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Study of interface delamination by a newly designed miniature mixed mode bending setup

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Abstract. A new miniature test setup capable of *in-situ* characterization of interface delamination is designed and constructed. Two unique features of the newly designed setup are its compactness to fit under a scanning electron microscope (SEM) and its ability to trigger delamination in bilayer samples over a full range of mode mixity from pure mode I to mode II loading. The present setup was aimed at studying delamination in interface structures representative of sizes typically present in system in packages (SIPs) and other miniature interface structures existing in microsystems. Another elegant feature of this new miniature version is its *loading mechanism* to accomplish mixed mode loading which works in the *horizontal plane* allowing real-time microscopic imaging (e.g., with SEM) during a delamination test. Consequently, this setup provides the benefits of *in-situ* testing to extract additional information from the delamination experiment such as the cracking mechanism, crack opening profile, and precise crack tip location in addition to conventional energy release rate, G_C , measurements. In this paper, first the design of the new test rig configuration, aimed at eliminating nonlinearities in the force displacement response arising from friction, geometry and gravity etc, is presented. Then, its working principle is discussed by highlighting some of the important practical issues and design constraints. Calibration performed using specially designed calibration samples indicated the presence of some nonlinearities originated from clearance in the dove-tail connectors used (to attach sample to the test setup). Nevertheless, a successful correction procedure to eliminate these nonlinearities is presented. Finally, results from *in-situ* delamination experiments conducted on homogeneous bilayer samples under SEM observation, enabling precise crack length determination, are discussed. The energy release rate (calculated from the measured crack lengths) as a function of mode mixity for these samples is presented.

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 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 large scale 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 should be known precisely to accurately calculate the fracture toughness. In general, visual observations with optical magnification lens systems are employed in order to track the crack. It has been identified that these techniques give inconsistent measurements leading to erroneous energy release rate measurements [10]. Therefore, high-resolution *in-situ* delamination characterization is crucial to pin-point the crack tip location, to measure additional delamination characteristics such as the crack opening profile, process zone size (to use them as input for simulations) and to obtain detailed insight of the fracture process occurring along the interface.

Evaluation of existing MMB setups elucidates the difficulties to use them for *in-situ* testing. For instance, the most well-known MMB-setup is that of Reeder and Crews [5], shown in Fig.1a, for which the lever length needs to extend to infinity in order to access the complete range of mode mixities. Apart from that, this test is difficult to perform in the horizontal plane (i.e. directions of load application lies in the horizontal plane) which is necessary to allow the microscope to follow the crack tip movement during delamination under *in-situ* testing. This is because the viewing axis of almost all microscopes is in vertical direction. Merrill and Ho's setup [8] shown in Fig.1b was also constructed with the loading direction in vertical plane, giving rise to microscopic visualization problems. Furthermore, in these two setups, the crack experiences preloads before the start of the test because of the self weight of the loading arm which presses on the specimen. Therefore, the present work focuses on the design and preparation of a miniaturized mixed mode bending setup that is not hampered by the above mentioned problems to enable *in-situ* delamination testing.

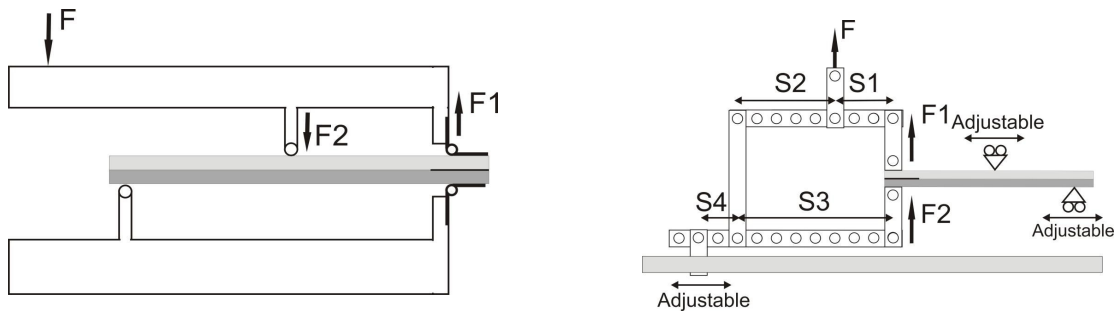


Fig. 1. The MMB setup configuration of (a) Reeder and Crews [5] and (b) Merrill and Ho [8].

Design and working principle of the miniature mixed mode bending apparatus

The key constraint in the design of the new setup is its size, which should be small enough, first, to handle miniature multi-layer structures such as the stacked layers present in SIPs and, second, to fit in the micro tensile stage shown in Fig. 2 (with the available design space of 55 x 47 x 29 mm) which in turn fits in a SEM chamber for *in-situ* delamination testing (and under optical microscopes). Simple down scaling of the existing MMB setups is not feasible because of their load frame configuration and the sample orientation that prevents *in-situ* microscopic observation. Therefore a *new miniaturized test configuration* was developed that meets the above mentioned requirements and still is able to apply MMB loading comparable to the loading conditions of the

Reeder and Crews configuration [5-7], see Fig. 1a, which is preferred because these loading conditions were standardized by ASTM (ASTM D6671-01) [6] and are generally accepted for characterization of interfacial delamination. A schematic representation of the loading geometry of the Miniature MMB apparatus (MMMB) is depicted in Fig. 3.

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 full 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. In addition the compact geometry allows it to be used in the chamber of an electron microscope. Moreover the setup 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_1 and P_2 . The ratio of the forces P_1 and P_2 depends on the position of the loading point on part 'B' triggering different loading modes. Another benefit of the design is the insensitivity of force measurements to its self weight.

This loading configuration has been transformed into a test setup, in which several components and fixtures to diminish the nonlinearities due to friction and geometry and to increase the stability of the setup were employed. For example, flexible elastic hinges were used instead of the normal hinges shown in Fig. 3. Details of the full design will be published elsewhere [11]. A detailed analysis of the new loading configuration was published in [13].

Calibration of the setup – clearance correction

Calibration of the setup was conducted in order to determine any inaccuracies that may result from the geometry, machine compliance, or any other possible factors like clearance at connectors etc. Calibration is done with specially designed calibration samples (shown in Fig. 4) suitable for loading from position 1 to position 13. These are homogeneous, single layer samples (i.e. without an interface and hence no propagating crack involved), but have a well defined notch, with an opening width of $30 \mu\text{m}$, representing an existing crack of a fixed length. Outer dimensions of these calibration samples are $35 \times 2.5 \times 1 \text{ mm}$ with 5 different notch lengths (3, 6, 9, 12 and

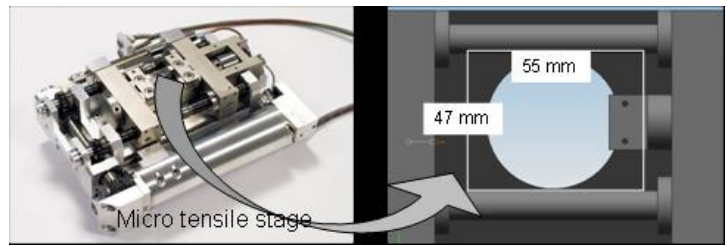


Fig. 2. The micro tensile stage (left) and its available design space for the MMMB setup (right).

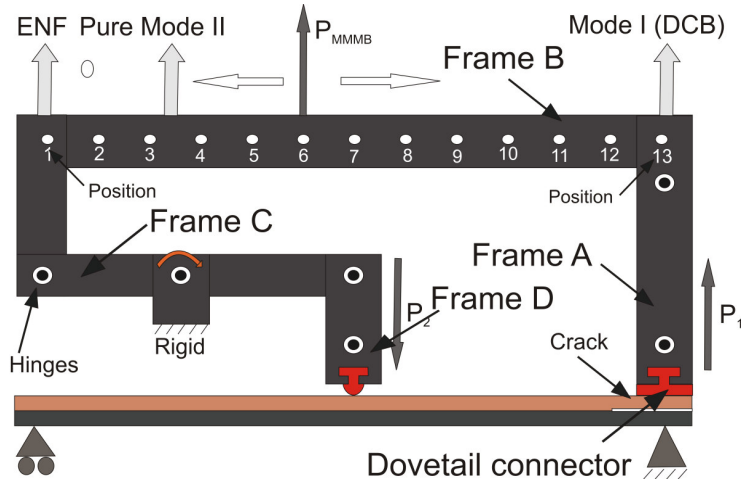


Fig. 3. The new miniature mixed mode bending setup configuration to achieve standard MMB loading. On frame B, loading positions from left to right (1 – 13) are indicated with small circles.

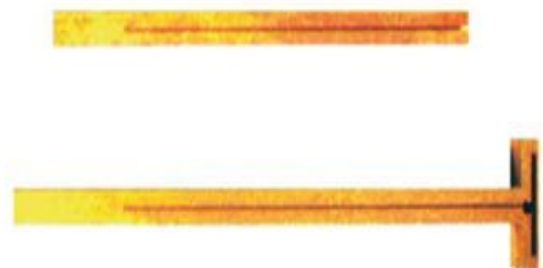


Fig. 4: Calibration samples: End parts of a Mode I/mixed mode sample (top) and a mode II sample (bottom).

15mm). Fig. 4 shows end portions of two different types of calibration samples: one (top) is designed for mode I and mixed mode loading and the other (bottom) specimen is designed for pure mode II loading with a vertical elastic beam at the end of the notch in order to prevent contact between two arms of the notched portion in mode II tests.

Results from one of those measurements at position 7 (mixed mode loading) for 5 different notch lengths are shown in Fig. 5. We observed a small hysteresis (about 2-3%) during loading and unloading of the calibration samples. From the calibration results, it can be remarked that the curves in the graphs are not completely linear, whereas finite element (FE) simulations carried out on the MMMB mechanism including the calibration samples showed a linear behavior. From this it is clear that the geometry of the MMMB device is not the cause of this non-linear behavior. Hence the source of deviation must lie in aspects that were not included in simulations for e.g., like clearance

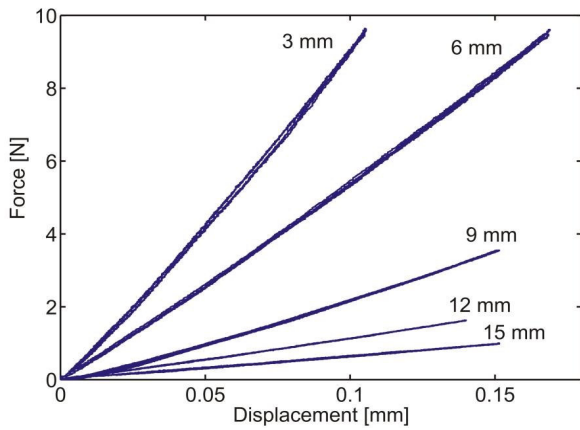


Fig. 5. Loading - unloading responses from calibration samples with different notch lengths tested at position 7

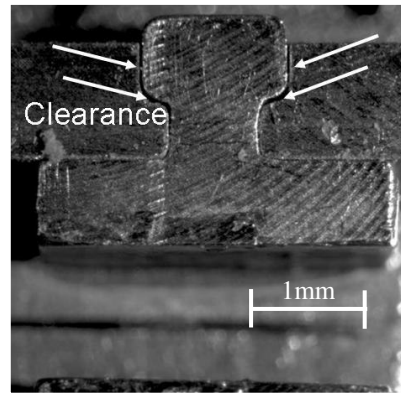


Fig. 6. Clearance at dovetail connector

at the dovetail connectors (which were used to realize all attachments between sample and frame of the test device). Although these connectors nearly perfect, still a clearance with maximum of 15-20 μm is present (Fig. 6). Figure 7 shows a measurement of a calibration sample having a notch length of 3 mm, loaded in Mode I (position 13). A kink appears at a force level ranging from $\sim 2 - 4\text{N}$, both during loading and unloading. The rest of the curve is also slightly bent. To make sure that this nonlinear behavior is due to the presence of the clearance a digital image correlation (DIC) technique was used. Vertical opening displacements are measured by tracking centre points of the dovetail connectors on both sides of the sample on a series of pictures taken during the delamination test. More detailed information about the DIC technique can be found elsewhere [12]. A corrected curve from these DIC displacement measurements plotted against measured forces is also shown in Fig. 8. The results from a FE simulation is also shown in the diagram. The corrected curve is found to have a reduced amount of hysteresis and matched pretty well with the curve from the simulation. The presence of any slight deviations in the corrected curve can be due to the slight angle rotation of the dovetail connectors due to clearance. It

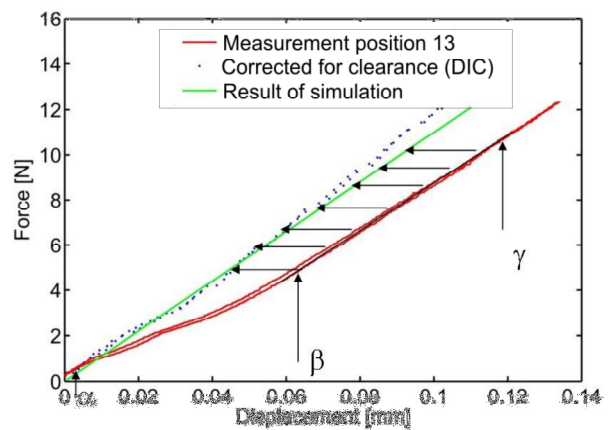


Fig. 7. Figure illustrating the influence of clearance at the dovetail connectors on the load-displacement diagram. This test is done at position 13 (mode I test). Also shown is the resulting curve from a FE simulation and the corrected curve from DIC measurements.

is also clear from the figure that the slip causing this deviation is significant only in the early stages of the test (displacement between ‘ α ’ to ‘ β ’ as indicated in Fig. 7). Later (between ‘ β ’ and ‘ γ ’) the slope of the curve is matching quite well with the result from the simulation and DIC. Finally, from the above observations it can be concluded that the MMBB setup itself behaves linearly and nonlinearities due to clearance at the connectors can be solved by supplementing the delamination experiments with DIC analysis.

Results and Discussion

A batch of bilayer samples, consisting of two brass layers glued together (the thickness of the glue is approximately $5\ \mu\text{m}$), is tested with this newly designed setup to find the interface strength. Figure 8 shows the result of a preliminary mixed mode loading experiment conducted in a SEM, where the sample is loaded in position 11. During the test at regular intervals the sample is unloaded and reloaded during which the crack length was measured by SEM observation. Stiffness lines were fitted to the unloading curves as shown in Fig. 8. Because of the high magnification in-situ SEM observation during testing revealed the exact location of crack tip [13]. Then, the energy release rate values were calculated from the area between the successive unloading slopes divided by the corresponding increase in the crack length. For a given loading position, energy release rate values stayed constant with crack propagation. It should be noted here that the correction for clearance has not yet been applied to these measurements. Preliminary results of the resulting energy release rates were plotted as a function of position of load application in Fig. 9. From this figure, it is also clear that the energy release rate values are increasing towards mode II dominant tests (towards position 1), which is an expected result. Additional advantages of in-situ testing to get detailed insight of the delamination mechanism were published elsewhere [13].

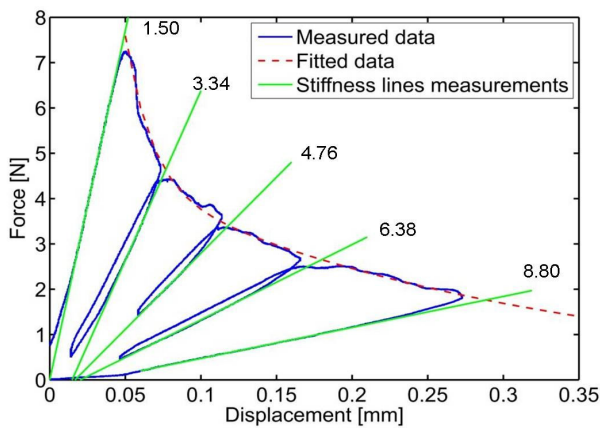


Fig. 8. A typical force displacement response from a preliminary mixed mode delamination experiment conducted under SEM at position 11. Numbers indicate the precise crack length measurements from SEM observation at each unloading interval.

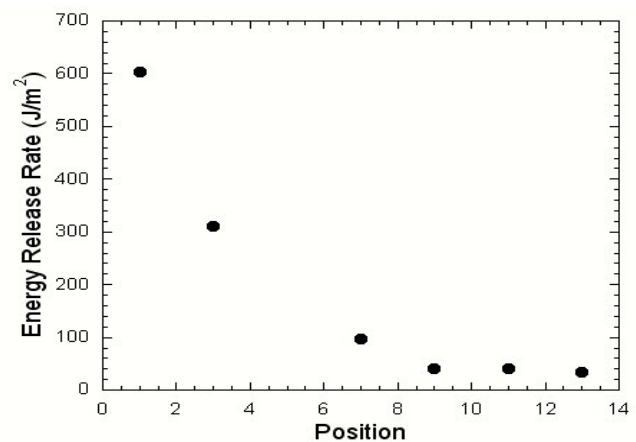


Fig. 9. Variation of energy release rate as a function of loading position (preliminary results).

Summary

Design of a new miniature mixed mode bending test setup for *in-situ* delamination is presented. Calibration of the setup is performed with specially designed calibration samples. Results from the calibration showed that the clearance at the dovetail connectors is causing some nonlinearity in the force-displacement response. A successful correction procedure was presented to surmount the influence of clearance on the force-displacement response. Finally, preliminary results from in-situ

experiments were showed where energy release rates were calculated using precise crack length measurements from SEM observation.

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