Nanoscale deformation analysis for fracture mechanical evaluation of interface cracks in electronic packages.

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ABSTRACT

The ongoing development of highly integrated electronic packages leads to a steadily increasing number of material interfaces within a package. In combination with increasing harshness (vibration, humidity, temperature) of the system environment the reliability of such packages is often dominated by interface fracture. Therefore interface fracture mechanics is one of the main focuses of electronics reliability research.. The authors present a combined simulative and experimental method for crack tip location determination and crack evaluation of interface specimens. The specimens are loaded in a testing apparatus which is an advancement of a mixed mode bending test. Based on crack length measurements and Finite Element Analysis crititcal energy release rates can be axtracted in a fast and inexpensive method.

Keywords: mode mixity, interface cracks, fracture mechanics, electronic packaging, mixed mode bending, gray scale correlation, deformation measurement,

1 INTRODUCTION

A great challenge for reliability assessment of todays high end electronics packages is the large number their inherent bi-material interfaces. Due to thermo-mechanical loads during processing (e.g. reflow), testing (e.g. moisture sensitivity level, thermal cycling) and operation (vibration etc) failure by delamination is one of the major failure mechanisms [1].

The determination of fracture mechanical properties of interface cracks is a substantial task for the design for reliability. Without experimental determined fracture mechanical parameters such as the critical energy release rate a reliability forecast based on simulation results cannot be given.

There are tests available where the measurement of the crack length is not necessarily needed for the determination of material and interface properties [2]. The trend towards close-to-production specimen requires a more flexible and general approach for the fracture mechanical characterization. The use of non-standard specimen geometries makes the determination of crack tip location and crack length inevitable. An example of such a test is the Mixed Mode Bending test developed by Xiao [3] which was also applied by the authors of this paper [4].

The goal of the research work presented in this paper is the advancement of this approach towards specimens taken directly from the production (packaging line). This goes along with a drastical reduction of specimen size demanding high accuracy of force measurement and high resolution capability of crack tracing methods [4]. The authors therefore makes use of the Digital Image Correlation (DIC) technique as the method of choice for crack tracing for such application [5][6]. They applied correlation based fitting algorithms for comparing experimental data with finite element data sets [6]. This approach is more general than methods comparing experimental data to analytical data.

For silicon to moulding compound (Si/MC) interface which is usually a strong interface with comparably low relative displacements between the material partners, the authors showed the applicability of the procedure, [7],[8]. In this work the focus is laid on Cu-leadframe to moulding compound (Cu/MC) interface.

In general interface cracks are dominated by a mode mix between tension and shear mode (crack driving modes I and II). A short theoretical description of mixed-mode loading and interpreation related to this paper can be found in [9].

2 ADVANCED MIXED-MODE BENDING

To keep the strong features of the Mixed-Mode Bending (MMB) test, [3][4], but make up for its weaknesses, a new testing concept is introduced called Advanced Mixed-Mode Bending (AMB), (schematic: Figure 1). It is designed according to the specimen-centred approach keeping in mind scalability, i.e. potential for smaller specimen testing. The AMB test is essentially a MMB test and uses the same kind of bimaterial specimen. However there is some significant changes: Instead of the bar splitting the force, independent displacement controlled actuators load the specimen by compressing against it rather than by tensile loading. At one end the sample is clamped (Figure 2), being only allowed to rotate.

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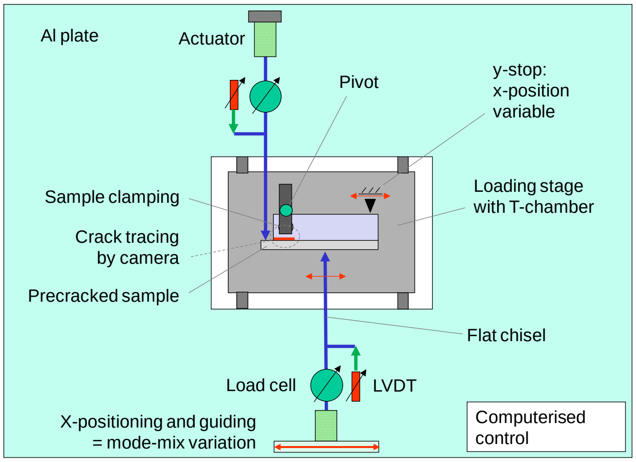

Figure 1: AMB schematic. Note the modular concept and open architecture.

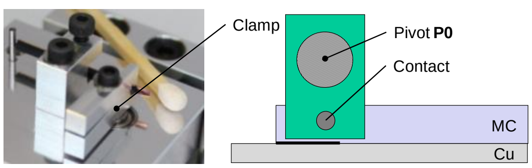

Figure 2: Miniature clamping mechanism of test-specimen in AMB test-stand and schematic representation. The clamp can be taken out for easy sample fixation and then remounted. It represents the rotation point.

This has a big advantage: The whole assembly becomes intrinsically stable, much simpler, and one more degree of freedom in loading the sample is gained which should be able to even increase the possibilities of varying the mode-mix to obtain full range in. The loads and displacements are measured by load cells and LVDTs. As they are directly coupled to the specimen, their readings can be put directly into a FE-model which can then only consist in the specimen itself and no other parts.

The assembly uses a loading stage (Figure 3) which can be taylored in order to harbour a special specimen size or design. This loading stage is easily exchangeable and manufacturable, as e.g. for a different specimen geometry, but does not interfere with actuation and sensoring.

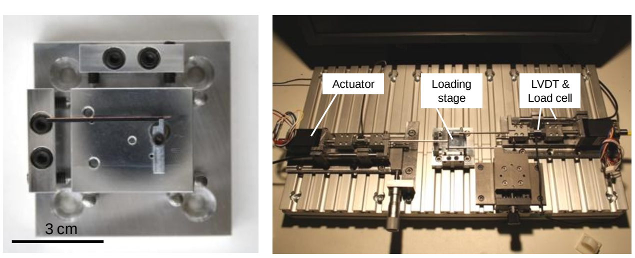

Figure 3: Loading stage (left). Note the tiny clamped specimen. Complete AMB assembly (right).

The load is truly displacement controlled, i.e. crack growth will be stable. Further, the design allows for a temperature and moisture loading, as the loading stage is covered by a small hood to contain convection and vapour chamber of 10 cm^3 volume.

A transparent glass lid is being developed and will allow greyscale-based crack length measurement. Last but not least, mostly OTS-parts were used which held the cost down.

3 CRACK TRACING

With exception of a four point bending test using a delamination specimen critical energy release rate $G_c(\psi)$ will usually depend on the crack length. Therefore, one needs to find methods to determine the crack length in-situ. In order not to interfere with the mechanical loading of the crack and to allow temperature and moisture application preference is usually given to contactless optical methods such as depicted in Figure 4.

Figure 4a pinpoints the crack tip at the crossing of the two measured displacement curves extracted from Digital Image Correlation. The frames are taken at different times during the loading and then analysed afterwards to assign a crack length to each point on the force-displacement curve [8]. Even higher accuracy is achieved by using a correlation technique for the crack tip fields (see Figure 4b): A simulated crack tip displacement field (inset) is compared numerically to the experimentally ob tained one. The crack tip is found where the correlation integral peaks [8]. Care has been taken that this greyscale-based method can also be applied to the AMB-test stand.

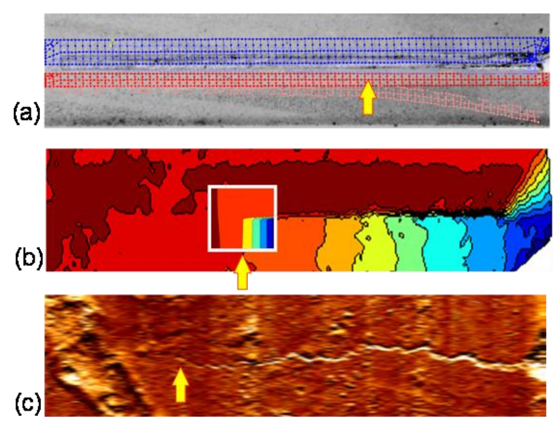

Figure 4: Crack tracing methods with increasing degree of sophistication.

4 FINITE ELEMENT MODELING

Interface fracture mechanics critical data evaluation needs experiments and simulations carried out in parallel to obtain the desired $G_c(\psi)$ values. Details on the finite element modeling of this papers experimental setup can be found in [9]. Figure 5 shows the nomenclature of the loads applied to the bimaterial sample.

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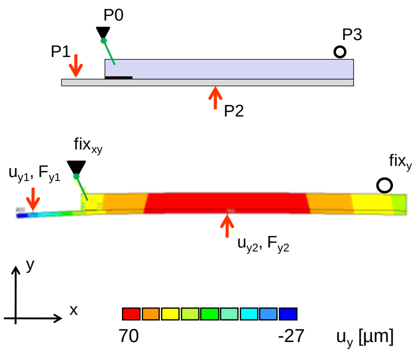

Figure 5: Constraints and loading for the FE-model and corresponding nomenclature of AMB testing.

5 EXPERIMENTAL RESULTS

During loading of the sample according to Figure 1and Figure 5 in the AMB test, the forces on the load application points increase as given in Figure 6.

Upon crack advance from point *A* to *B*, the force F_1 drops as expected, the stiffness of the sample starts to decrease. F_2 which governs the shear or mode-II loading still increases, but at a smaller slope. As the mode mix is intentionally changing (here: increasing) all the time during loading, the F_1 curve differs qualitatively from the ones shown in other experimental setups (MMB) such as shown in [3] and [4].

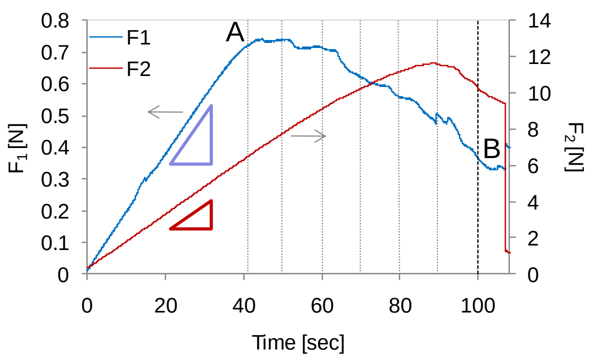

Figure 6: Forces F_1 and F_2 during loading for positive mode-II. Crack propagation starts in point *A*. The vertical lines indicate the values taken for evaluation.

Any two values on these curves at a certain time and crack length can now be used to calculate $G_c(\psi)$, given that the displacements are also known and machine stiffness corrected. These values are now put into the simulations at any measured crack length value.

Two curves, one for each recorded force, emerge then upon mixed-mode loading as depicted in Figure 7, where corresponding loading velocities are given as $v_1 = 4\ v_2$ for positive and $v_1 = 2\ v_2$ for negative mode-II loading. This assures an increasing (decreasing for negative shear loading) mode mix with time.

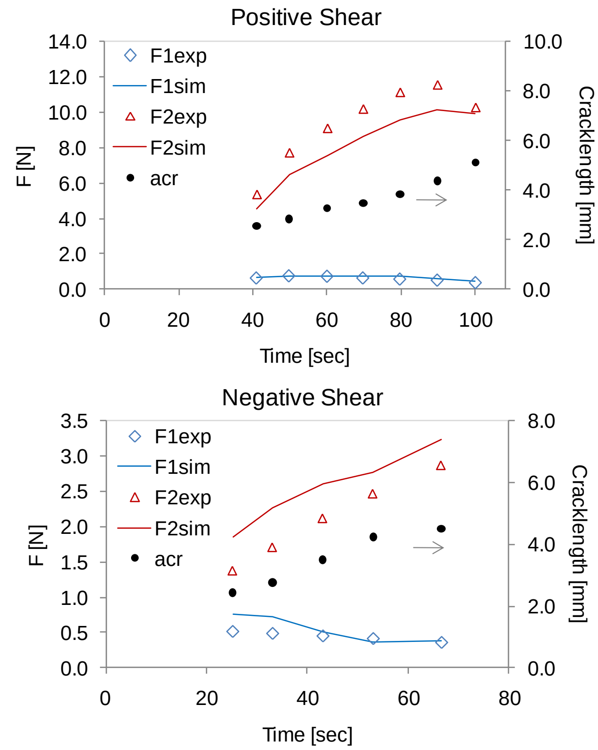

Figure 7: Experimental vs. simulated results. Curves are obtained for one specimen each. a_{cr} is the crack length.

The black dots describe the optically measured propagation of the crack during the measurement in discrete loading steps (as is to be seen in Figure 8).

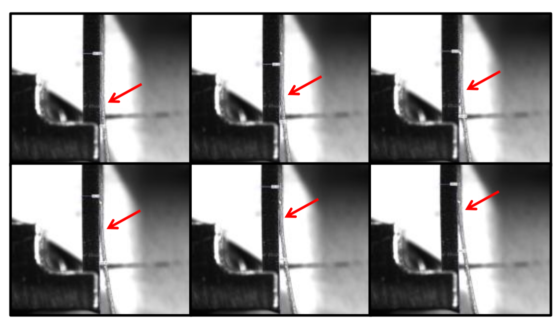

Figure 8: Loading sequence. The red arrow points out the crack tip.

One observes, that F_1 values are very accurately reproduced, whereas there is some discrepancy for F_2 in both cases. This discrepancy is still to be checked for in terms of parasitic effects during measurement, elastic and plastic data, anisotropy etc. The nearly constant F_1 values suggest an increasing fracture toughness by increasing mode angle, as due to increasing crack length those values should rather drop.

The final result is depicted in Figure 9 where the $G_c(\psi)$, curve is depicted for positive (right) and negative (left) shear loading, which is precisely the desired result. Due to the arbitrariness of the chosen reference length λ (in simulation) the curve is not centered on the y-axis. As explained, however, this can be done by varying it. A fit function suggests that a minimum value for G_c is at around $\psi_\lambda \approx 11°$. It should be noted that in order to record this curve only two test specimens have been used, which represents a substantial speed up in measurement time and an important saving in resources, both of which have up to now made interface characterisation so complicated. The whole procedure to obtain the desired curve as presented here took only approximately two hours.

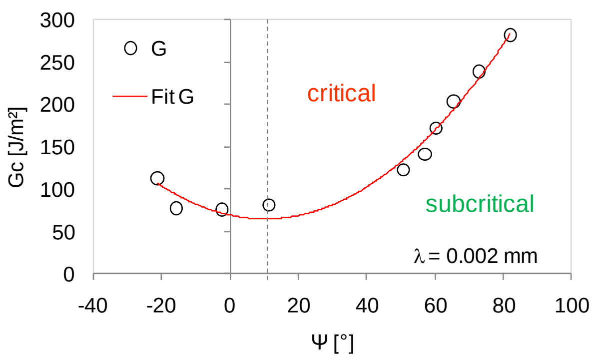

Figure 9: Result data $G_c(\psi)$, curve for negative and positive values of ψ. Values are for two test specimens only. The dotted line represents the symmetry axis and the new and absolute zero angle characteristic for this very interface.

Needless to emphasise that a couple of more specimens would be used to obtain error bars on all presented data. However, as the presented data is to serve as a proof of concept for the time being, we have shown what we expected to see. A benchmark and qualitative analysis will follow as well as a mending of the discrepancies between experiment and simulation.

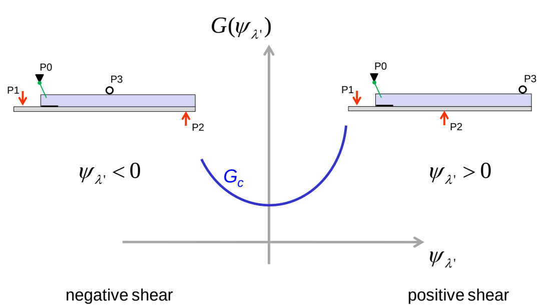

Figure 10: Load reversal on specimen to obtain positive or negative mode-II.

A nice feature is the fact that by simple rearrangement of the loading points *P2* and *P3* in the AMB tester setup one may switch from positive to negative mode-II loading as is highlighted in Figure 10. One may, if possible, also just turn the specimen upside down.

6 CONCLUSIONS

We have presented an efficient and comprehensive method for rapid, inexpensive and accurate fracture-mechanical interface testing for electronic packages and their lifetime prediction. The test-specimens and test-stand proposed are found to meet key requirements for industrial application. In the next step the setuo will be placed under an AFM to achieve high resolution nanoscale images of the crack tip.

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