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Advanced Miniature Mixed Mode Bending Setup for In-situ Interface Delamination Characterization

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ABSTRACT

A novel test frame configuration was developed and employed to design a new miniature mixed mode bending (MMMB) setup for in-situ characterization of interface delamination in miniature multi-layer structures to accomplish full range of mode mixities. This advanced setup is specially designed with sufficiently small dimensions to fit in a scanning electron microscope and under an optical microscope for detailed real-time fracture analysis during delamination. Analysis of the loads in the new test configuration was performed and a special loading configuration was identified which replicates pure mode II loading better than the conventional end notch flexure (ENF) test. Special care was taken to minimize non-linearities, such as friction, the influence of gravity and geometrical non-linearities. Finite element simulation of the designed setup were performed to show its ability to access all loading modes. Preliminary delamination tests conducted on homogeneous bilayer samples under scanning electron microscope (SEM) proved the new setup configuration is capable of measuring the crack length, crack opening profile and crack delamination mechanism in addition to the conventional energy release rate measurements.

1. INTRODUCTION

The demands by the semiconductors industry for high levels of integration, lower costs and a growing need for complete system solutions has led to the emergence of "System In Package" (SIP) solutions in which "the package contains the system". Since SIP-microsystems have multiple thin and stacked layers manufactured using different processes and materials, internal (intrinsic and/or thermal) mismatch stresses are inevitably present, making interface delamination a primary failure mechanism [1, 2]. No adequate methodologies are currently available for the proper characterization of interfacial properties (e.g. fracture toughness) in SIPs. In addition it is necessary to characterize interfaces in these systems over a complete range of mode angles since the interface fracture toughness varies with the mode angle [1]. As a consequence, the industry is still heavily depending on trial-and-error methods for product/process development. Consequently, a strong demand exists for a generic and accurate mixed-mode bending (MMB) delamination setup that yields interface properties over the full range of mode mixities.

A number of experimental techniques have been developed to measure specific interfacial properties such as the fracture toughness. Fracture toughness diagnostics reported in the literature include the well-known double cantilever beam (DCB) test for pure mode-I loading [3] and end notch flexure (ENF) test for measuring pure mode-II loading [4], whereas the mixed-mode bending (MMB) setup [5-9] yields the fracture toughness over a much larger range of mode mixities. But all of the existing MMB setups are scaled up tests which can only handle large samples which poorly represent miniature multi-layer structures in SIPs. Moreover, a primary difficulty for all of these delamination experiments is identification of the crack tip location in order to track the crack length, which

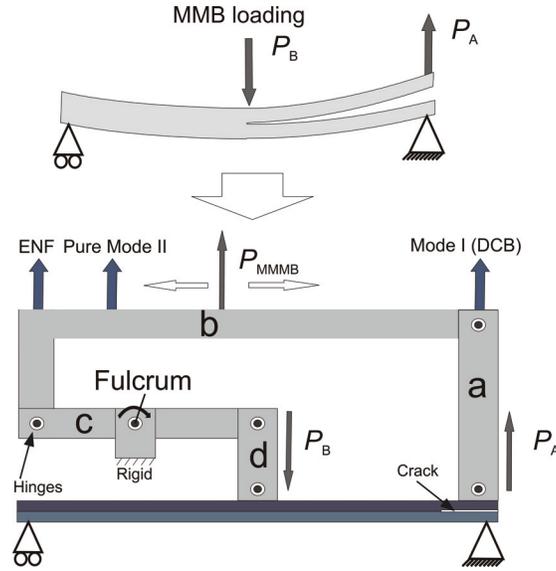


Fig. 3. The standard MMB loading (top) and the new miniature mixed mode bending setup configuration to achieve standard MMB loading (bottom).

The setup consists of four rigid parts (a to d in Fig. 3) connected with hinges. Advantages of the present design are its working mechanism that allow to access the maximum range of loading modes, from double cantilever bending (Pure Mode I delamination), to pure Mode II delamination, to end notch flexure in a single setup and the compact geometry (allowing it to be used in the chamber of an electron microscope). This was realized by an innovative new lever mechanism. The center of frame 'c' is pinned to the outside world allowing it only to rotate in the test plane. By the application of a force P_{MMMB} on a certain point of part 'b', frame 'd' moves downward and part 'a' moves upward generating two opposite forces P_A and P_B . The ratio of the forces P_A and P_B depends on the position of the loading point on part 'b' triggering different loading modes as discussed in more detail in the next section. Another benefit of the rig design is the insensitivity of force measurements to its self weight, because loading of the sample is done in the horizontal plane which also allows the microscope to be able to track the crack tip during delamination.

In the process of realization of a working setup from the developed loading configuration, we made several components and fixtures to diminish the nonlinearities due to friction, geometry and to increase the stability of the setup. For example, we used flexible elastic hinges in place of the normal hinges shown in Fig. 3. Details of the full design, drawings of all components with their specifications together with the calibration procedure which is not the focus of the present paper and will be published elsewhere [11].

3. ANALYSIS OF THE MMMB DESIGN

An analytical study of the applied mixed mode bending loading on the sample in the new test rig is performed. The loads experienced by the sample (P_A , P_B , P_C , P_D) can be written as:

$$P_A = P_{MMMB} \left(\frac{H}{\gamma} \right), \quad (1)$$

$$P_B = -P_{MMMB} \left(\frac{\alpha}{\beta} \left(1 - \frac{H}{\gamma} \right) \right), \quad (2)$$

$$P_C = \frac{-P_B}{2}, \quad (3)$$

$$P_D = P_A + \frac{P_B}{2}, \quad (4)$$

where P_{MMMB} is the applied mixed mode bending load, H is position of load application, and α , β , and γ are the dimensions of the test rig as shown in Fig. 4.

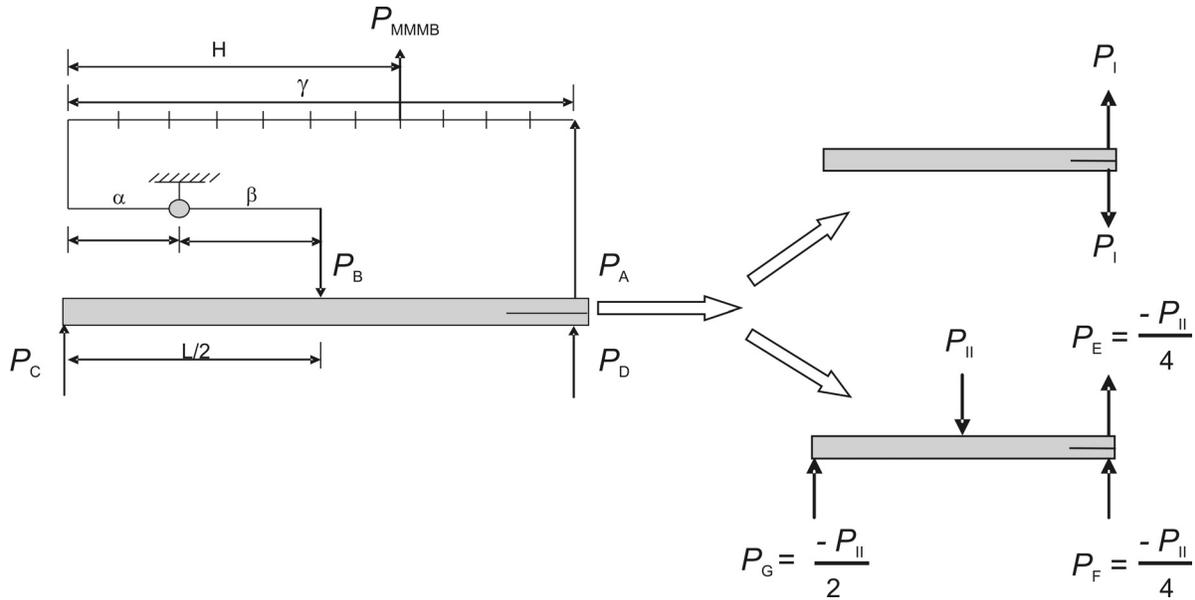


Fig. 4. A line diagram of the setup showing the loads experienced by the sample when P_{MMMB} is applied (left) and the decomposition of the applied loads into pure mode I and pure mode II loads (right).

All of these loads on the sample are then decomposed into pure Mode I and pure Mode II loads, P_I and P_{II} , respectively, which are depicted in the top and bottom right hand side of the Fig. 4, respectively. Corresponding expressions for pure Mode I and pure Mode II loads can be written as:

$$P_I = \frac{P_A + P_D}{2} = P_{MMMB} \left(\frac{H}{\gamma} - \frac{\alpha}{4\beta} \left(1 - \frac{H}{\gamma} \right) \right), \quad (5)$$

$$P_{II} = P_B = -P_{MMMB} \left(\frac{\alpha}{\beta} \left(1 - \frac{H}{\gamma} \right) \right). \quad (6)$$

The pure Mode II loading is chosen such that the two loads P_E , P_F acting on top and bottom arms of the specimen in precracked region should be equal in order to have zero Mode I component on the interface, see bottom right of the Fig. 4.

It is clear from the above analysis that when the load is applied at the right hand side of the upper lever (part 'b') i.e., when $H = \gamma$, the applied loading resembles pure mode I or DCB loading i.e., $P_I = P_A = P_{MMMB}$ and $P_{II} = 0$. On the other extreme when the load is applied at the left hand side end of the upper lever (part 'b') i.e., when $H = 0$, then the applied load resembles conventional ENF-loading i.e., $P_{II} = P_B$ but $P_I \neq 0$. Substitution of $H = 0$ in the Eq. 6 gives a compressive Mode I component expressed in the following equation in addition to the pure Mode II component.

$$P_I = -P_{MMMB} \left(\frac{\alpha}{4\beta} \right). \quad (7)$$

This analysis clarifies that the End Notch Flexure (ENF) test, which is most generally used for mode II fracture analysis, does not accurately represent a pure mode II test but represents a combination of mode II test with a compressive mode I component on top of it. The compressive mode I component, which effectively presses top and bottom layers on each other, is expected to promote friction between two contacting layers sliding over each other leading to energy release rate measurements which overestimate the interface toughness in the experiments. In contrast we identified a position ($H = \alpha\gamma/(4\beta + \alpha)$) in our new design where the compressive mode I component vanishes to produce a pure mode II loading.

The MMMB setup together with a homogenous bilayer sample is modeled in a finite element program (Msc. Marc/Mentat). Simulations were performed by assuming plain strain with linear elastic material behavior. Mode angles from the simulations are calculated from the normal and shear stress profiles ahead of the crack tip using the following standard formula [1],

$$\psi = \arctan\left(\frac{\sigma_{12}}{\sigma_{22}}\right), \quad (8)$$

All loading positions are simulated and the calculated mode angles are plotted in Fig. 5. It is clear from the figure that for the first 3 load positions the mode angle stays almost constant at $\sim 90^\circ$. Then the mode angle drops down 0° at the position 13. The reason for this behavior can be explained from the previous analysis of the applied MMMB loading where we identified a special position ($H = \alpha\gamma/(4\beta+\alpha)$) between position 3 and 4 at which pure mode II loading can be applied. This position is marked in the Fig. 5. But when the load is applied at a position smaller than the marked position (positions 1, 2, or 3) there exists an additional compressive mode I component on top of the pure mode II component acting at the crack tip. However, the presence of the compressive mode I component influence the mode angle calculation only indirectly, yielding a calculated mode angle that is constant at $\sim 90^\circ$, as seen in Fig. 5.

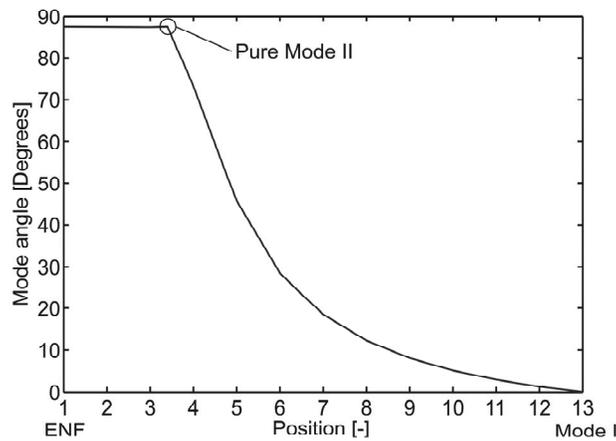


Fig. 5. The variation of mode angle with the loading position. A special position is tagged where pure mode II loading can be applied.

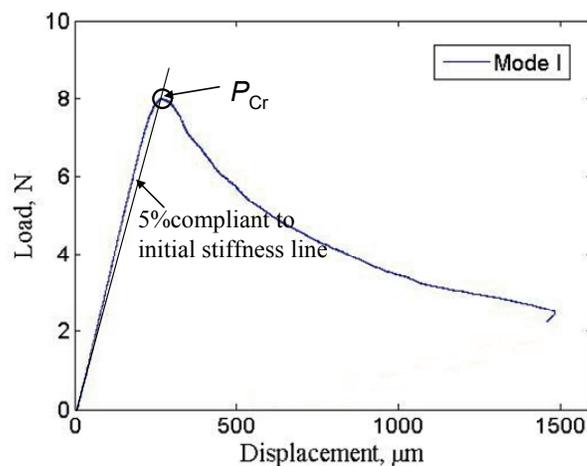


Fig. 6. Load displacement curve of a Mode I delamination experiment with new setup.

4. IN-SITU EXPERIMENTS: RESULTS AND DISCUSSION

In-situ experiment on a bimaterial sample (a brass layer glued to another brass layer) was performed under Scanning Electron Microscope (SEM). The load displacement curve for one Mode I experiment is shown in Fig. 6. The curve clearly shows initial elastic loading until a critical load then the onset of delamination following a continuous drop in load during delamination. The critical load, P_{Cr} , is calculated using a line of 5% compliant to initial stiffness.

The energy release rate for this particular specimen was calculated to be 220 J/m^2 , using a standard modified beam theory procedure [12]. The delamination mechanism could be clearly observed with very good resolution. SEM images of the interface, which is under mode I loading, just before and after crack advancement are shown in Fig 7. From the SEM images, the mechanism of the crack growth is much clearer than under normal optical visualization, while even much higher resolution SEM characterization of the crack tip is possible if needed. Fig. 7a shows the formation of small cracks ahead of the propagating crack front. Then these small cracks grow and connect each other leading to a full crack as shown in Fig. 7b. Knowing the crack tip position more accurately, it is possible to measure the crack length more precisely. Fig. 8 shows an SEM image which was prepared by stitching three images taken at same magnification in order to accurately measure the full crack length.

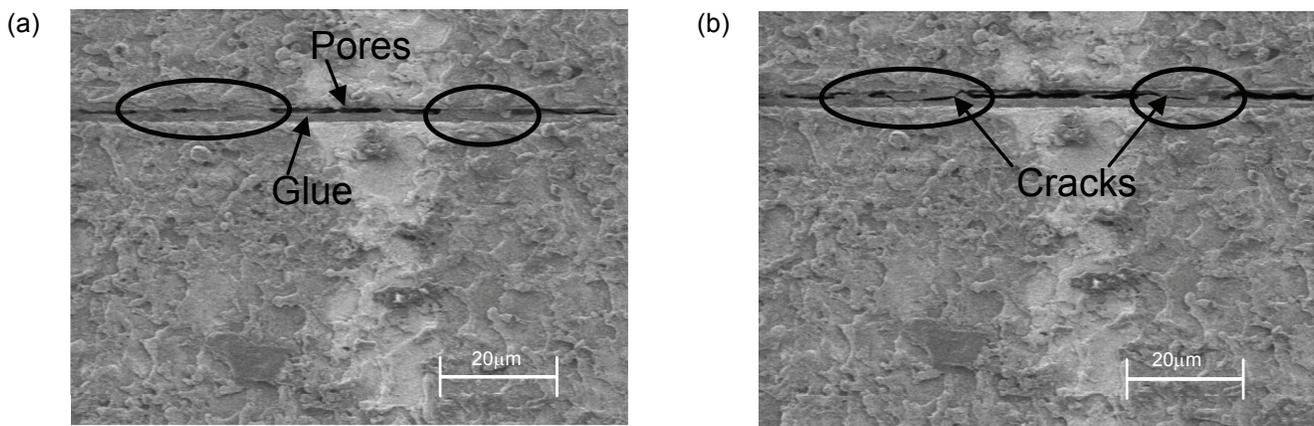


Fig. 7. SEM images of the interface (a) before crack advancement and (b) after crack advancement.

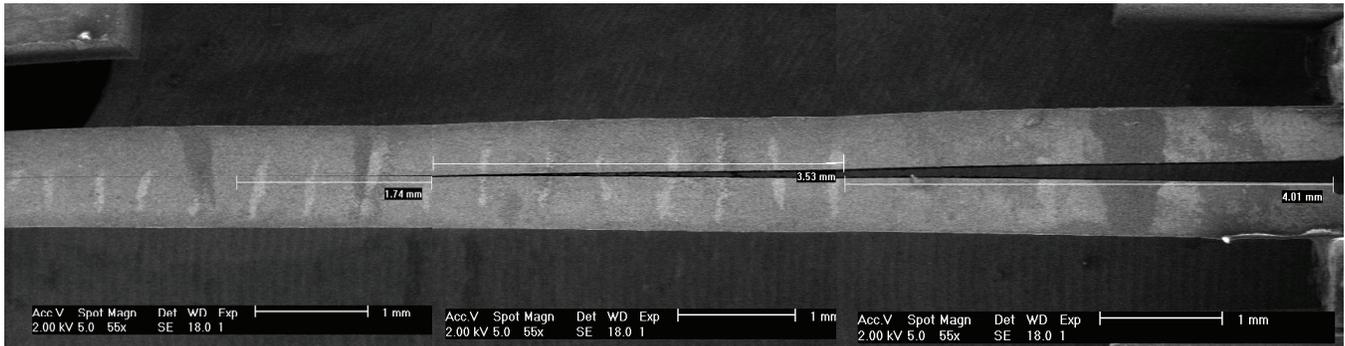


Fig. 8. Three SEM images taken at equal magnification are stitched to cover the total crack length of 10.54 mm.

5. CONCLUSIONS

A new test configuration capable of applying mixed mode bending load was successfully introduced. An analysis of the setup proved the capability of the new setup to achieve full range of mode mixities. The analysis also revealed the fact that conventional ENF test is not a true representation of Mode II delamination, but that both ENF and pure mode I loading is achievable with the new setup. Finally, an *in-situ* test done under SEM showed a high-resolution observation of the delamination mechanism. It is also found that the crack length can be determined more precisely.

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