Application of Moiré Interferometry to Determine Strain Fields and Debonding of Solder Joints in BGA Packages

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Abstract—Moiré interferometry (MI) has proven to be a very useful tool for testing the reliability of many different electronic packages. Historically, MI has been used for monotonic thermo-mechanical loading or steady-state conditions induced strain measurements but never for fatigue testing. Interface failure of microelectronics devices is a significant concern in packaging since it may cause a device to malfunction while in service. In this study, solder joint fatigue mechanisms, and their interfaces, are experimentally observed by means of a MI system. In addition, scanning electronic microscopy (SEM) was extensively utilized to support and document the MI observations. The combination of these two techniques and the robustness of the MI system is shown to be effective for the determination of the failure mechanisms of electronic packaging interfaces.

Index Terms—Fatigue test, interface reliability, microelectronic packaging, moiré interferometry.

I. INTRODUCTION

Driven by trends toward miniaturization and higher-levels of integration, the complexity of electronic packaging grows every day. High reliability of assembled components is critical to maintain final product quality. Ball grid array (BGA) and fine ball grid array (FBGA) packages are some of the most popular packaging choices in the microelectronics industry due to the ever shrinking device size and increasing need for input and output. These packages continue to be the technology of choice for both single and multi-chip module products.

The Pb/Sn eutectic solder alloy, which is highly studied and documented, is widely used as a joint material for BGA and FBGA. It is well known that the dominant failure mode for solder joints is low cycle thermal fatigue caused by mismatches of the coefficient of thermal expansion (CTE) of the joined component. Thermally induced stresses within a package can be attributed to heat dissipation of high power densities during device operation. Traditionally, the solder interconnects and interfaces have been evaluated in order to assess the overall reliability and integrity of the package in question.

Although many researchers have studied thermal cycling, until recently it was not possible to quantitatively measure thermal plastic strains in a package during cyclic fatigue testing. Due to their small size, traditional strain gauge technology for measuring strains cannot be used for electronic packaging.

Recently there has been an increasing interest in experimental analysis of solder joints and interfaces subjected to thermo-mechanical loading. A Moiré interferometry system developed in the UB Electronic Packaging Laboratory allows the recording of inelastic strain accumulations for cycled thermomechanical fatigue loading. Moiré interferometry provides whole field maps of in-plane deformation contours with sub-micron resolution. This technology also provides valuable information on both normal and induced shear strain deformation values. Such a capability is extremely useful for studying the thermo-mechanical behavior of electronic packaging structures. In this paper, the term MI system refers to the entire process of testing including but not limited to specimen preparation, optical diffraction grating replication, measurement process and digital signal processing. The inelastic strain accumulation behavior of the package can be used to evaluate the solder joint reliability of electronic package because inelastic deformation is directly related to fatigue life.

Historically Moiré interferometry has been used to measure the response to instantaneous and steady state temperature change and various material properties but not for solder joint fatigue testing [1]–[18], [20]–[22]. The Moiré interferometry technology developed at the University at Buffalo Electronic Packaging Laboratory allows measuring of the plastic strain field in a package during fatigue testing up to and including the failure point of the suspect area. The sensitivity of the...
technique is 0.417 μm/fringe. This experimental technique allows for easy determination of failure mechanisms and allows one to measure the plastic strain accumulation with micron accuracy. Furthermore, the technique can be used to determine the interfacial delamination point, along with the plastic strain field as a function of thermal cycles.

The temperature profile used in the study reported here is shown in Fig. 1, i.e., 0 °C to 100 °C with 15 min peak dwells and a 15 °C/min ramp. A Thermotron Super AGREE thermal chamber, which keeps a constant humidity of 60% during the thermal cycling and has a temperature control accuracy of ±1°C, was used as the environmental chamber. The test was performed on five production quality FBGA specimens, shown in Fig. 2, with each sample being thermally cycled up to 100 thermal cycles. Before cycling, the Moiré interferometry optical system was aligned for the initial field to ensure baseline accuracy. During the testing process, each sample was measured using Moiré interferometry after every 20 thermal cycles.

II. MOIRÉ INTERFEROMETRY

The MI system used in this study has been described in detail by Zhao et al. [20], [21]. The major advantage of MI is its high sensitivity, high resolution, and the whole field view of deformation distribution of the specimen surface. In this process, a cross-line optical diffraction grating with 1200 lines/mm is replicated on to the specimen surface. It is essential to ensure that the diffraction grating remains on the specimen through the end of the testing process. A technique has been developed to ensure this.

Specifically, the observed fringe pattern can be related to in-plane strains quantitatively as given by Post et al. [14]

\[ \varepsilon_x = \frac{\partial U}{\partial x} = \frac{1}{f} \left[ \frac{\partial N_x}{\partial x} \right] \]  
\[ \varepsilon_y = \frac{\partial V}{\partial y} = \frac{1}{f} \left[ \frac{\partial N_y}{\partial y} \right] \]  
\[ \gamma_{xy} = \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} = \frac{1}{f} \left[ \frac{\partial N_x}{\partial y} + \frac{\partial N_y}{\partial x} \right] \]

where \( N_x \) is the horizontal fringe order and \( N_y \) is the vertical fringe order and \( f \) is the virtual grating frequency. In this project, the grating frequency is \( 1/f = 0.417 \) μm.

The specific structure of the five FBGA packages studied in this work is shown in Fig. 2. The package has a typical sandwich structure. The component substrate is BT and the circuit board is a high Tg FR-4 substrate. The package size is 13 x 15 mm with 165 0.64 mm x 0.43 mm balls in the FBGA which has a 5.95 x 11.11 mm die attached. The solder balls are distributed evenly in 11 rows with 15 joints in each row. The separation between neighboring joints is about 0.3 mm. The exposed cross
section is on the ninth row. Eutectic solder joints constitute the FBGA which connects the die to the circuit board. In order to test the five samples in a consistent way, the sample boundary conditions should not vary from one temperature cycle to another for the same sample, and from one sample to another. Furthermore, any test should replicate the actual service condition (boundary conditions) as closely as possible. Based on these considerations, a special fixture was designed to hold the sample through the thermal cycling and Moiré analysis process. The fixture is shown at the bottom of the sample in Fig. 2(a).

The specimen preparation for the Moiré interferometry testing procedure follows similar steps as described in [20] and [21]. Specifically, the sample was cut through the center of a row of BGA solder joints utilizing a high-speed precision diamond blade saw. The exposed cross section is then polished, cleaned and dried. The optical diffraction grating replication procedure as described by Zhao et al. is followed to transfer a cross-line grating pattern onto the specimen cross-section.

Moiré interferometry is used to record the deformation field. Typical resulting Moiré fringe patterns are shown in Fig. 3(a)–(d) for the U-field and V-field respectively. The overall accuracy of this Moiré measurement relies on the proper establishment of the initial reference field. Moreover, the optical system is protected from any disturbance and adjustment during testing. In addition, a specimen position register is designed to ensure that the specimen always occupies the same optical space. A commercially available kinematic platform is modified to add the functionality as a position register as well as to serve as a specimen-positioning platform. Two translation stages are used to facilitate the adjustment of the initial position of the specimen on the optical table and to insure adequate error tolerance. To ensure the accuracy of the alignment and the specimen holder, the specimen was placed and removed numerous times and each time the same optical null field was obtained. The initial null field fringes resulted from the imprecise location of the pin in the holding fixture. The presence of these initial fringes does not affect the results of this study.

Some typical fringes from the tests are shown in Fig. 3.

III. Strains Analysis

Using the strain-fringe relations, given by (1)–(3), strain can be calculated. For example, if the horizontal separation between two adjacent fringes is 400 μm in the U-field, the corresponding axial strain is \( \varepsilon_x = 0.417 \cdot \frac{1}{400} = 1.0425 \times 10^{-3} \). Similarly, the vertical distance between two adjacent fringes in the V-field determines the peeling strain, and the summation of horizontal fringe pitch in the V-field and vertical fringe pitch in the U-field determine the shear strain. The thermally induced strains are the
Fig. 4. Arithmetical averages of strains for the five specimens tested.

Fig. 4(a)–(c) show inelastic axial, peeling and shear strain accumulation as a function of the number of thermal cycles for solder balls one to eight, respectively. Fig. 4(d)–(f) show inelastic axial, peeling and shear strain accumulation for each solder joint after 20 cycles and 100 cycles.

From Fig. 4(d)–(f) it is obvious that the strain distribution curves at 20 cycles and 100 cycles are quite different, which indicates that there is a formidable stress release in some of the solder joints due to interface failure. If there was not an interface (copper pad-PWB) failure the factors affecting the distribution of the stress and strain in the solder joints would show their influence at the very beginning and usually persist through the joint fatigue life [20], [21]. The general trend shown in Fig. 4(a)–(c) is similar to earlier findings reported by Zhao et al. [20], [21], which indicates that the plastic strain in the solder joint increases in the first forty cycles rapidly but then levels off and increases very slowly beyond that. This is probably due to the fact that Pb/Sn is a microstructurally evolving material [19], [23], [24]. It is obvious that the strain distribution curves at 20 cycles and 100 cycles have very similar shapes, which indicates a similar distribution trend. Testing, if properly designed and conducted, should not alter such trends significantly enough to influence results. As the Pb/Sn alloy is cast it becomes a thermodynamically unstable material in a classic eutectic structure. With thermal cycling it evolves into a stable equiaxed grain structure which continually coarsens. The coarsening process allows the solder to become more resistant to creep and plastic deformations. Therefore, after forty cycles the gradient of plastic strain increments reduces significantly, albeit plastic strain continues to increase as cyclic loading continues. The observed behavior violates the traditional Coffin–Manson fatigue model, where it is assumed that plastic strain experienced in each cycle is constant. Therefore, eutectic solder con-
Fig. 5. Some representative fringe fields after 60 thermal cycles (a) specimen 1, cycle 60, U-field, (b) specimen 2, cycle 60, U-field, (c) specimen 3, cycle 60, U-field, (d) specimen 4, cycle 60, U-field, and (e) specimen 5, cycle 60, U-field.

 Constitutive models based on Coffin–Manson calculations typically underestimate fatigue life of BGA solder balls [20], [21], [25].

 The observed strain distribution shows that the maximum stress is experienced at the free edge solder joint or the maximum distance from neutral point (DNP). As you move toward the middle of package the stress is reduced. The plastic strain distribution usually follows the stress distribution, hence the largest plastic strain is experienced at the free edge solder joint. Fig. 4(a) indicates that the plastic strain increases in solder joint number 1 up to the 60th cycle and at the 80th cycle plastic shear strain and axial strain is smaller than at the 60th cycle. This indicates that there is stress relaxation in the solder joint, possibly due to a crack initiation at the copper pad-PWB interface. This observation is also reinforced by the observed fringe field patterns. Specifically, it was observed that the change in shear strain and axial strain from 20 cycles to 100 cycles was negligible, on the other hand increase in peeling strain is significant. This is a good indicator for a delamination point. A close inspec-
tion of the fringe fields indicates that at the 60th cycle and beyond, fringes become discontinuous at the solder joint number 1, see Fig. 5. If one looks at the initial fringes it is easy to see that fringes are continuous across the solder joints, see Fig. 3(a) and (b). After thermal cycling fringes are no longer continuous across the solder joints near the free edge. This indicates that there is a physical discontinuity between the solder and joined layers. Moiré fringes can be thought of in a similar manner to an electrical potential field, they must be continuous unless there is a discontinuity. If there were not a discontinuity, the fringes would be continuous across a solid medium. The initial fringe fields effectively demonstrate this since there is a very small initial strain induced during the curing of the optical diffraction grating and due to boundary conditions. If the bond between the solder bump and the joined layers remained continuous the Moiré fringes would also remain continuous across the interfaces. However, the intensity of the fringes would increase in the solder joints, due to CTE mismatch or boundary conditions.

This study demonstrates that often in new generation electronic packages the interface delamination point of the interface is not always known prior to testing due to heterogeneity of the system and the initial defects due to manufacturing or defects in solder bumps and interfaces. The whole field optical fringe field approach detects any initiation of interface delamination immediately with great accuracy. This accuracy is 0.417 μm as defined by the frequency of the applied diffraction grating.

The average inelastic strain value at the end of 100 cycles is rather small in these packages. This is due to the proximity of the CTE between the bonded PCB layers and due to the weak bond between the solder pad and the upper PCB. An SEM picture, Fig. 6, indicates that the bond between the upper PCB and copper pad becomes debonded after thermal cycling, which greatly reduces the shear stresses on the solder joints. This latter observation was consistent among all solder bumps that experienced interfacial delamination. Fig. 4(d) and (f) show that these solder joints did not experience any increase in additional shear and axial plastic strain due to the additional thermal cycling conditions. However, it is also true that where there was no interfacial delamination, inelastic shear and inelastic axial strain continued to increase. Once the interfacial delamination starts the solder ball starts to experience stress relaxation. Therefore, strain values are very consistent among all visible solder joints. Also extensively documented is the fact that the intermetallics are usually much stronger than materials they interconnect with. Fig. 6(a) shows the initial SEM picture of the first solder bump of specimen one. Fig. 6(b), is a SEM picture of the same solder after 100 thermal cycles indicating a debonding at this interface as pinpointed with the elliptical circles. These SEM pictures are in excellent agreement with, and provide additional support for the strain data obtained from MI test. Note that the size of this image is 600 μm x 500 μm, and thus the corresponding thickness of the void due to delamination is ≈ 7 μm.

IV. CONCLUSION

A Moiré interferometry technique was used to study fatigue reliability of electronic packaging interfaces.

Solder joints in the packages exhibited classic BGA solder ball thermo-mechanical response. All strains in the solder joints were very small due to minimal CTE mismatch between the joined PCBs and the bonding failure and the subsequent crack initiation between the top copper pad and the top PCB layer. Because of the small creep strain levels, no failure was observed in any solder joint. It is not possible to determine the number of cycles to failure after the solder joint separates from one of the PCB layers.

The Moiré interferometry measurements are supported by scanning electron microscopy observations, which were also used to study failures that occurred in the interface between the upper pad and PCB layer. We suspect that failure is probably due to the imperfect initial bond between the component pad and the BT layer or the imperfect initial bond between the copper pad and PCB, which is bonded by a resin epoxy and appears to be one of the weaker points in the package. Any solder ball that is not properly bounded to its associated copper pad will not develop any strain when subjected to thermal cycles. All other bonded joints will develop and exhibit strain. As a result, we can pinpoint the defective ball by the lack of fringes on that ball.

The temperature profile used in this testing is much higher than a typical service use environment, which also may have accelerated this interface degradation. Therefore, even if there is not a major problem with in-field failures, the partially bonded interfaces usually lead to reduced electrical performance primarily due to high electrical resistance at the interface.
Consequently, being able to detect interface delamination with great accuracy, utilizing this advanced technology can be a valuable asset for microelectronic packaging designers and reliability engineers.

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REFERENCES


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William Casey, photograph and biography not available at the time of publication.