze it from the point of view of interface reaction and the corresponding IMC growth. It is well studied that interface reaction may cause defect accumulation, giving rise to the weakening of the interface [2-5]. The increase in reflow / aging duration also significantly increases the IMC thickness. A thicker IMC layer makes it more vulnerable to high stresses. Close to the beam / solder interface, the high rigidity of the copper adherend provides stress shielding to the IMCs. However when the IMC grows thicker, its far end goes further away from the stress shielding zone. Therefore it is

understandable that in the extended reflow case, the percentage of brittle IMC failure is higher, resulting in more IMC cleavage and decrease in fracture toughness. Thermal aging (case 3) does not cause as much decrease in the fracture toughness as reflow (case 2) because solid state aging is much slower process for IMC growth [29].

The critical energy release rates obtained in the current work lie between 170 to 620 J/m². These values are higher than the reported fracture toughness of pure IMCs [30-34]. For example, the fracture toughness of Cu₆Sn₅ IMC was reported to be 55.9±7.3 J/m² in [33]. This is because that in the current work, the fracture is a mixed ductile solder deformation / decohesion and IMC cleavage. The former consumes much larger amount of energy than the latter, so even if the fracture surface consists of significant portion of IMC cleavages, the total fracture energy may still be much higher than pure IMC following the rule of mixture.

4. Conclusion

A fracture toughness assessment methodology for solder joint fracture toughness was developed in this work. Studies were performed to study the effect of processing parameters such as extended reflow and isothermal aging that may degrade the fracture toughness of solder joints. Results offered were conclusive and provided good experimental repeatability. By adopting a fracture mechanics approach, the critical energy release rate, G_c , could be quantified explicitly. Fractographic analysis established that the fracture has a mixed micromechanism of dimple and cleavage. The dimples are formed as a result of the separation between the hard intermetallic IMC particles and the soft solder material. When the IMC thickness is large, the proportion of IMC cleavage failure increases, and this was reflected in the decrease of the critical energy release rate.

References

- [1] J. H. L. Pang, B. S. Xiong, C. C. Neo, X. R. Zhang, and T. H. Low, Proceedings of the 53rd Electronic Components and Technology Conference, New Orleans LA, United States, 2003, pp. 673-679.
- [2] M. He, Z. Chen and G. J. Qi, Metallurgical and Materials Transactions, **36A**, 65 (2005).
- [3] A. Kumar, Y. Yang, C. C. Wong, V. Kripesh, Z. Chen, Journal of Electronic Materials, **38**, 78 (2009).
- [4] Z. Chen, M. He, A. Kumar, and G. J. Qi, Journal of Electronic Materials, **36**, pp. 17 (2007).
- [5] M. He, Z. Chen, and G. Qi, Acta Materialia, **52**, 2047 (2004).
- [6] M. He, A. Kumar, P. T. Yeo, G. J. Qi and Z. Chen, Thin Solid Films, **462**, 387 (2004).
- [7] A. Kumar, Z. Chen, S. Mhaisalkar, C. C. Wong, P. S. Teo, and V. Kripesh, Thin Solid Films, **504**, 410 (2006).
- [8] A. Kumar, M. He, Z. Chen and P. S. Teo, Thin Solid Films, **462**, 413 (2004).
- [9] M. He, Z. Chen, G. J. Qi, C. C. Wong and S. Mhaisalkar, Thin Solid Films, **462**, 363 (2004).
- [10] W. H. Moy and Y. L. Shen, Microelectronics Reliability, **47**, 1300 (2007).
- [11] Y. L. Shen, N. Chawla, E. S. Ege, and X. Deng, Acta Materialia, **53**, 2633 (2005).
- [12] B. J. Van de Wal, G. Kendall, B. Sammakia, C. Sahay, and J. Constable, International Journal of Damage Mechanics, **10**, 256 (2001).

- [13] R. Darveaux, Proceedings of the Electronic Components and Technology Conference, Lake Buena Vista, FL, USA, 2005, pp. 882-893.
- [14] J. Y. H. Chia, B. Cotterell, and T. C. Chai, *Materials Science & Engineering A*, **417**, 259 (2006).
- [15] J. W. Kim, J. Joo, D. J. Quesnel, and S. B. Jung, *Materials Science and Technology*, **21**, 373 (2005).
- [16] R. S. W. Lee and X. Huang, *Soldering & Surface Mount Technology*, **14**, 45 (2002).
- [17] R. Darveaux, C. Reichman, and N. Islam, Proceedings of the 56th Electronic Components & Technology Conference, San Diego, CA, USA, 2006, pp. 906-917
- [18] K. H. Prakash and T. Sritharan, *Materials Science and Engineering A*, **379**, 277 (2004).
- [19] A. Kumar, and Z. Chen, *Materials Science and Engineering A*, **423**, 175 (2006).
- [20] A. A. Volinsky, N. R. Moody, and W. W. Gerberich, *Acta Materialia*, **50**, 441 (2002).
- [21] Z. H. Gan, S. Mhaisalkar, Z. Chen, S. Zhang, Z. Chen and K. Prasad, *Surface & Coatings Technology*, **198**, (2005).
- [22] Z. H. Gan, Zhong Chen, S. G. Mhaisalkar, Zhe Chen, K. Prasad, Sam Zhang, N. Jiang, *Applied Physics Letters*, **88**, Art. No. 233510 (2006).
- [23] F. Aviles and L. A. Carlsson, *Engineering Fracture Mechanics*, **75**, 153 (2008).
- [24] A. G. Atkins, Z. Chen and B. Cotterell, *Proceedings of The Royal Society of London*, **A454**, 815 (1998)
- [25] A. Kuhl and Q. Jianmin, *Journal of Electronic Packaging*, **122**, 147 (2000).
- [26] J. W. Hutchinson and Z. Suo, *Advances in Applied Mechanics*, **29**, 63 (1992)
- [27] S. Loo, X. Zhang, H. S. Ng, T. Y. Tee, and S. G. Mhaisalkar, *Journal of Electronic Materials*, **36**, 110 (2007).
- [28] Z. Chen, B. Cotterell and W. T. Chen, *Surface and Interface Analysis*, **28**, 146 (1999)
- [29] Z. Chen, M. He and G. Qi, *Journal of Electronic Materials*, **33**, 1465 (2004).
- [30] B. Balakrisnan, C. C. Chum, M. Li, Z. Chen and T. Cahyadi, *Journal of Electronic Materials*, **32**, 166 (2003).
- [31] Z. Chen, M. He, B. Balakrisnan, C. C. Chum, *Materials Science and Engineering A*, **423**, 107 (2006).
- [32] Z. Chen and Z. Gan, *Thin Solid Films*, **515**, 3305 (2007).
- [33] R.J. Fields, S.R. Low III, G.K. Lucey Jr., in: M.J. Cieslak, J.H. Perepezko, S. Kang, M.E. Glicksman (Eds.), *The Metal Science of Joining*, TMS, Warrendale PA, 1992, p. 165.
- [34] G. Ghosh, *Journal of Materials Research*, **19**, 1493 (2004).