FAILURE ANALYSIS AND ASSEMBLY PROCESS SIMULATION OF PACKAGE-ON-PACKAGE (POP) MODULE

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ABSTRACT
With the never ending drive for smaller, lighter and more advanced features on handheld products, Package on Package (PoP) assembly that integrates logic die in the bottom package and memory die in the top package into a single 3D package is one of the most promising solutions to enable these requirements. However, there are still some challenges to assuring mounting reliability and yield for PoP module during manufacturing processes.

In this paper, both failure analysis and finite element analysis (FEA) were utilized to study the thermally-induced yield loss for POP modules. Failure analysis involves a serial of tests: X-Ray inspection, microsectioning and SEM analysis, package warpage measurement, etc. FEA was conducted to analysis the package warpage evolution and stress/strain evolution behavior of the PoP module during the full assembly process from the package molding to module reflow. Finite element techniques such as element birth and death as well as restart were used to transfer the values of stress and warpage from one process to the next.

The results show that the thermally-induced warpage is an important manufacturing risk and a yield detractor in the fabrication process of mobile electrical products. For the failure PoP module samples in this paper, the top and bottom packages exhibited different warpage evolution behaviors during reflow process and the maximum deformation difference happened at the peak temperature (260℃). And there was mainly tensile stress in the top solder joints and compressional stress in the bottom ones during assembly process. This significant thermal-induced deformation and stress were the main cause of the soldering defects, such as solder incomplete fusion and cracks in solder joints, especially for the top layer. The FEA result was consistent with experimental observation and result. The developed FEA model in this paper can be used to do further parametric studies to optimize the package structure design and help material selection for improving the PoP module reliability.

Key words: failure analysis, package warpage, PoP module, FEA, assembly process

INTRODUCTION
Current portable elctronic products are driving component packaging towards three-dimensional (3D) packaging technologies for integrating multiple memory die and application processors [1]. As a increasingly promising mainstream package technology, PoP packaging has good flexibility of combination and sourcing, which makes lower assembly costs and facilitates flexible design and product upgrading for electronic terminal equipments [2].

The major advantage of PoP packaging is that the top and bottom packages can be tested individually before they are assembled. The yield loss of the whole PoP module can be reduced significantly. However, due to the coefficient of thermal expansion (CTE) mismatch ae well as stiffness mismathe exist among substrate, molding compound (MC) and the silicon die stack, warpages on both top and bottom packages are often observed. Large warpage could cause solder joint open failure and substrate delamination, leading to the electrical connection failure of the assembled PoP module.

There are three approaches can be used to solve the assembly yield loss for PoP module: package design, material selection and process optimization [3, 4, 5]. Assembly failure analysis for PoP module is useful to find out the root cause of related failure modes, thus corresponding improvement measures can be put forward, which has very important theoretical and practical significance, for revealing failure mechanism as well as improving assembly yield.

Actually, the failure of PoP module is a complex thermal-mechanical induced degtadation process, which is attributed to the mismatch in thermal expansion coefficient of the different device constitutive materials. Therefore, it is important to study the stress/strain evolution behavior of PoP solder joints during package/assembly process. In addtion, more attention should be paid to the experimental analysis technologies.

To address these problems, both experimental work and FEA tool were utilized in this study. A serial of experimental analysis technologies were used to obtain the informations such as solder joints' microstructure, distribution of failure solder joints, cracks, voids, package warpage, etc., which deduced the main failure modes for the PoP module. On the other hand, finite element simulation was conducted to analysis the stress/strain evolution behavior of the PoP module during the full assembly process from the package molding to module reflow. This work made a thorough analysis on the root causes of related failure modes, and some relevant failure mechanisms were revealed for PoP module.

TESTS AND FAILURE ANALYSIS

Sample Discription

The test samples used for this research were some failure modules from downline products of board level assembly field for mobile electrical products, which contained PoP modules. The failure phenomenon was manifested as that the corresponding whole machine's monitor could not display images, and the malfuncion rate reached about 20% of the whole yield in the same manufacturing lot.

Failure analysis was performed for these failure samples, and some packages with the same production batch with the PoP modules were used for assistant analysis, as shown in Figure 1.

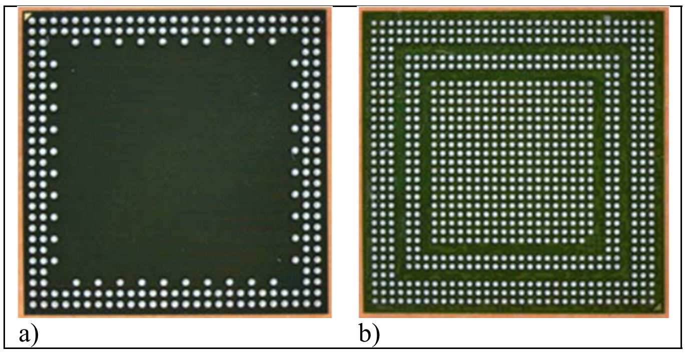

Figure 1. Representative View of Package Samples
a) top package; b) bottom package

X-Ray Inspection

X-ray inspection was conducted to boserve the PoP solder joints in the failure module samples. Some morphological abnormalities were found in the top layer joints, which was like head in pillow (HIP) morphology, marked as red dotted box, especially for the edge position of the package, as shown in Figure 2.

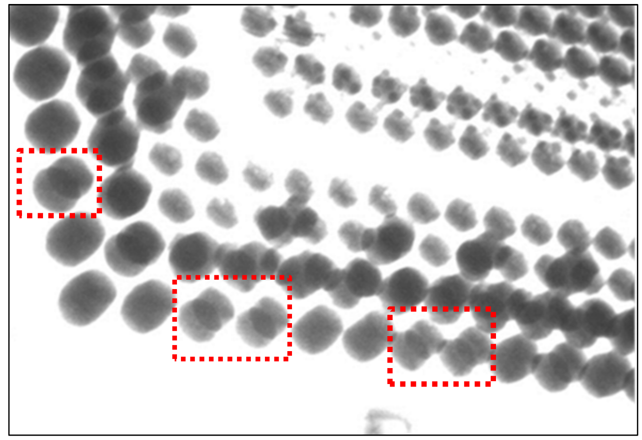

Figure 2. Representative Views of X-ray Inspection for the PoP Solder Joints

Microsectioning and SEM Analysis

Microsectioning and scanning electron microscopy (SEM) were used to further identify the failure modes of the solder joints, which had abnormal morphology under the X-ray observation. The representative cross-sectional views of the solder joints, lying in the BGA's periphery, are as shown in in Figure 3 to Figure 5.

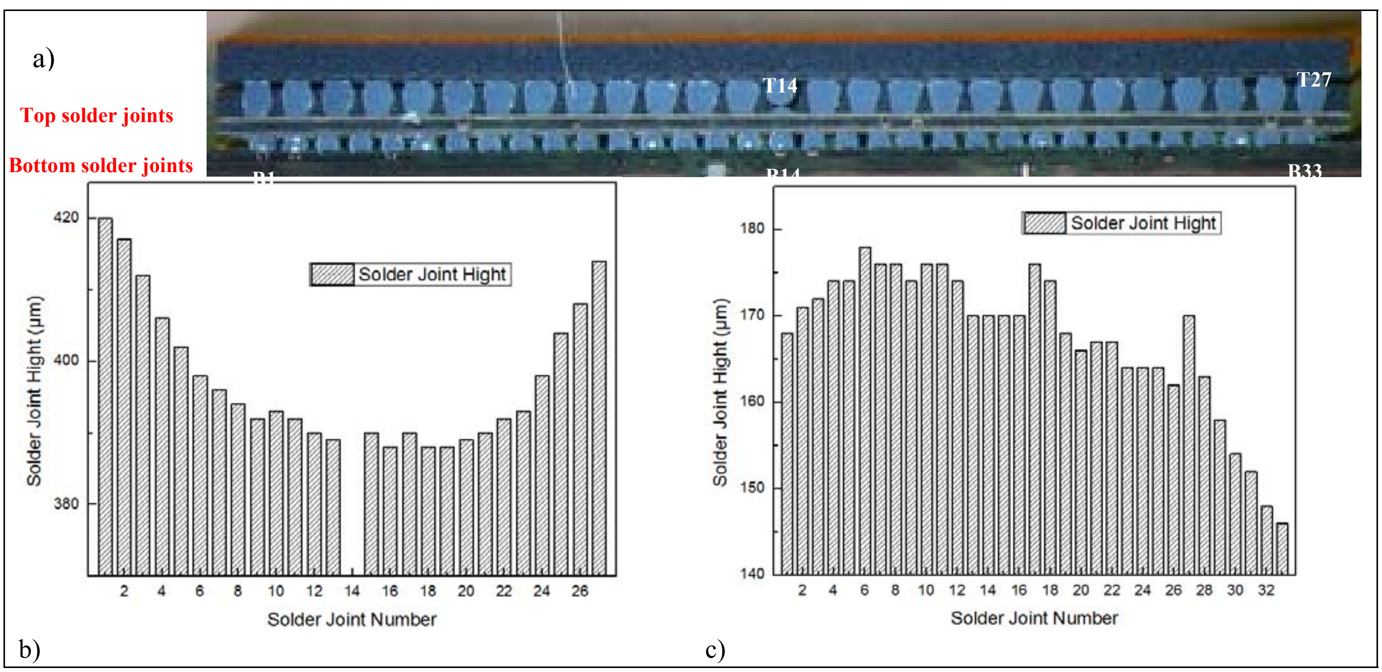

Figure 3. Representative Cross-sectional View of PoP Solder Joints and the Measured Height Data
a) representative cross-sectional view; b) top solder joints' height distribution; c) bottom solder joints' height distribution

Figure 3 shows the representative cross-sectional view of PoP solder joints. Solder joints lied in two different layers, named as top solder joints (nubered as T1~T27) and bottom solder joints (numbered as B1~B33). The height of the middle solder joints was smaller than that of the other regimes for the top layer, while for the bottom layer, the height data showed a opposite trend, as shown in Figure 3b and Figure 3c. This results indicated that the top and bottom pakages had warping deformation coresspondly. The warpage of the top package was concave shaped, while the other was convex shaped.

Figure 4 details the micromorphology of some representative solder joints in the top layer. Soldering defect of incomplete fusion was found in the midle solder joint (marked as T14) , which could present as HIP morphology under X-ray inspection (as shown in Figure 2). The distance of top and bottom pads was about 300µm for S14, which was far smaller than that of T27. Moreover, as shown in Figure 4b and Figure 4d, there was uniformly continuous intermetallic compound (IMC) layers growing on the top and bottom interconect interfaces of the solder joints, and the IMC thicknesses were 2~5µm, which could generally rule out the possibility of that heat shortage during reflow resulted in incomplete fusion defect.

In additon, cracks were found in corner solder joints of the bottom layer, which was related to the thermal stress during reflow. The large pakage warpage and the coefficient of thermal expansion (CTE) mismatch between the materials in the module were the main stress sources. And the large voids in the solder joint could enhance the stress' effect, as shown in Figure 5b.

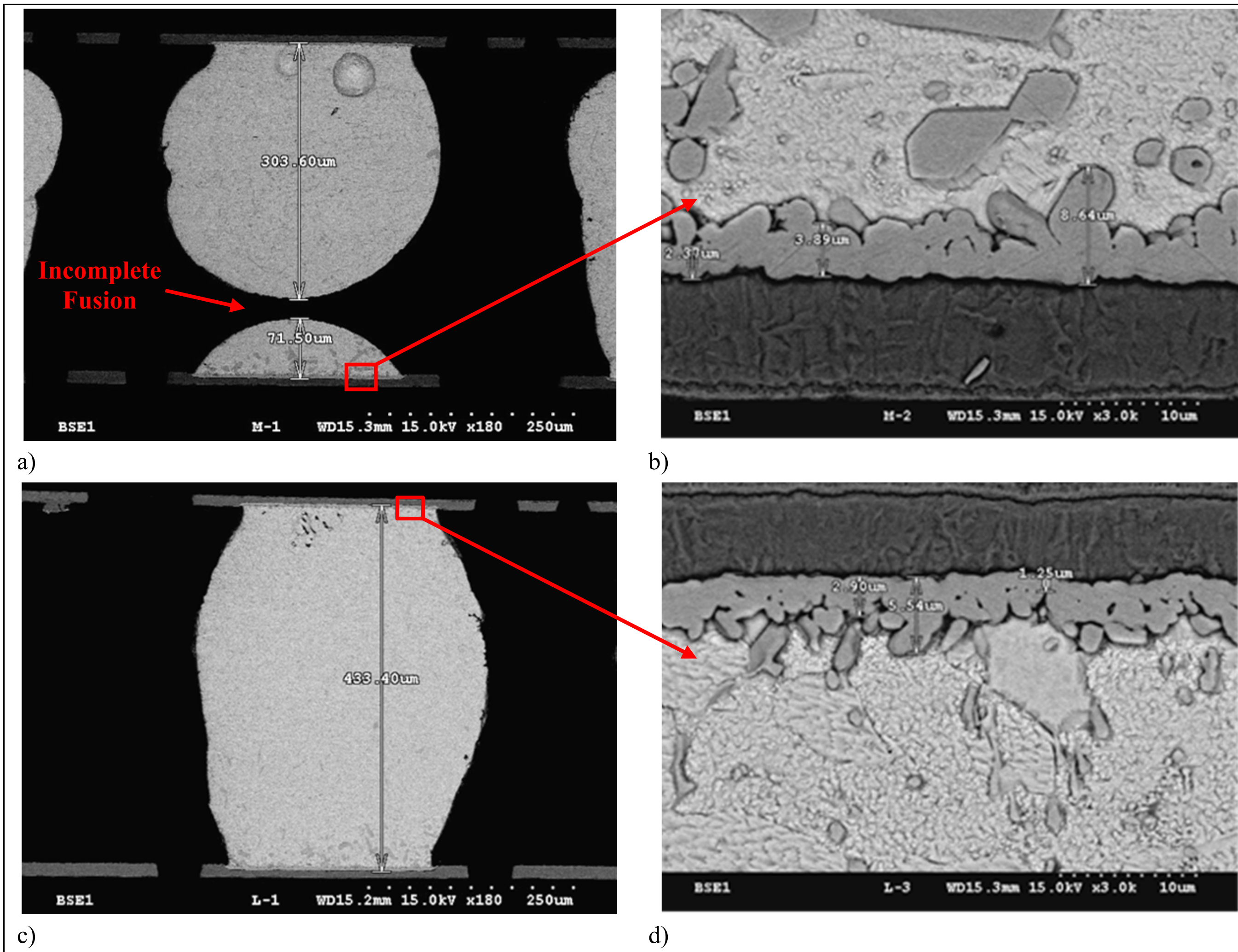

Figure 4. Micromorphology of Some Representative Solder Joints in the Top Layer
a) solder joint T14; b) micromorphology of PCB pad/ solder interfacial zone in T14; c) solder joint T27; d) micromorphology of chip pad/ solder interfacial zone in T27

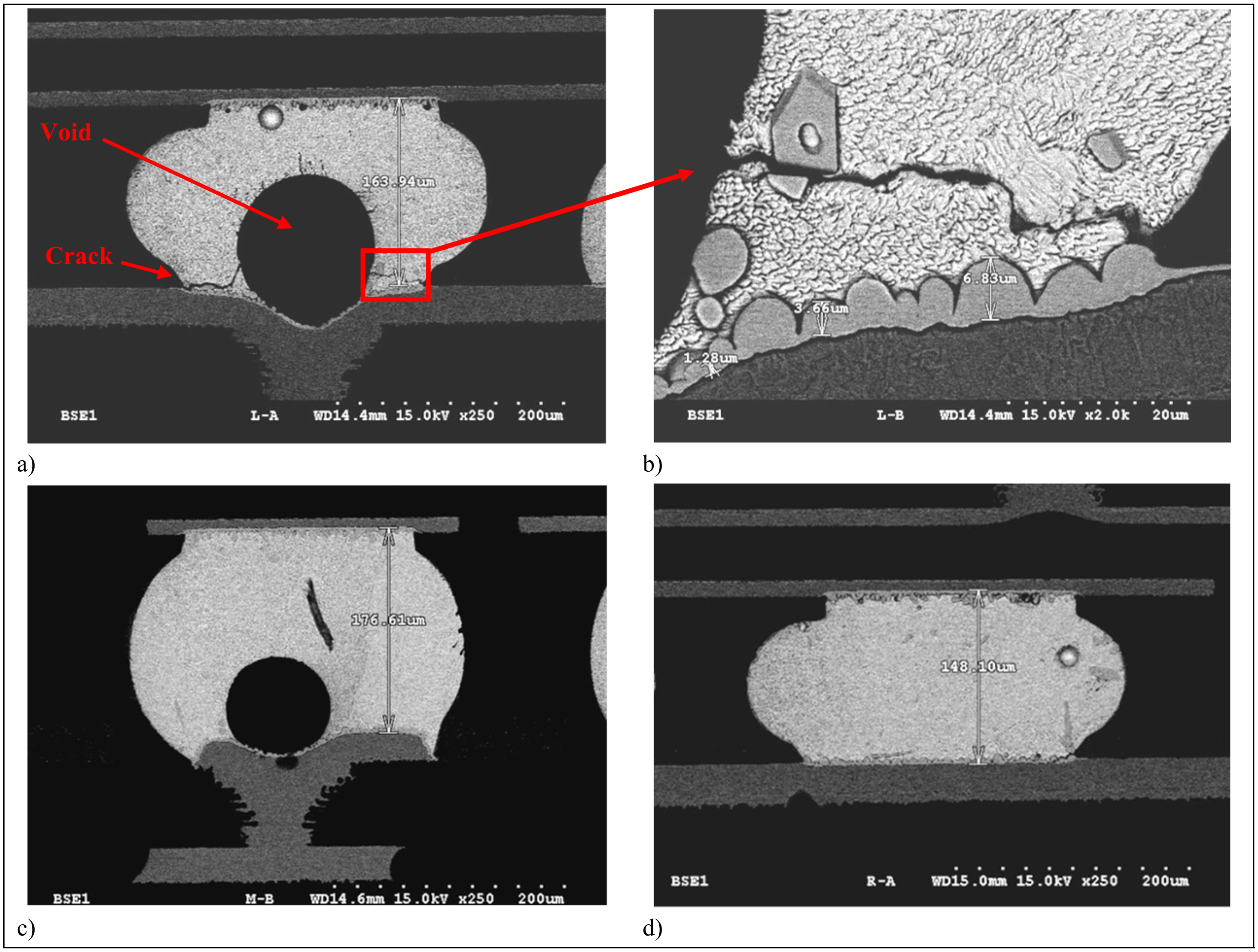

Figure 5. Micromorphology of Some Representative Solder Joints in the Bottom Layer
a) solder joint B1; b) crack near a large void; c) solder joint B17; d) solder joint B33

Package Warpage Measurement

In order to identify the effect of packags' thermal deformation, warpage measurement for top and bottom packages was conducted by thermal shadow moiré method according to JESD 22B112 [6]. Figure 6 shows the setting reflow profile.

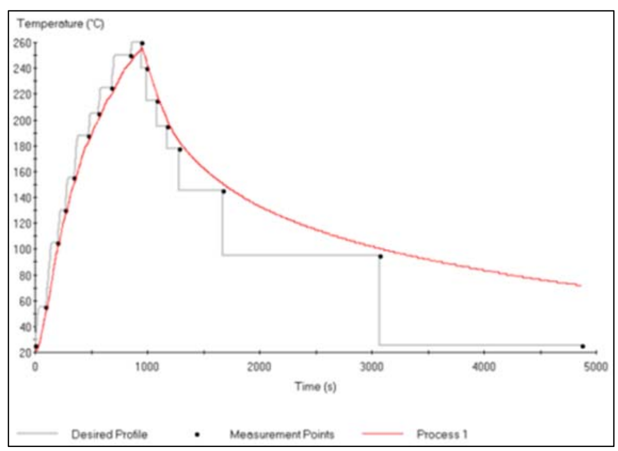

Figure 6. Plot of Package Body Temperature vs Time

According to JEITA ED-7306 [7], the solder balls in the packages (as shown in Figure 1) were removed before the thermal shadow moiré test. The warpage direction definition is shown in Figure 7. Looking at the side of the package with the solder balls facing down, the concave shape was defined as smiling warpage and the convex shape was defined as crying warpage. The data of concave shape warpage was negative value and data of convex shape warpage was positive one. Figure 8 shows the representative evolution curve of package warpage versus reflow temperature for the package samples.

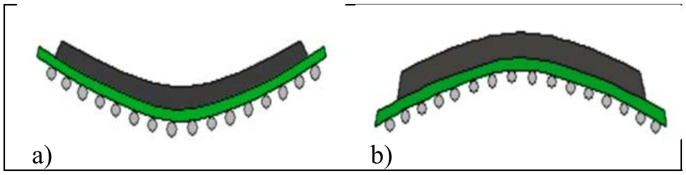

Figure 7. Definition of Package Warpage
a) concave shape (“-”); b) convex shape (“+”)

As shown in Figure 8, the top and bottom packages exhibited different warpage evolution behavior during reflow process. The maximum deformation difference happened at the peak temperature (260℃), where the top package warpage reached the extremum negative value (-228μm) and the bottom package reached the extremum positive one (+200μm). Figure 9 shows the 3D thermo-moiré plots at the peak temperature, as that the top package was smiling shaped and the bottom package was crying shaped. This remarkable deformation difference in PoP module would cause high thermal stress in the corner region, resulting in soldering defects such as solder incomplete fusion and cracks in solder joints, especially for the top layer.

In addition, there was initial warpages for the packages before the thermal shadow moiré test. They might correspond to the residual deformation after molding process for the packages, which could influent the coplanarity of the BGA components.

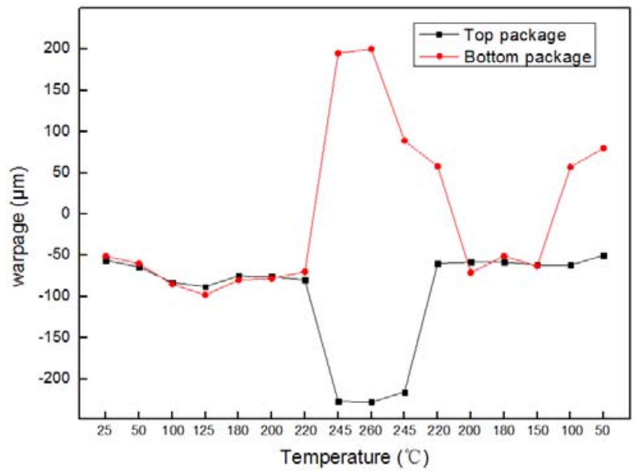

Figure 8. Test Results of Warpage Measurement for Top and Bottom Packages

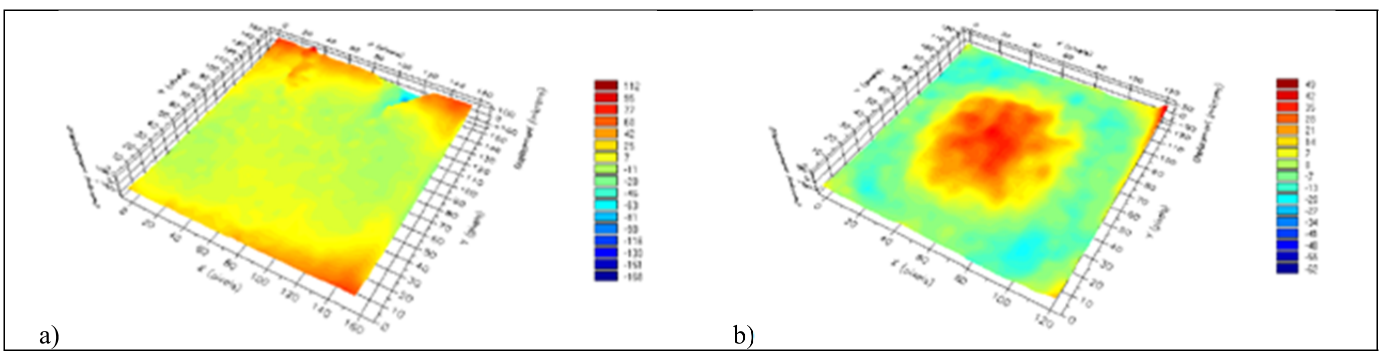

Figure 9. Representative 3D Thermo-moiré Plots at the Temperature of 260℃
a) top package; b) bottom package

FINITE ELEMENT MODELING ANALYSIS

Finite Element Model

The PoP module structure scheme for the test sample above is shown in Figure 10. The package in the sample consisted of four main structures, the substrate, the molding compound (MC), the silicon die stack and solder balls. There were four dies (named as die1, die2, die3 and die4, respectively, from top to bottom) stacking in the top package and one die (named die5) in bottom package. The top package, bottom package, and PCB board were connected together by the solder ball arrays after reflow soldering. Finite element analysis was performed to analyze the warpage and stress/strain evolution behavior of the PoP module during the full assembly process from the package molding to module reflow.

Considering the structural symmetry of the PoP module, a 3D octant finite element model for the testing sample was built up, as shown in Figure 11. There were some assumptions in this model as below: (a) the effect of the copper wires in the module was ignored; (b) all material interfaces have perfect adhesion; (c) temperature load was applied on the whole model homogeneously.

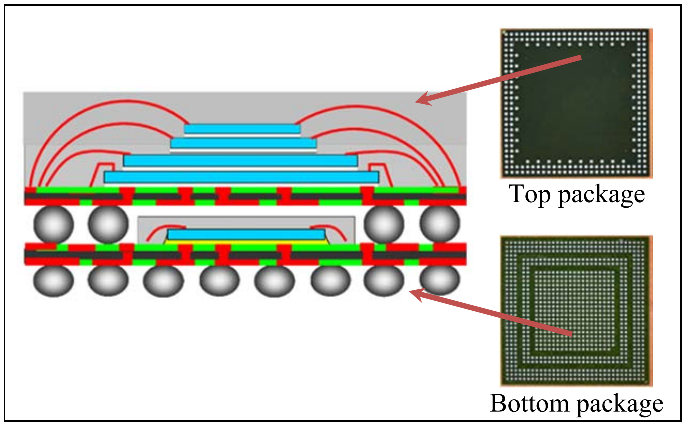

Figure 10. PoP Module Model Structure

There were some boundary conditions applied on the model during analysis process. The symmetric boundary condition was applied in the symmetry plane, the vertical degree of freedom (DOF) of the substrate was constrained, and the center of substrate was fixed.

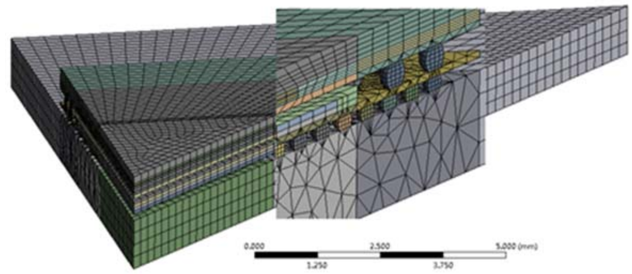

Figure 11. Finite Element Model for PoP on Board Level Assembly

Loading Procedure

To implement the whole process simulation, two difficulties should be overcome. One difficulty existed in the simulation of MC curing process, because MC curing was a chemical reaction and existing commercial FEA software could not handle the simulation of chemical reaction. The other difficulty was to link all the manufacturing processes seamlessly to ensure the deformation variance and stress evolution continuous.

To address above problems, this work used some novel FEA techniques. First, the temperature effect on materials' property and MC shrinkage was considered during model building. Table 1 and Table 2 illustrate the materials' properties used in the simulations of molding process and reflow soldering process, respectively. Second, finite element technologies such as element birth and death as well as restart were used to link the manufacturing processes. Figure 12 shows the simplified temperature loading profile for the whole manufacturing process. Figure 13 illustrates the corresponding simulation steps.

Table 1. Temperature-dependent Material Properties Used for the Modeling of Molding Process [8]

Materials	Elastic Modulus (GPa)	Poisson's Ratio	CTE (ppm/^{o}C)
Substrate	17@25℃ 15@125℃	0.25	20 (xy plane) 80 (z)
Die-attach Film	4.8@25℃ 0.01@100℃ 0.005@200℃	0.4	245@25℃ 300@100℃ 300@125℃
Die	130@25℃ 129@125℃	0.3	3@25℃ 3.5@152℃
MC	21@25℃ 3@125℃ 2@174℃ 0.01@175℃	0.25	17@25℃ 25@125℃ 35@144℃ 35@175℃

Table 2. Temperature-dependent Material Properties Used for the Modeling of Reflow Process [9, 10]

Materials	Elastic Modulus (GPa)	Poisson's Ratio	CTE (ppm/^{o}C)
Substrate	17@25℃ 15@125℃	0.25	20 (xy plane) 80 (z)
Die-attach Film	4.8@25℃ 0.01@100℃ 0.005@200℃	0.4	245@25℃ 300@100℃ 300@125℃
Die	130@25℃ 129@125℃	0.3	3@25℃ 3.5@152℃
MC	21@25℃ 12@125℃ 0.5@183℃ 0.5@260℃	0.25	17@25℃ 25@125℃ 35@200℃ 50@260℃
Solder balls	21@25℃ 3@125℃ 2@174℃	0.37	24
PCB	66@25℃ 68@100℃ 48@140℃ 34@220℃	0.28	13@25℃ 14@47℃ 32@130℃ 74@220℃

Note: The properties of MC in reflow process was different from that in molding process.

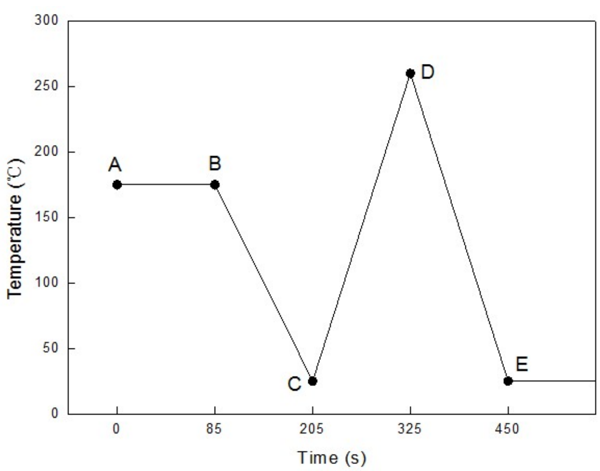

Figure 12. Temperature Loading Profile for the Whole Manufacturing Process

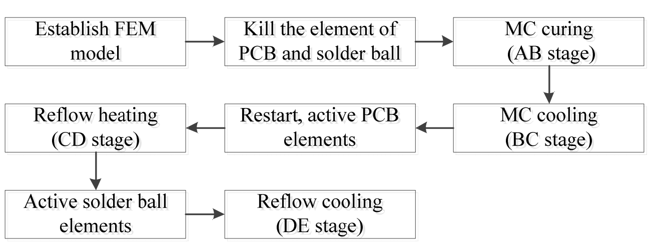

Figure 13. Simulation Steps Corresponding to Figure 12

PoP Module Warpage and Stress Analysis

The warpages of the top and the bottom packages are presented in Figure 14. During the whole process, the warpages of both packages were constantly changing. In the MC molding process (BC stage), the top package was convex shaped, its warpage was 40um after molding; the bottom package was concave shaped, its warpage was -33um after molding. Figure 15 shows the warpage patterns after MC molding for the packages.

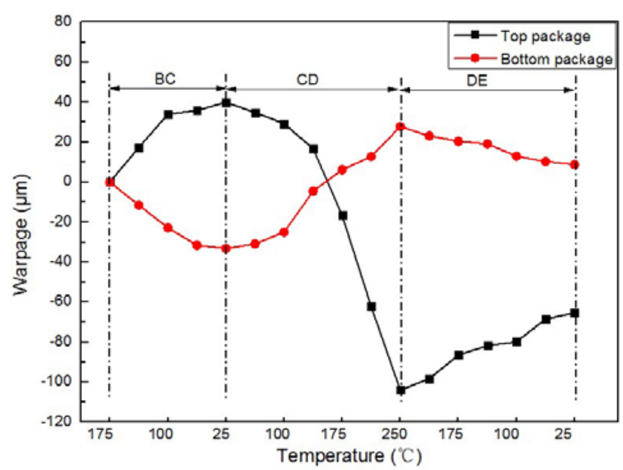

Figure 14. Warpage Value Evolution during the Whole Process.

In reflow process (the CD stage and DE stage), the top package deformed from convex to concave, the maximum warpage value reached -104μm at the peak temperature (260^{o}C). The bottom package deformed from concave to convex. Figure 16 shows the warpage patterns at the peak temperature of reflow for the packages. The warpage difference between the top and bottom packages as well as the PCB may lead failure of the corner solder joints.

Moreover, it can be conclude from Figures 8, 9, 14 and 16 that the simulation results matched well with the measurement results, indicating the technique of seamless packaging process simulation was theoretically reasonable for this work.

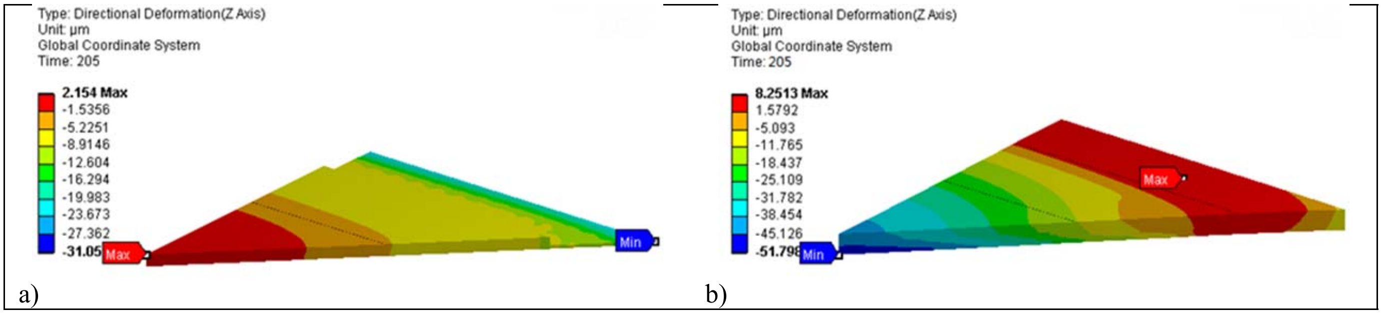

Figure 15 Warpage Patterns after MC Molding for the Packages, a) top package: convex, b) bottom package: concave

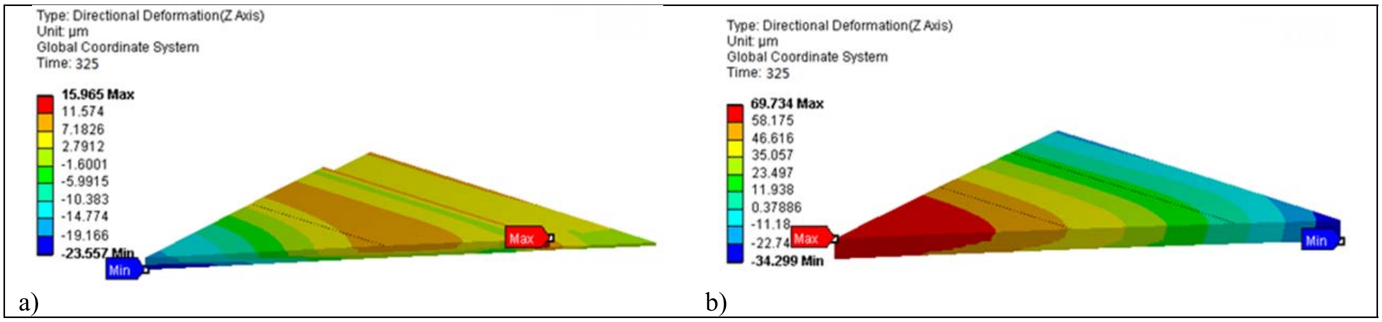

Figure 16. Warpage Patterns at the Reflow Peak Temperature, a) top package: concave; b) bottome package: convex

Figure 17 shows the time histories of die stresses, in which the die 4 and die 5 had larger stress. At the peak temperature of reflow (325s), the stress in die 4 reached the maximum value 321MPa. There was residual stress in the dies after reflow process, in which the die5 has the largest value.

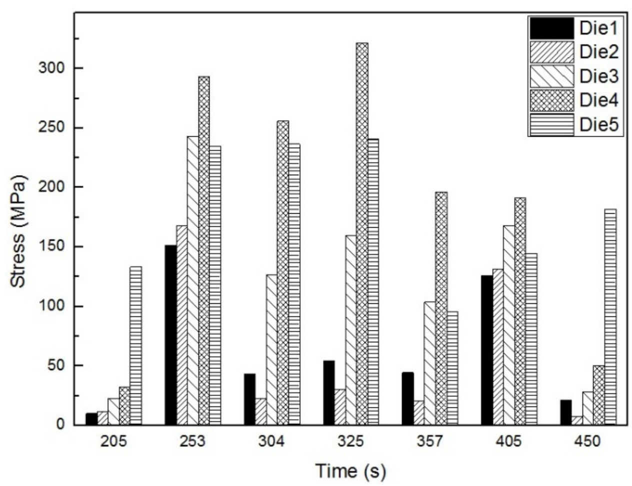

Figure 17. Stress Evolution in Dies during Reflow Process

As the difference in warpage patterns, there was tensile stress remained in the top solder joints and compressional stress remained in the bottom ones after reflow. Figure 18 shows the stress distribution in solder joints after the reflow process. It can be found that the value of stress in bottom solder joints was larger than that of top ones. The maximum stress existed in the bottom corner solder joint, the value of which was 38MPa. This significant thermal stress may result in cracks in corner solder joints, as shown in Figure 5a.

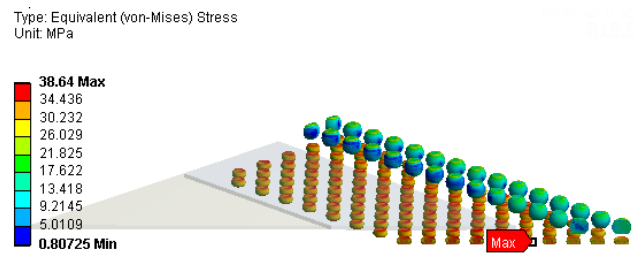

Figure 18. Stress Contour for Solder Joints after Reflow

As the stress and warpage are caused by thermal mismatch of different material in the PoP module under temperature loading, they can be reduced by choosing appropriate materials and by optimizing structure size.

CONCLUSION

The thermally-induced warpage is an important manufacturing risk and a yield detractor in the fabrication process of mobile electrical products.

Failure analysis is an effective tool to find out the root cause of related failure modes for PoP module, which involves a serial of tests: X-Ray inspection, microsectioning and SEM analysis, package warpage measurement, etc. For the failure PoP samples in this paper, the failure analysis results show that the top and bottom packages exhibited different warpage evolution behavior during reflow process and the maximum deformation difference happened at the peak temperature (260 ℃). This remarkable deformation difference is the main cause of the soldering defects, such as solder incomplete fusion and cracks in solder joints, especially for the top layer. In addition, there was initial warpages for the packages before assembly, which corresponds to the residual deformation after molding process for the packages and will influent the coplanarity of the BGA components.

Following the failure analysis tests, finite element simulation was conducted to analysis the stress/strain evolution behavior of the PoP module during the full assembly process from the package molding to module reflow. Finite element techniques such as element birth and death as well as restart were used to transfer the values of stress and warpage from one process to the next. The warpages of both packages constantly changed during the whole process and presented difference patterns. And there was mainly tensile stress in the top solder joints and compressional stress in the bottom ones. This significant thermal-induced stress would result in cracks in corner solder joints.

The FEA result was consistent with experimental observation and result. The developed FEA model in this paper can be used to do further parametric studies to optimize the package structure design and help material selection for improving PoP module reliability. This work will be presented in next step for our research project.

ACKNOWLEDGEMENTS
This study was partially supported by the Fund Project of Chongqing Science & Technology Commission under Grant No. cstc2016jcyjA0303, and Guangdong Province Public Welfare Research and Capacity Building Special Fund Project under Grant No. 2015A030401022, which were acknowledged.

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