Fracture mechanical test methods for interface crack evaluation of electronic packages

J. Keller[1], I. Maus[2], H. Pape[2], B. Wunderle[3,4] and B. Michel[4]

[1]AMIC, Angewandte Micro-Messtechnik GmbH, Berlin*
[2]Infineon Technolgies AG, Neubiberg, Germany
[3]Chemnitz University of Technology, Chemnitz, Germany
[4]Micro Materials Center Chemnitz at Fraunhofer ENAS, Chemnitz, Germany

ABSTRACT

The experimental determination of fracture mechanical properties of interface cracks is a substantial task for the design for reliability of electronic packages. As interface cracks are dominated by a mode mix between tension and shear mode (crack driving modes I and II) a mixed mode bending method was developed to adjust the ratio of the two modes (mode mixity). For a correct extraction of an energy release rate from this kind of tests a finite element simulation has to be carried out. As the crack driving force is not independent from the crack length, correct crack tip detection has to be guaranteed during the test. The authors present a combined simulative and experimental method for crack tip location determination at interface specimens. The specimens are loaded in the testing apparatus and images of the crack tip at the interface are taken at different load states during the testing procedure. Then images are analyzed by image correlation techniques and the displacement fields are determined. In the next analysis step the displacement fields are compared to fields from finite element analysis of the same specimen geometry with similar boundary conditions as the experimental setup. The point of the best matching of the experimental and simulative field is the actual crack tip location. If finite-element data or analytical solution for the crack tip displacement field is available the method can be applied for a variety of different interface samples.

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

1 INTRODUCTION

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. 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 [1]. 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 [2]. The goal of the research work presented in this paper is the detection of crack tip position by a non-contacting optical method.

Digital Image Correlation (DIC) technique is the method of choice for this application. Compared to methods which make use of brightness gradients at the crack faces the DIC approach can also be used if gradient techniques fail due to inadequate lighting conditions.

Recently Digital Image Correlation was intensively applied for fracture mechanical analysis [3],[4]. The authors of this paper also applied correlation based fitting algorithms for comparing experimental data with finite element data sets [5]. 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, [6],[7].

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). In the following a short theoretical description of mixed-mode loading is given followed by the experimental and numerical methods applied for interface characterization.

* AMIC Angewandte Micro-Messtechnik GmbH, Volmerstraße 9B, 12489 Berlin, Germany, Ph: +49 (30) 6392 2540 , Fax: +49 (30) 6392 2541, corresponding author: Juergen.Keller@amic-berlin.de.

2 MIXED-MODE LOADING

The material parameter of interest for interface crack characterization is the critical energy release rate G_c which serves as failure criterion

$$G > G_c \tag{1}$$

If the current loading at a material interface expressed as energy release rate ist higher than a critical value G_c crack propagation occurs. In general G_c is depending on the bi-material material properties and the loading conditions including temperature T and moisture concentration C in the polymer part of the bi-material configuration. In addition G_c depends on the intrinsic mode-mix also described as mode-angle ψ, [8]. At interface cracks of electronics packages ψ depends on the loading condition during package production, storage and thermal cycling. In order to account for this environmental conditions the critical energy release rate has to be determined experimentally according to:

$$G_c = G_c(\psi, T, C, t) \tag{2}$$

where also rate-dependence $f(t)$ may be important.

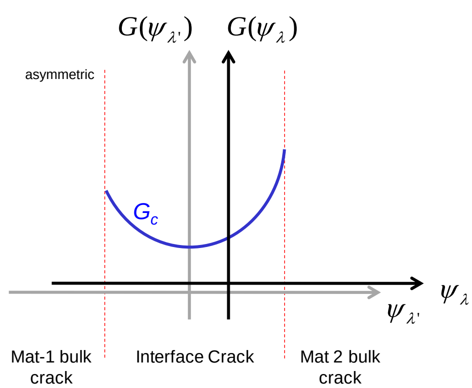

Figure 1: Schematic of critical energy release rate G_c for a bi-material system. The ψ-axis is given for two different values of reference length λ, [9].

A more detailed discussion of mode-mixity can be found elsewhere [8],[9]. The focus of this work is laid on the experimental setup for the variation of the mode-angle ψ and the required detection of crack length during testing procedure.

3 EXPERIMENTAL SETUP

Experimental testing was carrried out with so-called mixed-mode bending (MMB) test. Compared to other crack initiation tests such as single edge notch bending (SENB) or 4-point bending it allows to cover a larger range of mode-angle ψ values. Figure 2 shows a schematic of the mixed mode bending configuration.

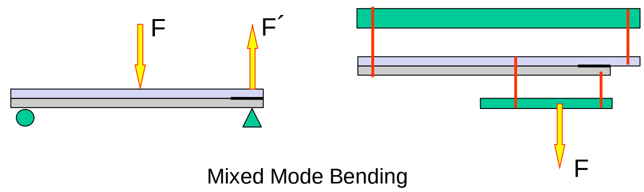

Figure 2: Mixed-mode bending test; pre-cracks are marked by a black line, [9]

For a mixed mode bending the application of the forces F and F´ is required. Additionally the force ratio $F´/F$ have to be varied to adjust the contribution of mode-I and mode-II loading. This can be achieved by a lever principle (Figure 2) as introduced for miniaturized specimen by Ernst [10] and Xiao [2]. Based on research work a new MMB system was developed and adapted to a DMA system which allows the variation of temperature and humidity during the test, Figure 3.

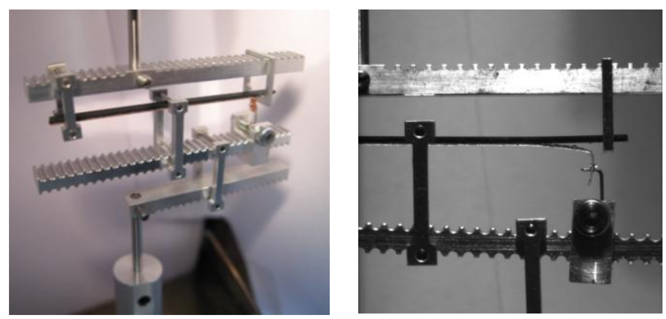

Figure 3: (left) Mixed-mode bending test apparatus adapted to commercial testing machine, (right) detail of bi-material specimen (Cu/MC) under loading

For accurate detemination of critical energy release rates the crack tip location have to be detected. If the crack length and the corresponding crack initiation force is known the whole configuration has to be simulated by means of finite elmente analysis and appropriate methods of extraction of energy release rates have to be carried out (e.g. as described in [11]).

4 CRACK TIP LOCALIZATION

For crack tip detection a correlation based comparison algorithm of experimental displacement data with numerical data was developed. The experimental data are extracted from crack initiation tests at bi-material specimen by means of digital image correlation and the numerical data are extracted from finite element analysis. The required steps are discussed in the following sections.

NSTI-Nanotech 2011, www.nsti.org, ISBN 978-1-4398-7139-3 Vol. 2, 2011

4.1 Digital Image Correlation (DIC)

The experimental data was extracted from images of the Cu/MC specimen loaded in the mixed mode bending setup as shown in Figure 3. The results of the DIC-analysis are shown in Figure 4 as yellow arrows above the blue crosses which are markers for the center of the correlation kernels. Details of the Digital Image Correlation technique for displacement field detemination can be found in previous work of the authors [5],[7],[12],[13].

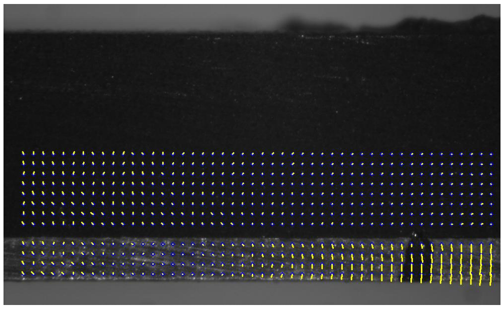

Figure 4: Displacement vectors (arrows) above and below the interface determined by cross correlation with VEDDAC® (Chemnitzer Werkstoffmechanik GmbH)

After the determination of the displacements for a rectangular grid of points with user defined pitches (mesh seed from VEDDAC®), a complete in-plane displacement field was determined (Figure 4).

4.2 Finite Element Analysis

Parallel to the experimental data a simplified FE-model of the crack tip surroundig region was developed and crack opening and shear loading was applied so that qualitatively similar displacement fields as in reality could be generated.

Figure 5 shows an example of the simulated displacement fields for a mode-I dominated configuration.

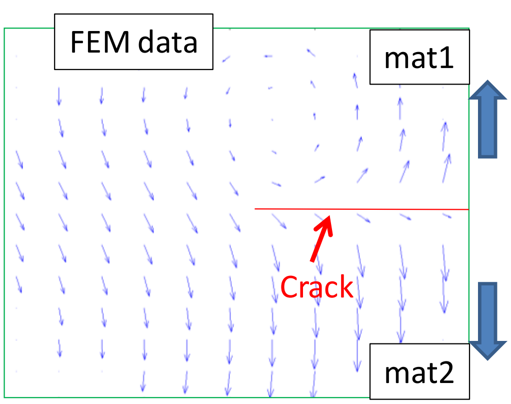

Figure 5: FE-results displacement vectors for a given mode-mix of opening and shear load (crack mode I and II)

4.3 Dislacement Field Comparison

Based on displacement field results from experiments and simulation a correlation based fitting algorithm was developed. . Correlation usually refers to the degree to which a linear predictive relationship exists between random variables, as measured by a correlation coefficient obtained from:

$$Corr(X,Y) = \frac{Cov(X,Y)}{\sqrt{Var(X) \cdot Var(Y)}} \tag{3}$$

where *X* refers to the displacement field determined by DIC (Figure 4) and *Y* refers to the field extracted from FE-analysis (Figure 5).

The algorithm virtually drags the finite element solution based displacement field data Figure 5 across the data from the experimental analysis so that the complete region of possible crack tip location is covered, Figure 6. At every point the FE data is dragged (Δx_i, Δy_j), the displacement values u_y are extrapolated to experimental data mesh points so that displacement data can be compared at the same *x*,*y* coordinates.

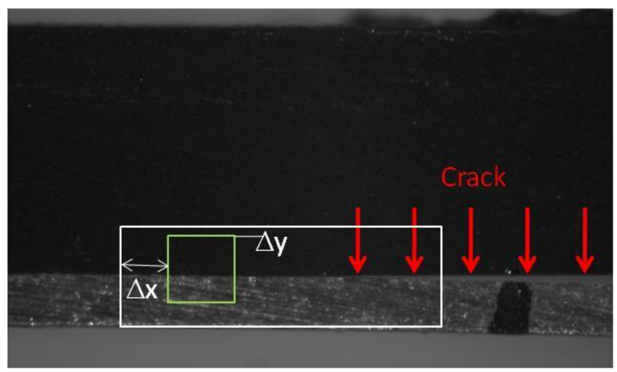

Figure 6: Method of dragging of search window (green) for the crack detection within expected crack tip region (white). The search window is a matrix with displacement data.

The comparison at each position (Δx_i, Δy_j), of the virtual path is carried out by calculating the correlation coefficient defined by eqn. 3. The crack tip position is obtained from the maximum value of the calculated correlation coefficients. For the presented example Figure 7 shows a complete set of determined correlation coefficients. The maximum value is marked with an arrow. This position is the point of best matching between experimental and simulative displacement data.

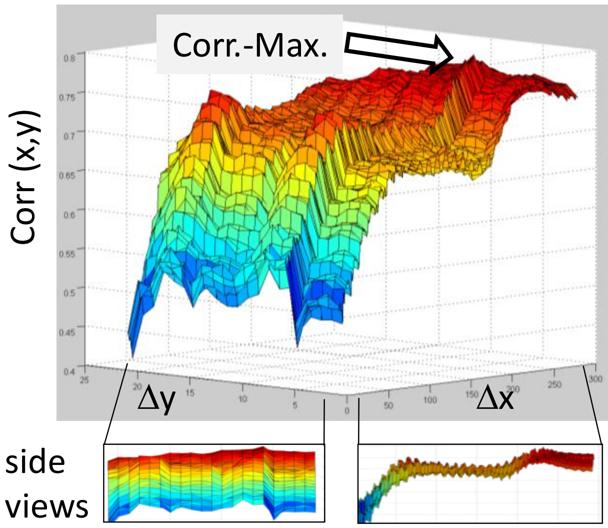

Figure 7: Correlation coefficient at different virtual crack tip positions. Maximum correlation indicates best matching of experimental and simulative displacement field data.

With the best matching position of the correlation the crack tip location can be extracted from known geometrical values of the complete testing setup. Finally the crack length of the specimen is determined by the presented method and FE analysis according to [11] will give the results for G_c as illustrated in Figure 1.

5 CONCLUSIONS

This paper demonstrates the applicability of Digital Image Correlation techniques for the crack tip detection at arbitrary sample geometries. By a correlation based comparison of displacement field data from experiment and simulation the crack tip can be identified and located. In the near future this method will be further verified and its accuracy will be defined.

6 ACKNOWLEDGEMENTS

We thank the European Commission for partial funding of this work in FP7 under project NanoInterface (NMP-2008-214371). The support of CWM Chemnitzer Werkstoffmechanik GmbH for the DIC analysis with VEDDAC correlation software is gratefully acknowledged.

REFERENCES

[1] H. Shirangi, B. Wunderle, O. Wittler, H. Walter, B. Michel, “Modeling Cure Shrinkage and Viscoelasticity to Enhance the Numerical Methods for Predicting Delamination in Semiconductor Packages”, Proc 10th EuroSimE, 2009, pp. 71-78

[2] Xiao, A., Schlottig, G., Pape, H., B. Wunderle, K. Jansen, and L. Ernst, “Delamination and Combined Compound Cracking of EMC-Copper Interfaces”, Proc 60th ECTC, 2010, pp. 114-120

[3] P. Lopez-Crespo et al., “The stress intensity of mixed mode cracks determined by digital image correlation”, J. Strain Analysis, 43, 2008, pp. 769-780

[4] S. Yoneyama et al: “Evaluating mixed-mode stress intensity factors from full-field displacement fields obtained by optical methods”, Engineering Fracture Mechanics, 74, 2007, pp. 1399-1412

[5] J. Keller, D. Vogel, A. Schubert, and B. Michel, “Displacement and strain field measurements from SPM images”, in B. Bhushan, H. Fuchs, and S. Hosaka, editors, Applied Scanning Probe Methods, pp. 253–276, Springer, 2004.

[6] G. Schlottig, I. Maus, H. Walter, K.M.B. Jansen, H. Pape, B. Wunderle, L.J. Ernst, „Interfacical Fracture Parameters of Silicon-to-Molding Compound”, Proc. 60th ECTC, Las Vegas, USA, June 1-4 2010

[7] J. Keller, I. Maus, G. Schlottig, H. Pape, B. Wunderle, B. Michel, “Interface fracture mechanics evaluation by correlation of experiment and simulation”, Proc. of Electronic System-Integration Technology Conf. (ESTC), 2010 3rd, Berlin, 2010.

[8] K.M. Liechti and Y.-S. Chai, “Biaxial loading experiments for determining interfacial fracture toughness”, Trans. ASME, 58:680–687, 1991.

[9] B. Wunderle, M. Schulz, J. Keller, G. Schlottig, I. Maus, D. May, O. Hölck, H. Pape, B. Michel, “Fracture-Mechanical Interface Characterisation for Thermo-Mechanical Co-Design – An Efficient and Comprehensive Method for Critical Mixed-Mode Data Extraction”, Proc. 61th ECTC, 2011

[10] L.J. Ernst, A. Xiao, B. Wunderle, K.M.B. Jansen, and H. Pape, “Interface Characterisation and Failure Modeling for Semiconductor Packages”, Proc. 10th EPTC, 2008.

[11] A. Agrawal and A.M. Karlsson, “Obtaining mode mixity for a biomaterial interface crack using the virtual crack closure technique,” Int. J. Fracture, pages 76–98, 2006.

[12] Dost, M.; Kieselstein, E. and Erb, R., “Displacement analysis by means of grey scale correlation at digitized images and image sequence evaluation for micro- and nanoscale applications”, Micromaterials and Nanomaterials (1), 2002, pp. 30-35.

[13] D. Vogel, A. Gollhardt, and B. Michel, “Micro- and nanomaterials characterization by image correlation methods”, Sensors and Actuators A: Physical, vol. 99, Apr. 2002, pp. 165–171.