The Application of Two-Dimensional X-ray Hot Stage in Flip Chip Package Failure Analysis

Yan Li, Rahul Panat, Bin Li, Rose Mulligan, Purushotham Kaushik Muthur Srinath, and Arun Raman

***Abstract*—Advancement of silicon and packaging technologies toward lower power and higher functionality requires better understanding between materials and process interactions. This paper illustrates the applications of 2-D X-ray metrology incorporated with a hot stage system for the first time in the literature, which allows one to simulate heating profiles of up to 300°C and observe the behavior of materials *in situ* within the packages. Three case studies are discussed: 1) segregation of metal particles in the next-generation thermal interface material, leading to corner thermal resistance (Rjc) degradation; (2) first level interconnect (FLI) solder bump bridging during chip attach of a large die server package with high substrate die area warpage in which limits of the die area substrate warpage need to be set in order to avoid FLI solder bump bridging during the chip attach solder reflow process; and 3) second level interconnect solder joint bridging at the surface mounting process of a large die package attached with an integrated heat spreader. By being able to study failures *in situ* at high temperatures, a new dimension to the package failure analysis is presented in this paper.**

***Index Terms*—*In situ* high-temperature 2-D X-ray, next-generation thermal interface material (NG-TIM), package failure analysis, solder joint bridging.**

I. INTRODUCTION

A FLIP CHIP microprocessor package consists of different layers of materials such as Cu integrated heat spreader (IHS) or lid, Si die, epoxy underfill, and an organic substrate made of many layers (see Fig. 1). Packages are assembled at high temperatures due to soldering processes involved in the first level interconnect (FLI) and second level interconnect (SLI) as well as the component attach. For lead-free and halogen-free packages, the soldering temperatures can go as high as 260°C [1]. Due to high temperatures involved in the assembly, the differential thermal expansion coefficients of the various package constituents can give rise to stresses in the package and result in warpage [2]. For example, in certain flip chip packages, a room temperature convex shape around the die area could gradually change to a concave shape upon heating [2]. The high temperature and package dynamic warpage can introduce issues such as solder bump bridging, solder voiding, substrate trace crack, and thermal interface material (TIM) thermal resistance (TRES) degradation. Usually, the defects are detected and analyzed at room temperature. Sometimes, it is very difficult to find the root cause of the failures without an *in situ* study at high temperatures.

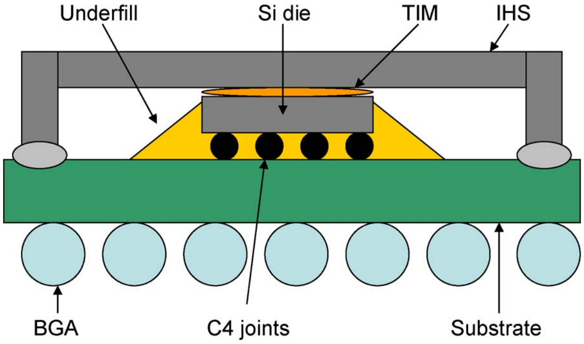

Fig. 1. Schematic diagram of a flip chip package, with C4 joint forming the FLI. IHS or lid is an optional part depending upon processor thermal requirements. The schematic shows a BGA as the SLI. The SLI could also be made of pins (PGA) or lands (LGA).

Two-dimensional X-ray imaging systems are customarily used for the inspection of both FLI and SLI solder joints inside flip chip packages after the reflow process. They are also important failure analysis techniques for detecting defects in packages, such as solder joint bridge, missing solder, substrate trace cracks, etc. To fully understand the failures happening at elevated temperatures, we put a hot stage, which can heat units up to the designed temperature and is transparent to X-ray, into a 2-D X-ray chamber. *In situ* X-ray observations of the failures happening at high temperatures are thus possible using the 2-D X-ray hot stage. This paper summarizes some important case studies at Intel, where failure mechanisms have been identified based on *in situ* 2-D X-ray studies at elevated temperatures.

II. BACKGROUNDS OF THE CASE STUDIES

A. NG-TIM Study

The TIM is the material between the die and the IHS (or lid), as shown in Fig. 1. It is the medium for heat conduction from the Si die backside to the IHS. Development of the next-generation TIM (NG-TIM) is needed as Si technology continues to develop according to Moore's law and thermal design power rises with added Si functionality [3]. The NG-TIM must provide a low-resistance thermal path, be mechanically stable in high-moisture environments and over the operating temperature, provide stress coupling between the die and IHS, and meet manufacturing process and equipment specifications

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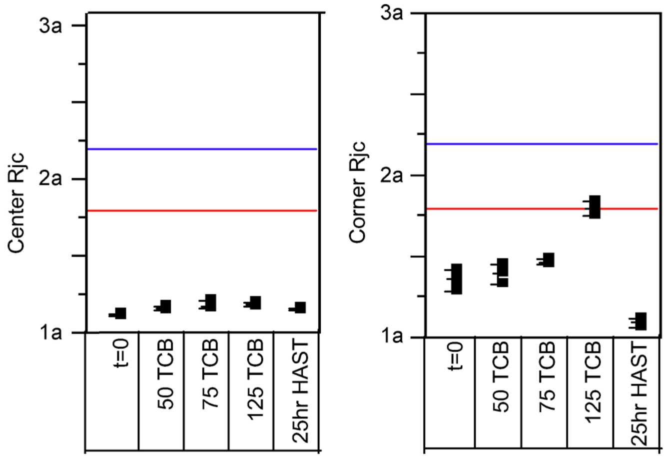

Fig. 2. TRES measurement shows corner Rjc degradation in the units with a NG-TIM material after 125-cycle TCB.

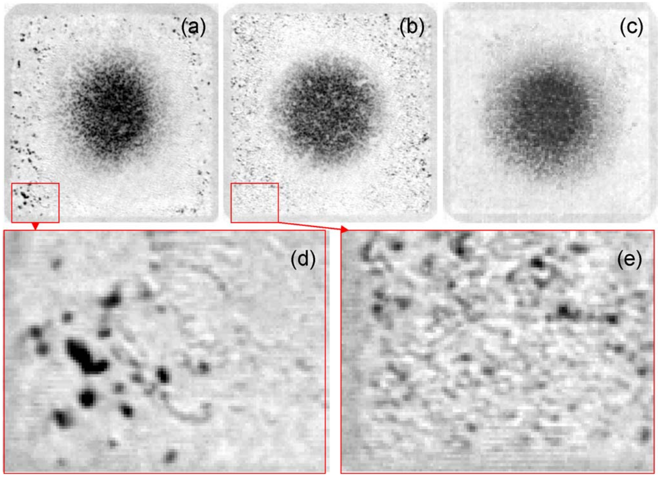

Fig. 3. CSAM images at lid-to-TIM interface from a unit after 125-cycle TCB (a); a unit after 25-h UHAST stress (b); and an unstressed unit (c). CSAM images on the die corners of a unit after 125-cycle TCB and a unit after 25-h UHAST stress are shown in (d) and (e), respectively. Dark contrast in the image shows the metal particles in that NG-TIM material.

[3], [4]. One of the NG-TIMs developed so far was studied, which is a polymer solder hybrid material with both polymer and metal particles. The metal particles are low melting alloys, and the melting point is about 65°C. It was used as the TIM between the die and IHS for performance evaluation. TRES measurements show that the TRES at the corners (corner Rjc) is degraded after 125-thermal-cycle (TCB, −55°C to 125°C) stress. The corner Rjc is good after a 25-h unbiased highly accelerated stress test (UHAST, 130°C, 85% relative humidity) (shown in Fig. 2). C-mode scanning acoustic microscope (CSAM) images (see Fig. 3(a) and (b)) at the lid-to-TIM interface were taken for units after the 125-cycle TCB and those after the 25-h UHAST stress. The metal particles in this NG-TIM material show up as dark contrast in the CSAM images. For both units, the distribution of the metal particles at the die corners is much lower than that at the die center. Compared with the unit after the 25-h UHAST, the unit after the 125-cycle TCB stress has even less distribution of metal particles at the corners, and the size of the particles at the corners is much larger, as shown in Fig. 3(d) and (e). At room temperature, when the material was applied to the die, the distribution of the metal particles was uniform. After the sealant cure (one of the processes during the IHS attach process with high temperature), the CSAM images of the unit before any reliability stress indicate that the metal particle distribution is similar with that in the unit after the UHAST, as shown in Fig. 3(c). To understand the reasons behind the change in the metal particle distribution in this NG-TIM material after the unit went through a high-temperature process, a 2-D X-ray hot stage was used to study its behavior at elevated temperatures.

B. *In Situ 2-D X-ray Studies of FLI Solder Joint Bridging*

The chip attach module (CAM) is the process of interconnecting the die to the substrate and is the most important part in the assembly process flow of flip chip packages. During the CAM process, a flux is printed on the top of solder balls on the substrate. The die is then placed on the solder balls with high precision. The die and the substrate then pass through an oven, and the solder balls are reflowed to make the required I/O and power connections between the die and the substrate. Adjacent solder bumps may get bridged during the reflow process due to the following reasons: 1) misplaced die at the onset; 2) die movement during reflow because of the bubbling of flux at high temperatures; 3) high substrate warpage in the die area; and 4) high warpage of the carrier of the microprocessor unit. The 2-D X-ray hot stage can be used to observe the solder joint bridging during CAM reflow. After the die placement, the unit can be placed on the 2-D X-ray hot stage to reflow the solder instead of using the oven. *In situ* 2-D X-ray images and videos can be recorded during the entire reflow process.

C. *In Situ 2-D X-ray Studies of BGA Solder Joint Bridging*

In surface mounting technology (SMT), the failure rate of solder bridging defects for ball grid array (BGA) components has increased significantly with the increase of package form factors. Although the literature on this solder bridging defect has focused mainly on fine-pitch packages [5], BGAs in large packages are not immune to the bridging defect even with relatively larger ball pitches. We found that BGA solder joint bridging occurred in the center area of a large lidded package with a 1-mm pitch. To understand the failure mechanism of the BGA solder joint bridging in large packages, the 2-D X-ray hot stage was applied to capture *in situ* X-ray images in the center area of a large package with IHS during SMT reflow.

III. EXPERIMENTAL APPARATUS AND PROCEDURE

A. *Two-Dimensional X-ray Hot Stage*

Fig. 4 shows a schematic diagram of the 2-D X-ray hot stage. An aluminum hot stage that is 65 mm × 45 mm in size and 4 mm in depth is used. Two heaters and one thermocouple are built inside the stage. The stage is attached to a fixture, which also contains of built-in fan and circuit controlling the temperature of the hot stage. The heating profile can be programmed using the software by setting up the ramping rate and sitting

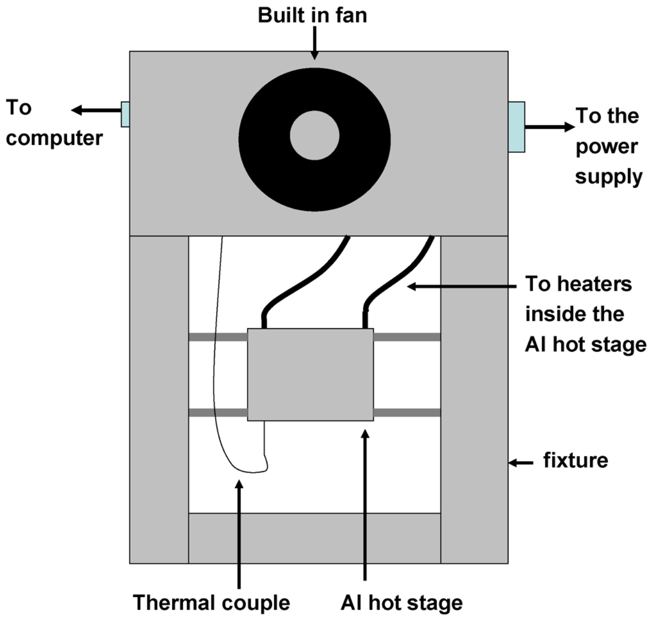

Fig. 4. Schematic diagram of the 2-D X-ray hot stage.

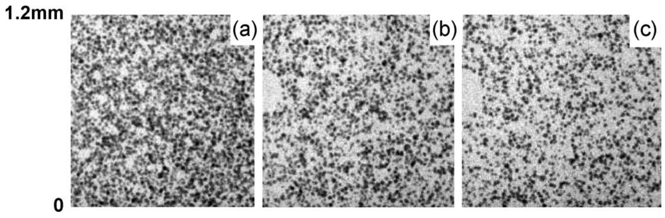

Fig. 5. *In situ* 2-D X-ray study of a NG-TIM material at 125°C: 2-D X-ray image taken (a) at room temperature, (b) at 125°C for 10 s, and (c) at 125°C for 15 min.

time at a certain temperature. Samples are put on the Al hot stage, and then, the whole setup sits in the X-ray chamber. Two-dimensional X-ray images or videos are taken while the hot stage is heated up according to the programmed heat profile.

B. NG-TIM Study Using Two-Dimensional X-ray Hot Stage

This NG-TIM film was cut into small pieces. Two thin glass slides were put on both sides of one small piece, and a sandwich structure was made. The sample was then put on the 2-D X-ray hot stage. The 2-D X-ray hot stage was heated up according to the programmed temperature profile. At the same time, 2-D X-ray images and videos were recorded. An *in situ* 2-D X-ray study of the material was performed at both 125°C and 260°C, as shown in Figs. 5 and 6, respectively.

C. In Situ 2-D X-ray Studies of C4 (FLI) Solder Joint Bridging

To understand the failure mechanism of C4 solder bump bridging during the CAM reflow process due to incoming substrate warpage, we select substrates with very high die area warpage. Fig. 7 shows a typical contour plot of high substrate warpage in the die attach area. All the substrates that we selected have spherical concave shapes, with one high corner. After flux printing and die placement, the units were put on the 2-D X-ray hot stage. The heating profile of the hot stage was programmed to mimic the reflow profile in the chip attachment. Two-dimensional X-ray images and videos were recorded during the experiment.

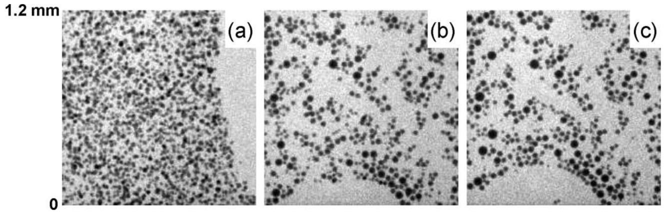

Fig. 6. *In situ* 2-D X-ray study of a NG-TIM material at 260°C: 2-D X-ray images were taken (a) at room temperature, (b) at 260°C for 10 s, and (c) at 260°C for 15 min.

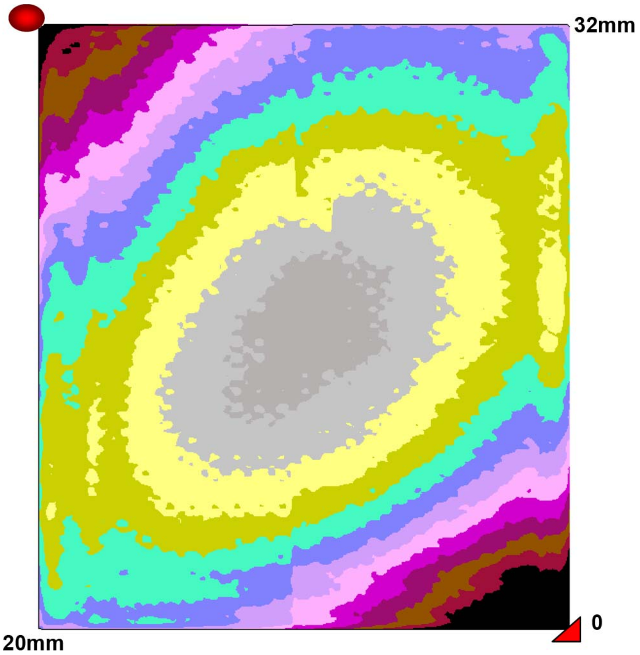

Fig. 7. Typical contour plot of the substrates selected for the C4 solder joint bridging experiment. The plot shows fixed increment contours on the substrate in the die attach area (before die attach). The shape is spherical concave, and the darker the color, the higher the contour elevation. The highest corner is labeled as red triangle. The solder bump bridging corner is usually the second highest corner, labeled as a red dot.

D. In Situ 2-D X-ray Studies of BGA Solder Joint Bridging

A large assembled package with IHS was placed on a board, which was already printed with solder paste with a stencil. The sample was then put on the 2-D X-ray hot stage and heated up to the reflow temperature; 2-D X-ray images and videos were recorded during the reflow.

IV. RESULTS AND DISCUSSION

A. NG-TIM Study Using Two-Dimensional X-ray Hot Stage

The dark contrast in the 2-D X-ray images shown in Figs. 5 and 6 indicates the metal particles inside the NG-TIM material. At room temperature, the distribution of the metal particles was uniform. The metal particles started moving around in the polymer matrix when the temperature reached around 65°C. The volume of the material expands, and the density of the metal particles became smaller and smaller as the temperature increased. Larger particles and areas without metal particles were formed. Larger movement of the metal particles happened when the temperature was about 220°C. The particle size and the area without any metal particles became even bigger.

Based on the *in situ* 2-D X-ray study of the material, we can have the following hypothesis for the corner TRES degradation. At room temperature, when this NG-TIM was applied on the die, the distribution of the metal particles was uniform. When the unit was heated up during process and reliability stress testing, the NG-TIM material tends to behave like a viscous fluid, and the mobility of low melting metal particles increases once the temperature reaches 65°C. Because of the dynamic warpage of the package, the convex shape around the die area gradually changes to a concave shape. The viscous fluid then tends to flow toward the die center area as more space between the IHS and the die would appear at the die center. During the movement, the melting metal particles could coalesce to form bigger particles. After the 125-cycle TCB stress, the unit is heated up 125 times, and more and more metal particles at the die corners move to the die center area, which may lead to low metal particle coverage at the die corners and cause higher corner TRES. To fix this problem, modification on this NG-TIM matrix polymer is needed so that the metal particles would not move around at elevated temperatures.

B. In Situ 2-D X-ray Studies of C4 Solder Joint Bridging

The X-ray images taken before heating up the hot stage show that there was no die misalignment on the units. Fig. 8 shows the heating profile as well as the X-ray images of the second highest corner (labeled as red dot in Fig. 7) taken at different locations of the heating profile. There is no significant change on the solder balls until the temperature reaches above the melting temperature of the lead-free solder. Solder joint bridging happened thereafter within 6 s. The X-ray images labeled 1–6 show how the solder bump bridging happened during 6 s. At first, a tiny solder line formed between two diagonally adjacent solder bumps (1 in Fig. 8). The width of the solder lines grew larger and larger until it became the same as the diameter of the solder bumps (2–6 in Fig. 8). No significant changes were observed on the solder bumps after 6 s.

For most cases, the solder bump bridging only happened at the second highest corner (labeled as red dot in Fig. 7). For all the other three corners, we did not observe any solder bump bridging. Fig. 9 shows the 2-D X-ray images of the highest corner and the solder bridging corner taken before and after the solder reflow. For other corners, no significant change was observed. In Fig. 9(d), we can see some gray dark circles around the solder bumps, which may indicate the bumps on the die. Considering the fact that there was no die misalignment before the reflow (shown in Fig. 9(c)), we can conclude that the die shifted toward the highest corner during the reflow.

Based on the observations made by the 2-D X-ray hot stage, we have the following hypothesis for the solder bump bridging due to incoming die attach area substrate warpage. Because of the large warpage of the substrate, the gap between the solder ball on the substrate and the die bump is the smallest for the highest corner. At the highest corner, the solder may wet the die bump a little earlier than the other three corners when the temperature reaches the melting temperature of the solder. Once the solder wets the die bump at the highest corner, the die will be pulled down and dragged toward that corner. The movement of the die while the solder is wetting the second highest corner may cause the solder bump bridging. We also found that the bump layout may also influence the result. If the warpage difference is small between the highest and the second highest corner and the second highest corner has a corner bump while the highest corner does not, solder bump bridging will happen at the highest corner. The solder may wet the corner bump at the second highest corner a little earlier, and the die

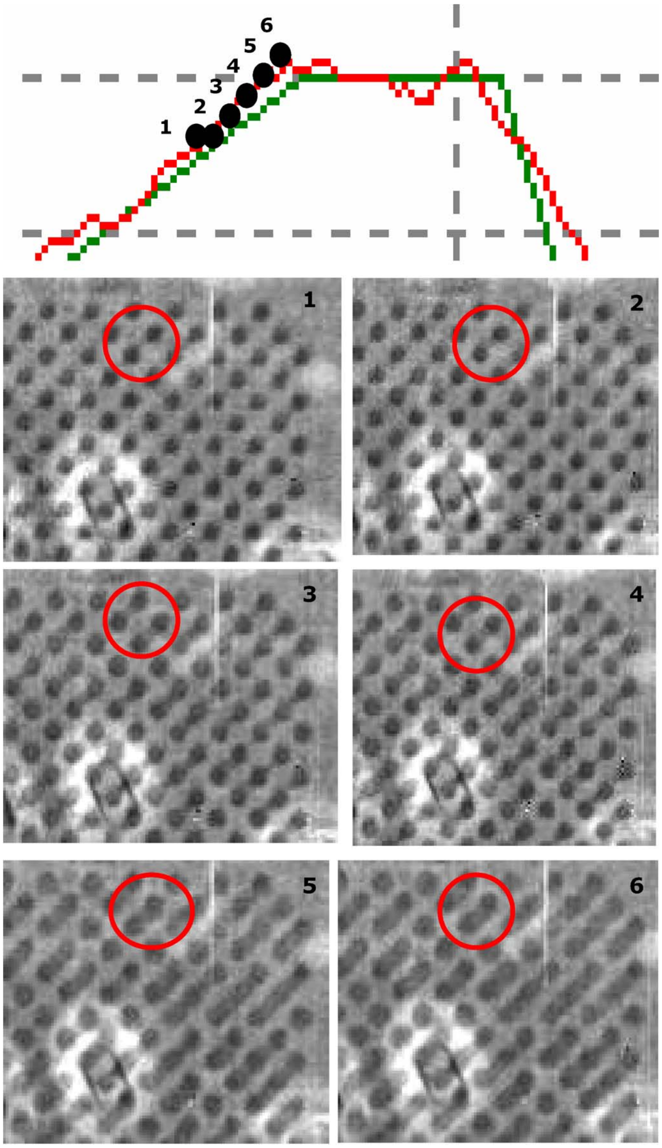

Fig. 8. *In situ* 2-D X-ray study of C4 solder joint bridging due to incoming die attach area substrate warpage. Solder joint bridging happened within 6 s when the temperature reaches the melting temperature of the Pb-free solder. The green line is the programmed temperature profile, while the red line shows the real temperature profile.

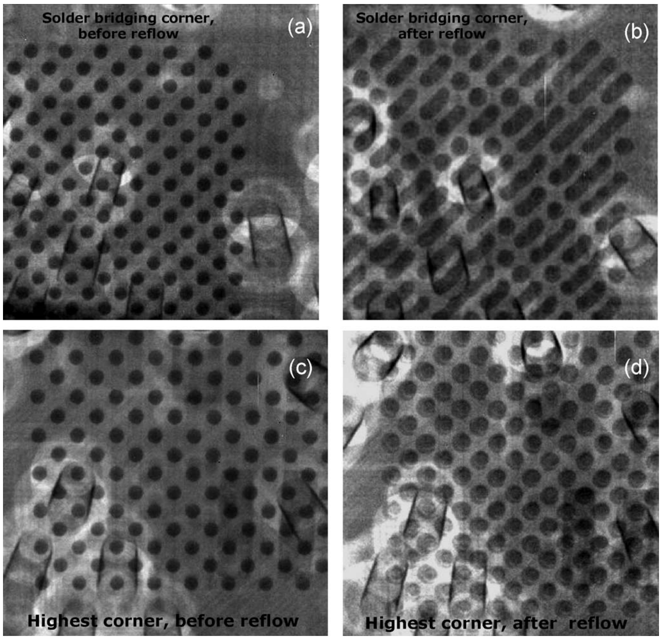

Fig. 9. Two-dimensional X-ray images of the solder bridging corner taken (a) before reflow and (b) after reflow. Two-dimensional X-ray images of the highest corner taken (c) before reflow and (d) after reflow.

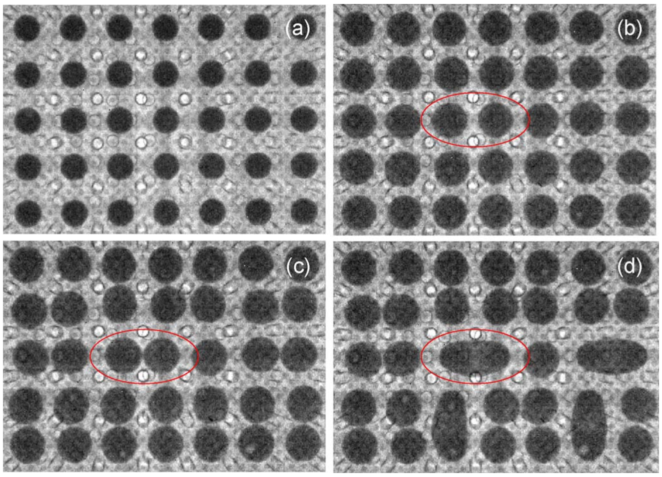

Fig. 10. *In situ* 2-D X-ray images showing formation of solder bridging at center area of a large package with IHS in SMT solder reflow. Two-dimensional X-ray images taken (a) before reflow and (b)–(d) during reflow. BGA solder joint bridging happened in the center of the package. The center solder bumps move around and touch the adjacent solder bumps and caused the bridging.

is dragged toward that corner and cause solder bump bridging at the highest corner. Limits of die area substrate warpage need to be set in order to avoid C4 solder bump bridging during the chip attach solder reflow process.

C. *In Situ Two-Dimensional X-ray Studies of BGA Solder Joint Bridging*

The 2-D X-ray image taken before the SMT reflow on the hot stage shown in Fig. 10(a) indicates that there was no package-to-board misalignment. Once the temperature reached the melting temperature of the lead-free solder, the center solder balls collapsed heavily, and the molten solder bulged out from the board pads, leading to a reduction of the joint gap distance (shown in Fig. 10(b)). Interestingly, it was observed that the molten solder moved around pads, and for some of the joints, the molten solder moved toward each other, resulting in a further reduction of the joint gap distance, which is shown in Fig. 10(c). When two adjacent molten solder balls are in contact with each other, a bridged joint is formed, as shown in Fig. 10(d).

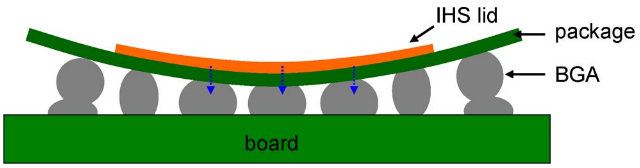

Fig. 11. Schematic diagram showing the failure mechanism of BGA solder bridging in a large package with IHS. Due to a heavy package weight and a large warpage of the large package, solder balls in the center collapse under a large pad force and bulge out from pad, leading to a reduction of joint gap distance.

Based on the *in situ* 2-D X-ray data, we come up with the following hypothesis for BGA solder joint bridging in large packages. As shown in Fig. 11, the weight of a large package with IHS is relatively heavy, sometimes around 40 g. Considering the dynamic warpage of the package, there will be a significant amount of force applied on the board pads in the center of the package during SMT reflow. Solder balls in the center area undergo a big collapse and bulge out from the pad periphery, which leads to a reduction in the solder joint gap distance. As two adjacent molten solder balls move and are in contact with each other, a bridged joint forms to reduce the total surface energy of the molten solder. The *in situ* 2-D X-ray imaging results clearly indicate that the failure mechanism of solder joint bridging in large packages with IHS is due to a large force applied on the center pad in the reflow, which is induced by the package weight and dynamic warpage as well as the dynamic motion of the solder in time at liquidus. To limit the BGA solder joint bridging, board pads need to be designed to keep solder balls from moving around.

V. CONCLUSION

The 2-D X-ray hot stage was used to observe failures of flip chip packages at elevated temperatures. The heat profile of the hot stage can be programmed to mimic the solder reflow profile in the manufacturing environment. *In situ* X-ray images and videos were taken while heating up the packages. The hot stage was employed to study a new TIM at high temperatures. It was found that the low-melting-point alloy filler particles in the material started moving around in the polymer matrix when the temperature was above the alloy melting temperature. The density of the metal particles became smaller and smaller, forming larger particles along with areas without metal particles. The unique property of this NG-TIM material can lead to a nonuniform metal filler distribution if applied as the TIM in a flip chip package due to the high-temperature process and the dynamic warpage of the package. It can also cause corner TRES degradation during reliability stress tests such as TCB. The C4 solder joint bridging during chip attach solder reflow in units with high die area substrate warpage was studied by the 2-D X-ray hot stage. The C4 solder joint bridging usually occurred at the second highest corner of the die area and happened within a few seconds once the temperature reached the melting point of the solder. The solder wets the die side bump at the highest corner first, and the die is dragged toward that corner. The die movement while the solder is wetting caused the solder joint bridging in the second highest corner. BGA solder joint bridging in large packages with IHS during surface mounting solder reflow was also analyzed using the 2-D X-ray hot stage. Due to the relatively heavy weight and the dynamic warpage of the large packages, the solder balls in the center area undergo a big collapse and bulge out from the pad periphery, when the temperature is above their melting point. The center solder balls also move around and are in contact with each other, which leads to the BGA solder joint bridging.

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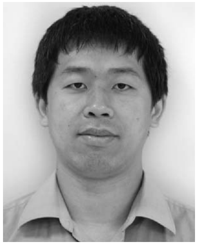

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