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Ensuring Accurate Results in Fracture Mechanics Four-Point Bending Interface Characterization

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Short Research Article

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ABSTRACT

Interface adhesion tests are conducted to obtain a quantitative value of the adhesion strength or interface fracture toughness to forecast initiation and propagation of interface delamination failures in semiconductor packages. One of the common methods of fracture mechanics interface characterization is the four-point bending test. Problems with the experimental setup would result in having inaccurate results. In this study, different issues with the four-point bending test using mold/copper bi-material beam with notch were addressed. It was shown that incorrect anvil alignment and centering could give inaccurate fracture toughness results. The distance between anvil supports and the depth of the notch is also very important. From the study, it can be concluded that issues with experimental setup and the test sample must be addressed to ensure accurate results from four-point bending interface characterization.

Keywords: Fracture mechanics; four-point bending; interface fracture toughness; mold/leadframe adhesion.

1. INTRODUCTION

Interface delamination in semiconductor packages is a challenging problem that depends on the adhesion strength of the interface between to package material components. There are several methods of measuring interface strength [1]. As shown in Fig. 1, some of the common methods are button shear/pull (BS/BP), four-point bending (FPB), double cantilever beam (DCB), modified ball-on-ring (MBOR), three-point bending (TPB), and mixed-mode bending (MMB).

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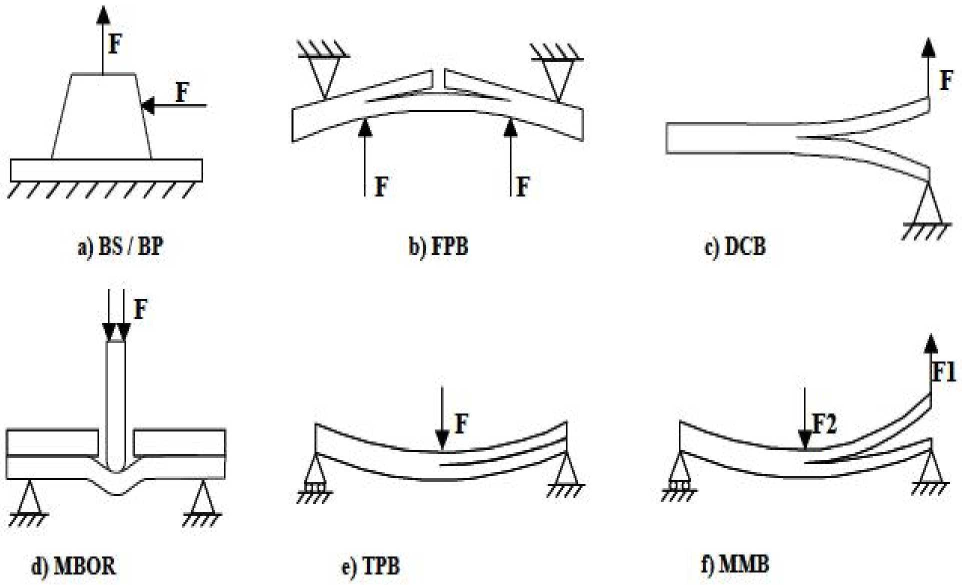


Fig. 1. Methods of interface characterization [1]

In the four-point bending (FPB) test [2], a stable crack propagation results in a constant load during delamination, which simplifies the determination of the fracture resistance because it is independent on the delamination length. Theoretical formula is available to calculate the fracture toughness. The four-point bend test is the method of choice in several industrial and academic laboratories [3]. It is a popular experiment for critical strain energy release rate characterization since it produces stable delamination at the interface and does not depend on crack length [4]. The independence on crack length makes this testing most attractive due to reduced testing uncertainty, and most practical to implement in reality [5]. The FPB loading configuration produces a constant moment between the inner loading pins. As a result, steady-state interfacial delamination occurs along the interface, evidenced by displacement increasing at a constant critical load [6]. FPB is considered an effective test method for evaluating the critical interfacial energy release rate for a bi-material interface in mixed mode loading conditions [7].

Though the four-point bend test method is widely used, problems with the experimental setup would result in having inaccurate results. This study aims to investigate the test setup problems encountered in an actual interface adhesion experiment for a mold/copper bi-material test sample. Fixing the test setup problems would ensure accurate results from such kind of interface adhesion characterization method.

2. MATERIALS AND METHODS

Mold and copper bi-material beam test samples were used in this study as shown in Fig. 2. These samples were produced by molding process using epoxy molding compound material on copper leadframe material. The copper material has a thickness of 0.25 mm and the molding compound material is 2.0 mm thick. The notch in the mold compound has a width of 320 microns (0.32 mm) and the depth is approximately 1.6 mm. This is 80% of the thickness of the epoxy molding compound as also used in previous related studies [8,9]. The notch was produced by doing partial cutting using a singulation blade on this 75 x 8 mm rectangular beam sample. There was also a test sample with a shallow notch (approximately 0.5 mm) created to check the impact of notch depth. In the current study, there were two different molding compound materials used on a bare copper leadframe and fracture toughness results were compared.

The notched rectangular mold/copper beam test samples were tested using the 4-point bending experimental setup shown in Fig. 3. In the experimental setup, the distance between upper and lower spans are 20 mm and 40 mm, respectively. The mold compound layer with the pre-crack or notch is at the bottom side. So the leadframe layer is the one that could be seen from the top side.

With the mold/copper beam samples, the four-point bending (FPB) was conducted using Instron MicroTester equipment with the corresponding 4-point bending fixture. Load versus displacement was recorded at a crosshead speed of 100 µm/min. Slow speed was selected so that the crack extension and delamination could be observed better, and any dynamic effects eliminated. The critical load, *P*, corresponding to the constant load (Fig. 4) was then recorded and used to evaluate the interface fracture toughness value, independent of the actual crack length.

As discussed by Shirangi [8], the slope of the linear part of the curve shown in Fig. 4 (point A to B) corresponds to the stiffness of the whole beam. The force at point B represents the required force for fracture in the upper bulk epoxy mold compound through the notch. This force is primarily a function of the shape and length of the notch and does not provide any information about the interface. When a vertical crack originated from the end of the notch formed, it moved very rapidly, reached the interface, and kinked into it (point C) as the actuator ramps up the displacement. Afterwards, the crack advanced along the mold/copper leadframe interface (point C to D).

After critical load, *P*, was determined from the actual four point bending experiment, the critical energy-release rate or interface fracture toughness, *Gc,* was then calculated using the formula shown below based on a simple beam theory [1]:

$$G_C = \frac{M^2(1-\upsilon_2^{\,2})}{2E_2}\left(\frac{1}{I_2} - \frac{\lambda}{I_C}\right) \tag{1}$$

where,

$$M = PL/2b$$

$$\lambda = E_2(1-\upsilon_1^{\,2})/E_1(1-\upsilon_2^{\,2})$$

$$I_2 = \frac{1}{12}h_2^{\,3}$$

$$I_C = \frac{1}{12}h_1^{\,3} + \frac{\lambda}{12}h_2^{\,3} + \lambda h_1 h_2 (h_1 + h_2)^2 \Big/ 4(h_1 + \lambda h_2)$$

The subscript 1 in equation (1) refers to the epoxy mold compound and subscript 2 refers to the copper leadframe. Fig. 5 shows the corresponding dimensions used in the equation above. Based on the experimental setup used in this study, the actual values are: L = 10 mm, b = 8 mm, h_1 = 2.0 mm, and h_2 = 0.25 mm.

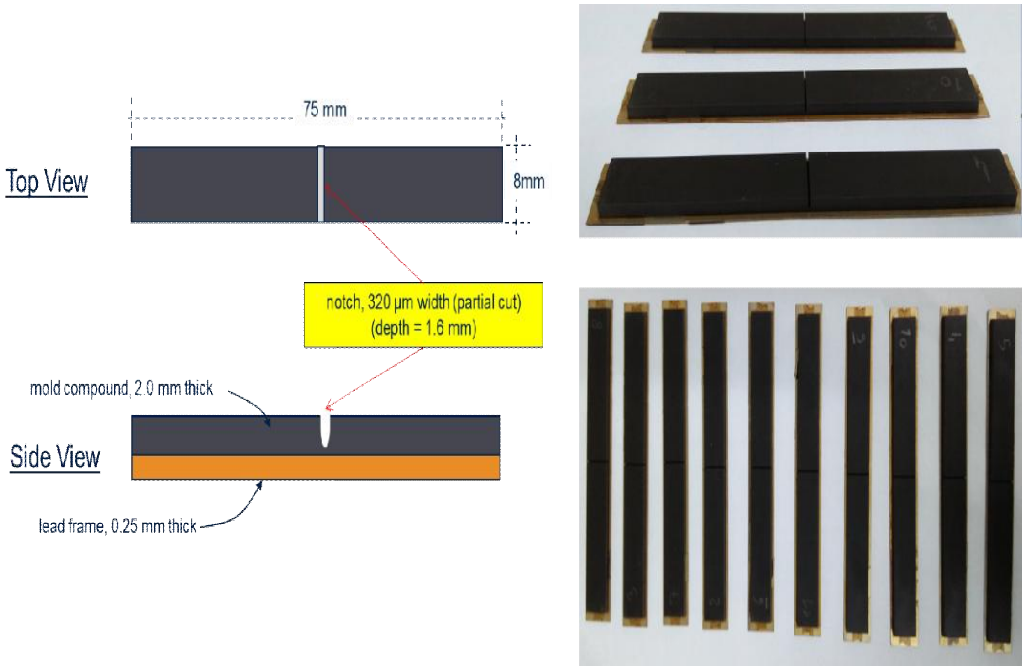


Fig. 2. Mold and copper bi-material sample

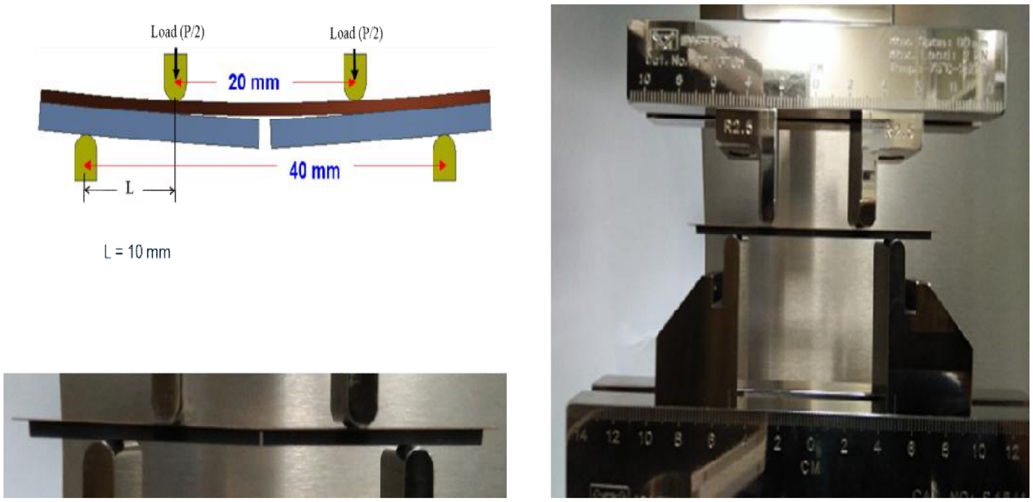


Fig. 3. Four-point bending (FPB) experimental setup

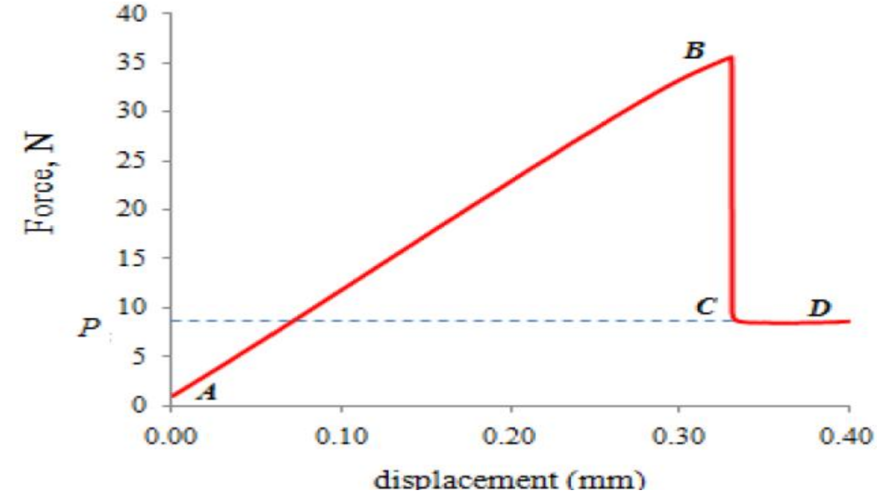


Fig. 4. Typical load-displacement curve of the four-point bending test [2]

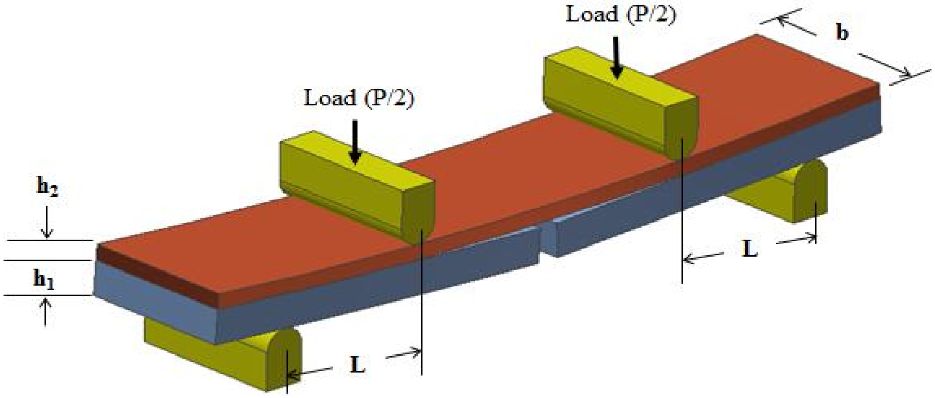


Fig. 5. Four-point bending schematic

3. RESULTS AND DISCUSSION

The result of the first trial had the copper leadframe deformed plastically before crack could propagate along the mold/copper interface. Fig. 6 shows the bent mold/copper beam with the copper leadframe already undergoing permanent plastic deformation. With the copper leadframe already deformed plastically, the result is not considered valid as there is no delamination propagation along the interface.

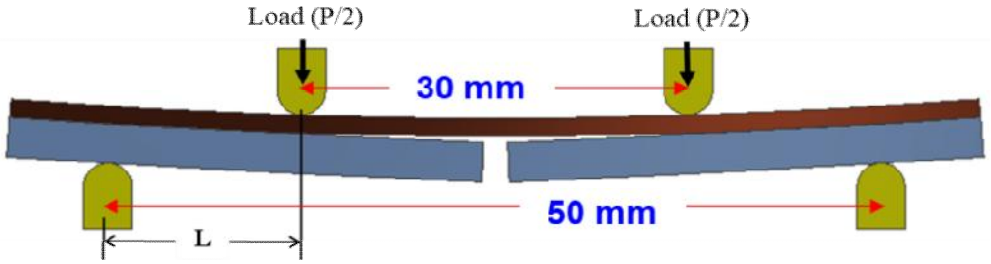
In the next trial conducted, the distance between the lower anvil supports was increased from 40 mm to 50 mm and the upper anvils from 20 mm to 30 mm as shown in Fig. 7. In this setup with increased anvil distance, the copper leadframe is not anymore showing permanent plastic deformation and the delamination propagation along the mold/copper interface could now be observed. However, the propagation is on the right side of the notch only (Fig. 7). The left side of the notch is showing no delamination propagation. We have here a non-symmetrical delamination propagation. So calculating the interface fracture using equation (1) could not be used in this situation because equation (1) assumes a symmetrical loading and delamination propagation. A significantly higher value of fracture toughness will be obtained if it is used in this situation. The fracture toughness value would be inaccurate and misleading.

Upon further investigation, it was discovered that there was a problem with the anvil alignment resulting in the non-symmetrical loading. Using a standard metal calibration bar, a gap could be seen between the calibration bar and the left upper anvil. It means that the right upper anvil is already touching the test sample, but the left upper anvil is not as shown in Fig. 8. Only the right upper anvil is applying the load or force to the test sample. This explains why the delamination shown in Fig. 7 is happening at the right side of the notch only.

After doing the anvil alignment using the calibration bar to ensure balanced loading, another trial was conducted. The result is now shown in Fig. 9 with a symmetrical delamination propagating from the notch or beam center. With this, equation (1) could now be used to calculate the interface fracture toughness.

On the other hand, the four-point bending test result for the shallow notch is shown in Fig. 10. The delamination is symmetric and implies the anvil alignment performed was effective. However, the load-displacement curve shows much higher breaking force or the required force for fracture in the upper bulk epoxy mold compound to occur through the notch. As a result, the critical load, *P*, or the constant load during interface delamination could not be identified in the curve shown. Since the required force for fracture is significantly higher than the expected constant load during delamination, the Instron MicroTester would stop as it considers the load is already zero after the bulk of the mold snaps. This result on the shallow notch confirms the need for a deeper notch, which is approximately 80% of the whole thickness of the epoxy molding compound as used in previous related studies [8,9] since this gives a good load-displacement curve and critical load could be clearly identified.

Fig. 6. Mold/copper beam deformed plastically



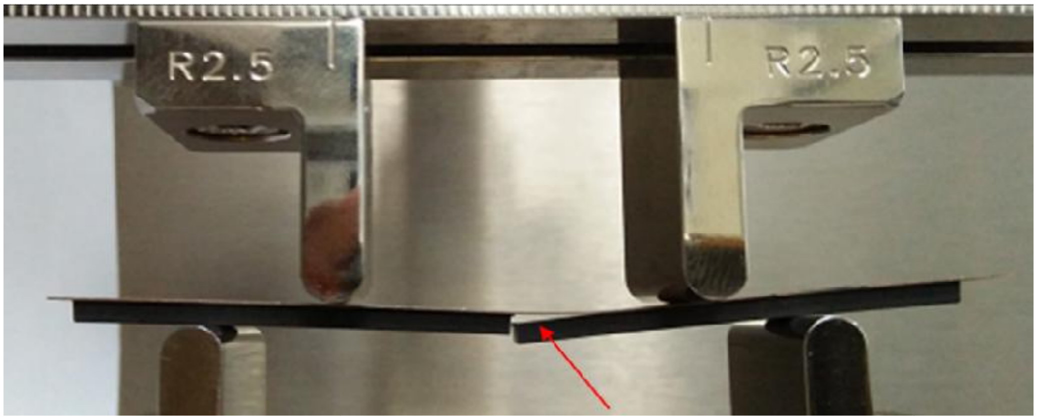


Fig. 7. Mold/copper beam with non-symmetrical propagation of interface delamination with the new adjusted anvil distance

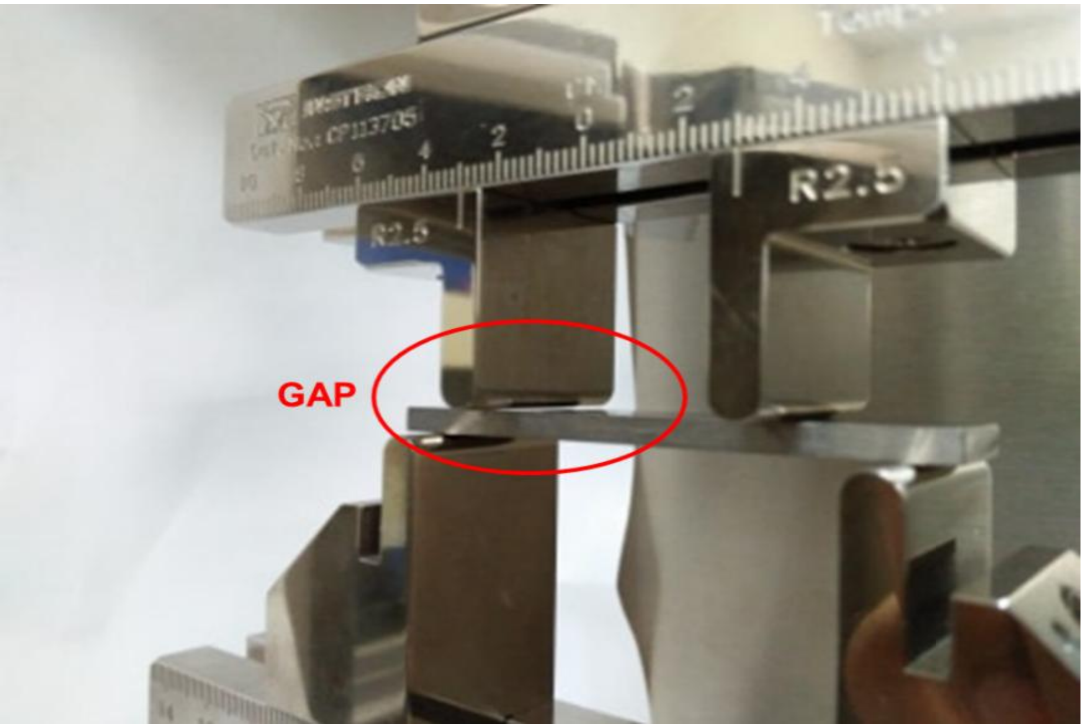


Fig. 8. Anvil alignment check using calibration bar is showing a gap

Fig. 9. Mold/copper beam with symmetrical propagation of interface delamination using the new setup after anvil alignment and increase in anvil distance

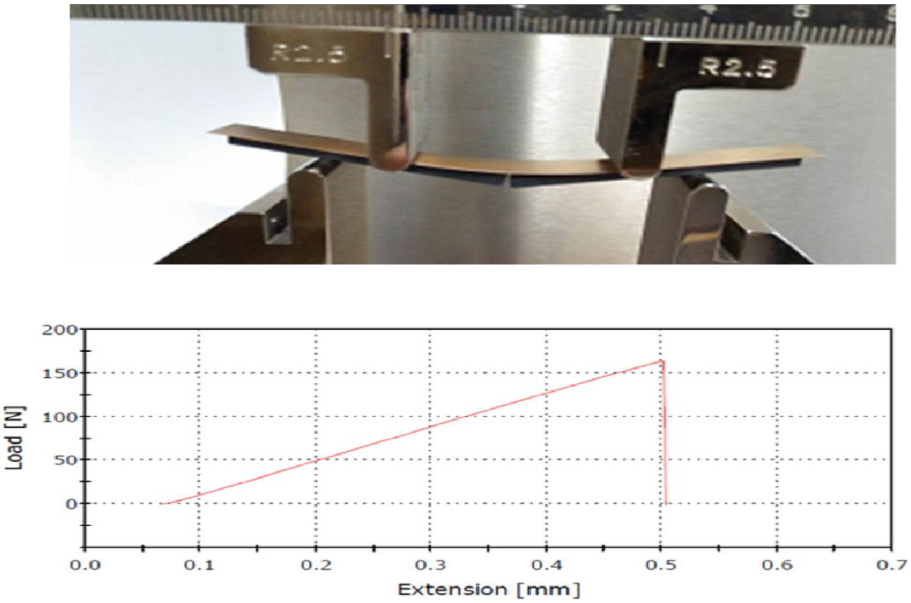


Fig. 10. Actual delamination and load-displacement curve for the sample with shallow notch

With the anvil alignment done, the load-displacement curve (Fig. 11) is close to the typical one described in [8]. Results are also showing good repeatability. The stable crack propagation could also be observed as demonstrated by the constant load during the delamination of the mold/copper interface.

In Table 1, the mold/copper interface fracture toughness result is compared to the result reported in the previous study [8]. The toughness results are quite close to each other and this is logical since the test samples used are similar (bare copper). The test method used is also the same. This interface fracture toughness for bare copper is much higher compared to the fracture toughness obtained by van Driel [1] using pre-plated leadframe (NiPdAu plating). This is expected as bare copper is known to have stronger adhesion to molding compound material as long as the oxidation in bare copper is controlled.

Comparison of the interface adhesion performance of the two different molding compound materials (Fig. 12) shows that molding compound B has lower fracture toughness than molding compound A. It appears that molding compound A is better than molding compound B. However, it is not clear whether this is because of an inherent stronger adhesion property of molding compound A to bare copper or the leadframe used with molding compound B has higher degree of oxidation since it is produced later than the sample using molding compound A.

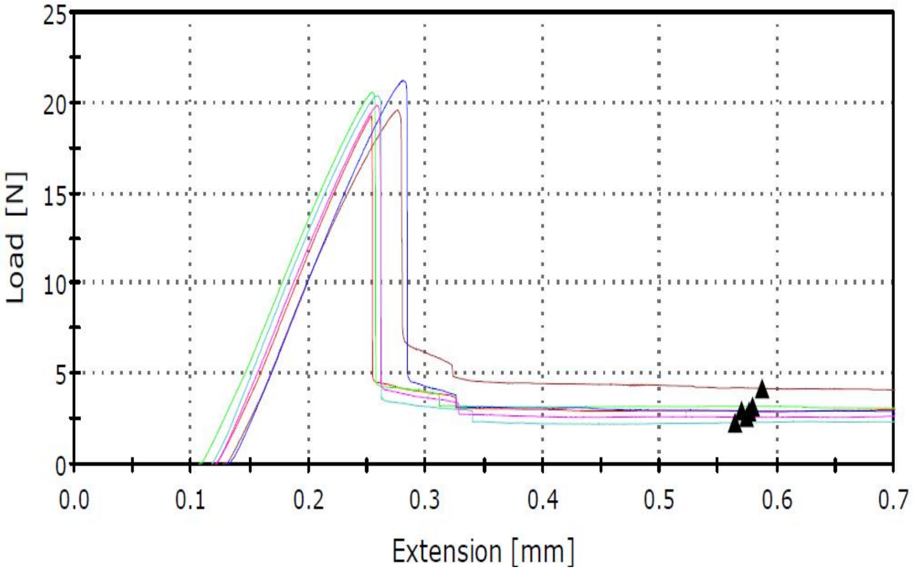
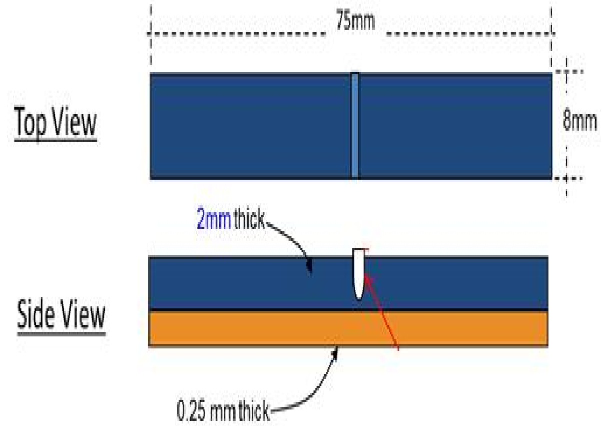
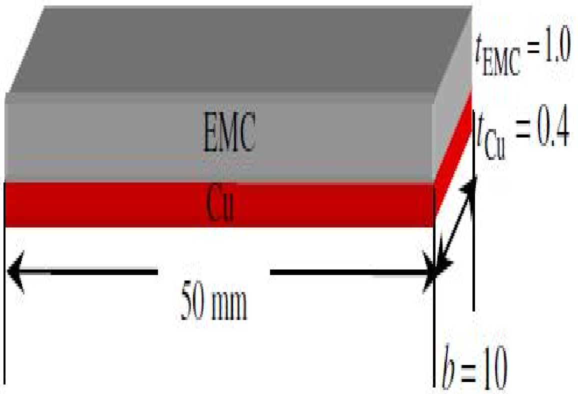


Fig. 11. Load-displacement curve result from FPB test

Table 1. Comparison of results with previous study [2]

Mold and Copper Sample	Fracture Toughness (G_c)
	24.94 J/m^2
	26.0 J/m^2 [2]

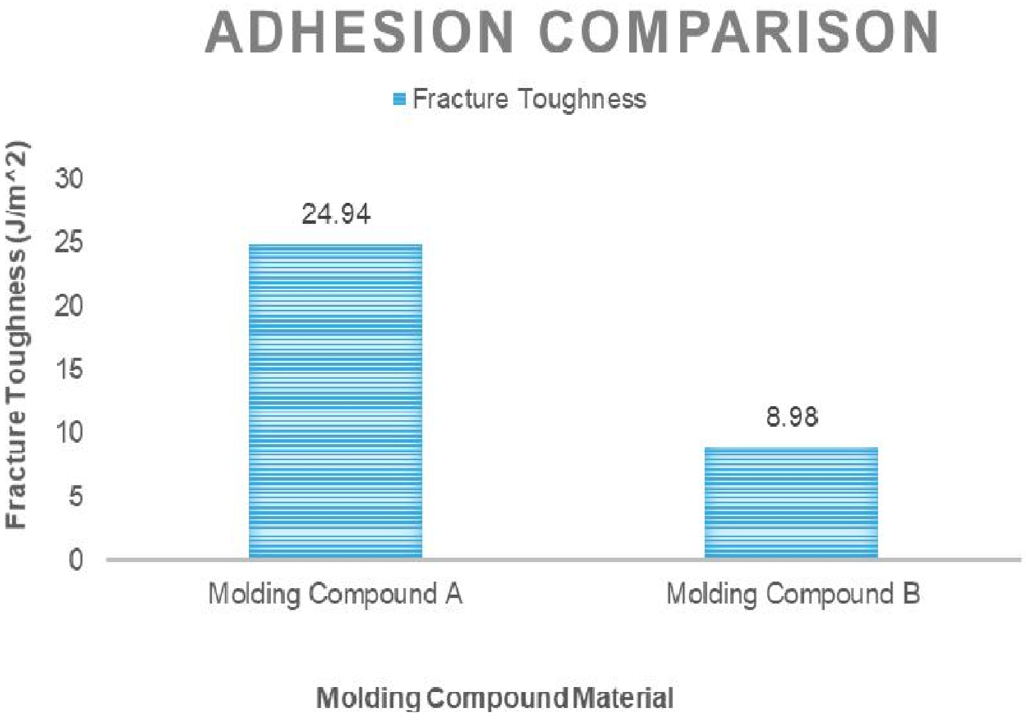


Fig. 12. Comparison of the adhesion performance of molding compound A and molding compound B on a bare copper leadframe

4. CONCLUSION

From this study, it can be concluded that correct anvil alignment and centering are very important to have accurate fracture toughness results. The distance between anvil supports must be set such that no copper leadframe plastic deformation occurs before interface delamination propagates. The depth of the notch needs to be approximately 80% of the epoxy molding compound thickness to achieve a good load-displacement curve and critical load could be clearly identified. Therefore, the issues with experimental setup and the test sample must be addressed to ensure accurate fracture toughness results from four-point bending interface characterization.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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