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THERMAL-INDUCED DAMAGE ON SOLDER JOINTS OF HIGH-DENSITY ADJACENT BALL GRID ARRAY COMPONENTS DURING THE REWORK PROCESS

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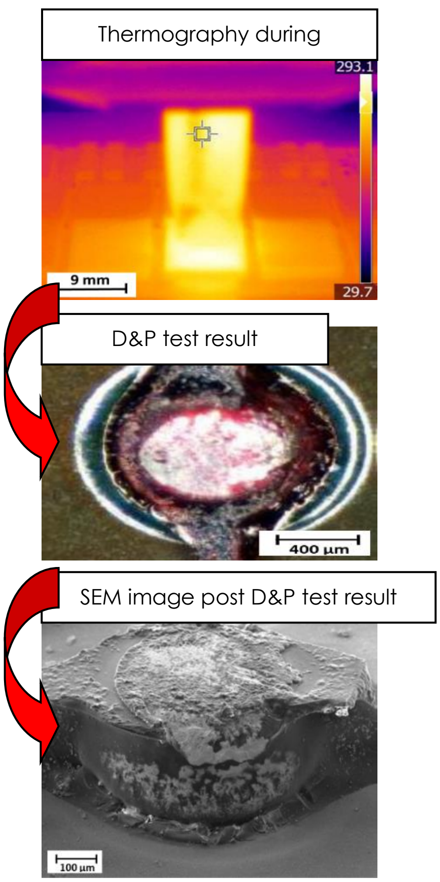
Graphical abstract



Abstract

Correlation between adjacent ball grid array (BGA) components' temperature and thermal-induced damage to their solder joints on both the top and bottom printed circuit board assembly (PCBA) sides during the rework process is studied in this work. Total often adjacent BGA components from the rework area on the top (F - K) and bottom (A - E) PCBA side were observed. The dye and pull (D&P) test results, infrared thermography images, and temperature measurements were analyzed for solder joint crack induced by the thermal damage with precise temperature measurement on each adjacent BGA component. Scanning electron microscope (SEM) analysis complemented the post-D&P test solder joint crack observation. The D&P test results shows that 76 % or higher and solder joint separation locations at the copper pad on BGA occurred when the temperature of the adjacent components of the rework location exceeded 195 °C and 210 °C on the centre and corner of the component, respectively.

Keywords: Thermal induce damage, solder joint damage, adjacent BGA components, rework, infrared thermography

Abstrak

Hubungkait antara suhu susunan komponen grid bebola (BGA) bersebelahan dan kerosakan akibat aruhan haba pada sambungan pateri pada kedua-dua bahagian atas dan bawah pemasangan papan litar bercetak (PCBA) semasa proses kerja semula dikaji dalam penyelidikan ini. Sebanyak sepuluh komponen BGA bersebelahan dari kawasan kerja semula di bahagian atas (F - K) dan bahagian bawah (A - E) PCBA dicerap. Keputusan ujian pewarna dan tarikan (D&P), imej termografi inframerah dan kejituan suhu dianalisis untuk keretakan pada sambungan pateri yang disebabkan oleh kerosakan haba dengan pengukuran suhu yang tepat pada setiap komponen BGA bersebelahan. Analisis mikroskop imbasan elektron (SEM) menyokong ujian D&P. Keputusan ujian D&P menunjukkan sekurang-kurangnya 76% pemisahan pad tembaga pada BGA berlaku apabila suhu komponen bersebelahan lokasi kerja semula melebihi 195 °C dan 210 °C masing-masing pada bahagian tengah dan sudut komponen.

Kata kunci: Kerosakan aruhan haba, kerosakan sambungan pateri, komponen BGA bersebelahan, kerja semula, termografi inframerah

1.0 INTRODUCTION

Rework on ball grid array (BGA) component is a crucial part of the manufacturing process as the current trend in printed circuit board assembly (PCBA) design focuses on the development of high-density component population placement to enhance the product performance. With the high cost of BGA components, the rework process is preventing the entire PCBA from being scrapped due to the component-related problem [1]. In times of difficulty procuring components [2] and reducing electronic waste in the environment [3], the rework process is becoming increasingly important. As a result, the PCBA reworking approach that is both effective and dependable is required.

Area array rework is the process of BGA components. This is hard to do because the solder joints are hidden under the body of the component [4]. Due to the high density of BGA components in high-performance products, nearby rework components are at risk of thermal reflows during the rework process [5]. Unintentional reflow of adjacent component solder joints can result in component damage, pad damage, and solder joint degradation [6]. If the intermetallic (IMC) layers on the solder joint of adjacent components become thicker, the solder joint tends to fail due to the solder crack [7]. These challenges can be overcome using precise thermal profiles and exceptional precision during PCBA rework procedures [8].

Thermal induced damage during rework on high-density BGA component placement on both sides of the PCBA with precise temperature measurement analysis on adjacent rework components has been the subject of only a few studies. Du [9] discussed post rework reliability after numerous BGA reworks on a single high-density PCBA. Otáhal *et al.*, (2017) reported on the structure of a BGA component solder junction affected by the direction of heat flow during reflow soldering [10]. Dušek *et al.*, (2016) studied the effect of temperature profiles on BGA soldering during reworks on electronic products, as measured by the distance between the PCBA and the BGA package [11].

This study's major goal is to look at the correlation between adjacent BGA component temperature and thermal-induced damage to their solder joints on both the top and bottom PCBA sides during the rework process. For this purpose, a) during the rework process, an infrared thermography camera was utilized to obtain the heat distribution on the surface regions of the BGA components; b) temperature measurements with thermocouple (TC) wires were used to validate the thermal distribution on the solder joint array; c) to detect solder joint quality issues, and printed board laminate fractures, D&P tests were performed to determine the post-rework effect; d) scanning electron microscope (SEM) analysis was used to inspect the solder joint surface topography of the post D&P test; and e) D&P test findings, as well as temperature measurements, were plotted and evaluated qualitatively and quantitatively to learn more about the correlation between adjacent BGA component temperature and thermally induced solder joint degradation during rework.

2.0 METHODOLOGY

2.1 Materials and Sample Description

The test vehicle used in this study consisted of a PCB assembled with BGA components that became a PCBA. There was a total of twelve BGA components at the top and bottom of the PCBA. On each side of the PCBA, six BGA components mirrored each other. However, only ten adjacent BGA components from the rework area on the top (F - K) and bottom (A - E) PCBA were studied for this experiment.

Rework component U1 and the mirror U1 BGA component on the bottom PCBA side have been excluded due to the direct contact with the rework heat source. Figure 1 depicts the measurement gap between the BGA components. A rework machine was used to rework a BGA component (U1) on the top side of the PCBA. The letter "U" was chosen because, according to ASME Y14.44-2008, it is a standard reference designator for an integrated circuit component [12].

The BGA component has 132 solder balls and one unpopulated middle column. The solder ball diameter of the BGA component was 0.49 ±0.5 mm with the material composition of Sn97.18 Ag2.0 Cu0.75 Ni0.07. There are 14 layers on the PCB with an organic solderability preservative (OSP) surface finish. Before the rework procedure, the BGA component assembly used a lead-free solder paste with an alloy composition of Sn96.5 Ag3.0 and Cu0.5 wt % (SAC305).

2.2 Rework Temperature Profiling Preparation

The TC wires were used to profile rework temperatures. The BGA component samples were drilled to appropriately put the TC bead and wires on the BGA component's solder ball as shown in Figure 2. Epoxy resin was used to fill the holes left by the drilling process. On both the top and bottom PCBA sides, the TC wires were placed on the adjacent components, as illustrated in Figure 1. The IPC-7095D-WAM1 recommendations for TC wire placement were used to represent the lowest to maximum thermal mass zones [13].

The TC wires were attached to the rework machine to monitor the temperature of the reworked and nearby components while hot air from the hot air nozzle and bottom convection heater was used to expose the intended rework BGA component area. Only temperatures of adjacent BGA components from the rework area on the top and bottom PCBA were measured and studied for this experiment.

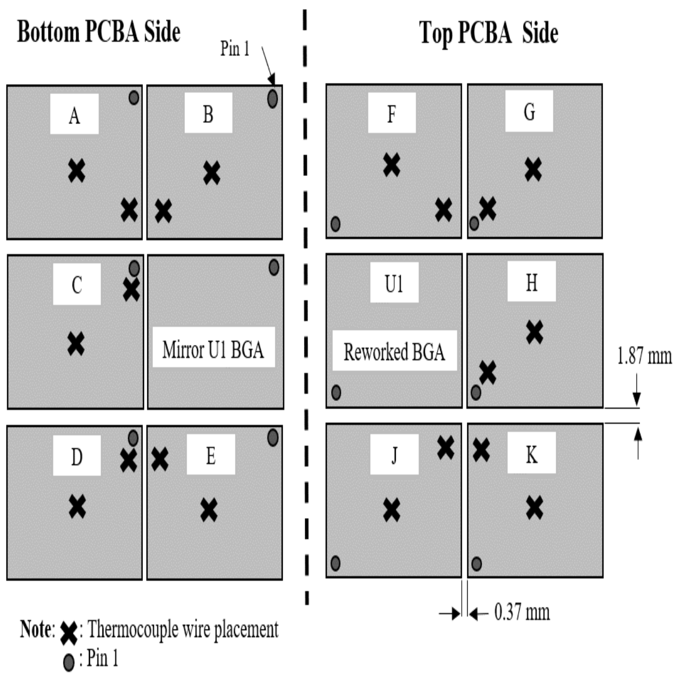


Figure 1 Schematic of the BGA components layout and reworked component location (U1)

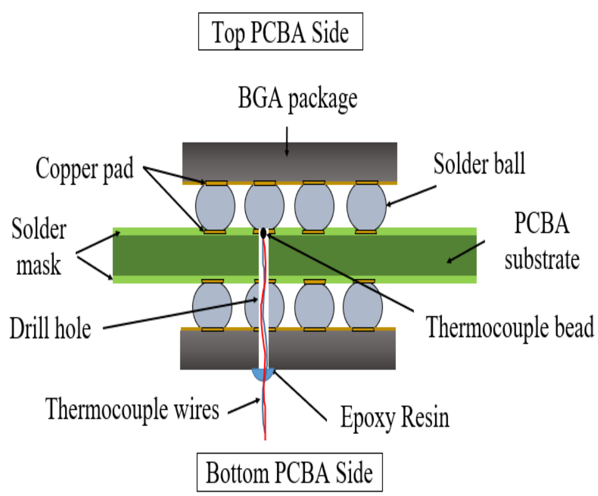


Figure 2 Schematic of thermocouple wire location on BGA solder joint

2.3 Rework Method

To avoid thermal shock, the PCBA was baked in the oven for 9 hours at 125 °C to remove any excess moisture [14]. The sample was placed on the rework machine after being secured on top of the rework pallet. The rework procedure included removing the damaged component, cleaning the component pads of solder residue, reinstalling the component, and reflowing the solder joints of the component.

The reflow profile was created using a lead-free rework process temperature profile that needed preheating at temperatures ranging from 100 °C to 190 °C. The activation temperature was 140 °C - 220 °C for 90 s of soaking. The component temperature ramped from 2 °C to 4 °C per second. For 80 s, the reflow dwell temperature was 220 °C. For 15 s, the solder joint's peak temperature was kept between 230 °C [15].

The rework machine's top nozzle and bottom convection heater provided hot air for removal and assembly as depicted in Figure 3. Using a hot-air nozzle and vacuum suction, the targeted reworked component U1, was removed from the PCBA. Solder residues on the PCBA were cleaned with a soldering iron and pre-fluxed copper braid after applying the paste flux. After that, the flux residue was removed with a cleaning solution.

By applying a paste flux to the solder joints of the reworked BGA component and then applying hot air reflow via the rework machine, the reworked BGA components were assembled. To achieve good metallurgical bonding between the solder alloys and the base metals of the PCB pads during component removal and assembly, all solder joints must meet the melting point of lead-free alloys in the range of 217 °C - 220 °C [16].

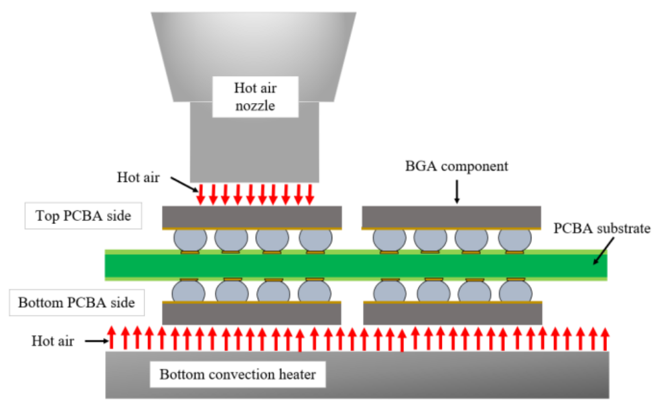


Figure 3 Schematic of BGA component being reworked with hot air rework machine

2.4 Infrared Thermography

During the rework process, a handheld Fluke Ti400 infrared thermographic camera was utilized to capture the heat distribution on the surface of the BGA component locations from the isometric view. Thermal imaging technology can detect the surface temperature of the BGA and provide information on heat intrusions and heterogeneity in the interior or subsurface of the object [17]. The infrared thermographic camera can detect and record infrared radiation emitted by BGA components. The camera's temperature range is -20°C to +1200°C, which is inside the rework soldering temperature range for the analysed BGA components.

2.5 D&P Test

The BGA component samples were dyed and pulled to look for potential solder joint cracks on the rework and adjacent BGA components [18]. The BGA component samples were subjected to initial optical and X-ray inspections to look for signs of physical damage or stress on the reworked and adjacent components. PCBA samples were placed into a small tray and immersed until completely soaked in the red dye solution. The tray with the soaked PCBA samples was placed into a vacuum chamber for 4 minutes. A pull tester was used to detach the BGA components from the PCB pads. A Nikon Eclipse LV150NL optical microscope was used to look for dye indications on the BGA components [19].

2.6 Dye Penetration Coverage Inspection

After the BGA components were removed, the solder joints for the BGA components were evaluated for dye penetration indications. The dye penetration coverage percentage was estimated using the IPC-TM-650 Test Methods Manual, 2.4.53, D&P Method, which was based on the dye coverage filling on the circular quadrant as shown in Figure 4 [20].

Table 1 was used to determine the percentage of dye penetration coverage results. The separation's location was identified according to Figure 5. Type 1X is separated at the BGA substrate, type 2X at the copper pad on the BGA, type 3X at the copper pad on the PCBA, type 4X at the PCB laminate, and type 5X at the BGA solder joints.

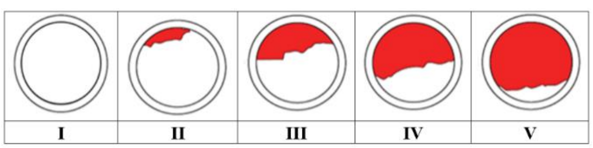


Figure 4 Dye penetration coverage percentage scale

Table 1 Dye indicator with coverage percentage

Dye Indicator	Dye Coverage Percentage
I	0%
II	1 to 25%
III	26 to 50%
IV	51 to 75%
V	76 to 100%

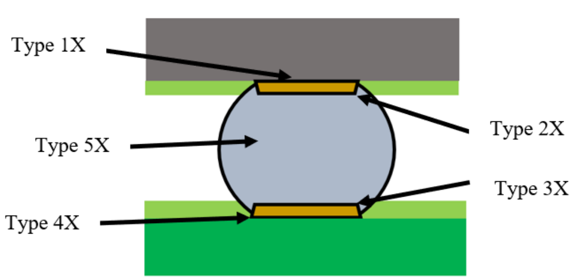


Figure 5 Schematic of D&P separation location type

2.7 Scanning Electron Microscope (SEM) Analysis

One BGA component from sample F was subjected to SEM analysis to obtain surface topography of the post-D&P test. This was also to inspect the severity of the crack and separation location with a high resolution better than 1 nm.

2.8 Quantitative Analysis

Minitab and JMP software were used for quantitative analysis of temperature and D&P test results. The peak temperature and variability chart for D&P test results were derived using the reworked results [21].

3.0 RESULTS AND DISCUSSION

The heat dissipation of the BGA components on the PCBA during rework was confirmed using infrared thermography. Brighter colours indicated warmer temperatures with more heat and infrared radiation emitted, whereas darker colors indicated lower temperatures with less heat and infrared radiation emitted. As a reference for the infrared thermography photos, photographs of the BGA components on the top PCBA side throughout the rework process were shot with a standard camera as shown in Figure 6 (a). Figure 6 (b) shows the bright yellow colour of the heat source, which came from the hot air nozzle indicating a surface temperature of 293.1 °C. The same colour can be observed on the side of adjacent components from the rework location.

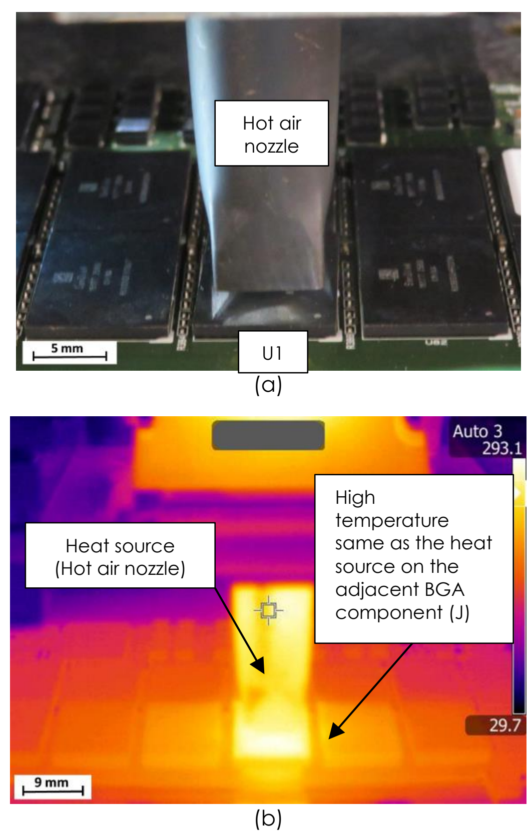


Figure 6 Photograph and infrared thermography image during the rework process: (a) photograph of the BGA components; (b) infrared thermography image

Figure 7 depicts the quantity of solder joints affected by dye penetration on the BGA components for both the top and bottom PBCA sides due to the solder joint crack. The solder joints of the BGA component on the top PCBA side were more impacted than the bottom PCBA side. BGA component J located on the side of the rework component was the most impacted by the solder crack. This is due to the top PCBA side has been exposed to the concentrated heat from the hot air nozzle. Tang *et al*., (2018) stated that thermal reflows pose a high risk of damaging nearby BGA components' solder joints during rework [22].

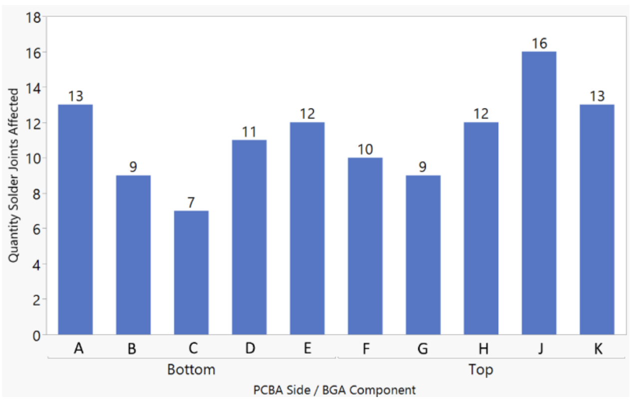


Figure 7 Bar chart on the quantity of solder joints affected by dye penetration due to solder crack

Figures 8 (a) and (b) show the dye penetration % severity and related to the surrounding component's centre and corner temperatures. Dye penetration of more than 76% mostly occurred on the bottom PCBA side except for the BGA component F on the top PCBA side since it was located on the side of the rework component location.

When the centre temperature of the adjacent components from the rework location exceeded 195 °C, dye penetration of 76 % or higher occurred. Once the corner temperature of the adjacent BGA component reached above 210 °C, similar results were obtained. These findings were also in line with Jiang *et al*., (2019) who found that temperature load has a substantial impact on solder joint quality and reliability, potentially inducing crack damage [23].

The interaction between the temperature on the centre and corner of each adjacent BGA component and separation location after the D&P test is shown in Figures 9 (a) and (b). The bottom PCBA side has the largest solder joint separation locations at the copper pad on BGA (2X) except for BGA component F on the top PCBA side. If the adjacent component's centre temperature exceeds 195 °C, separation at 2X was likely to occur. When the corner temperature of each adjacent BGA exceeded 210 °C, an identical observation was made. Xu *et al*., (2020) reported that due to the thermal exposure, cracks can be found on the solder joints close to the copper pad on BGA [24].

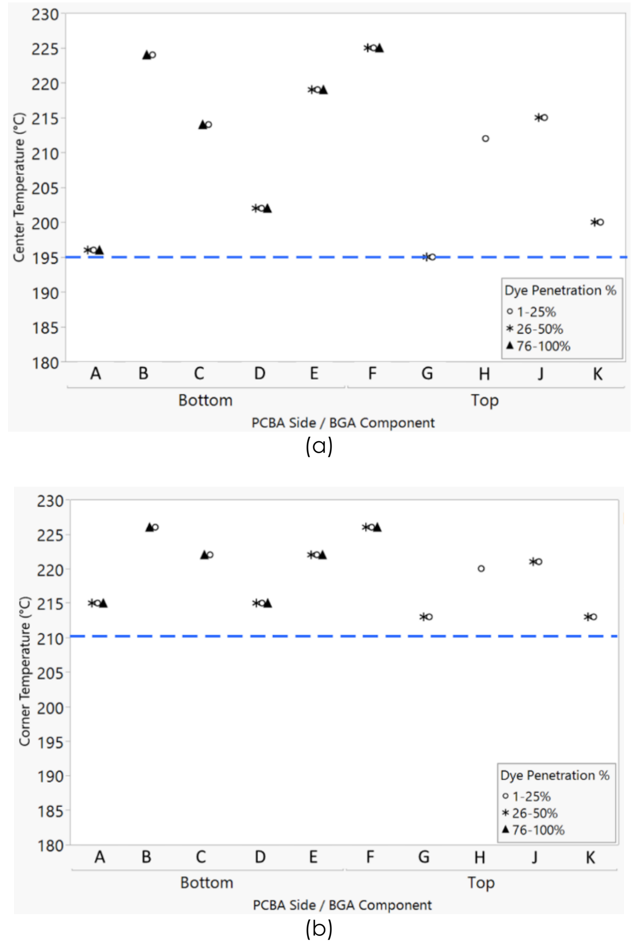
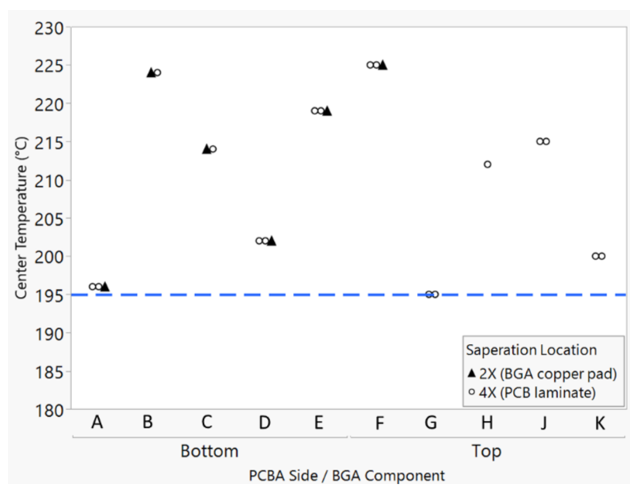
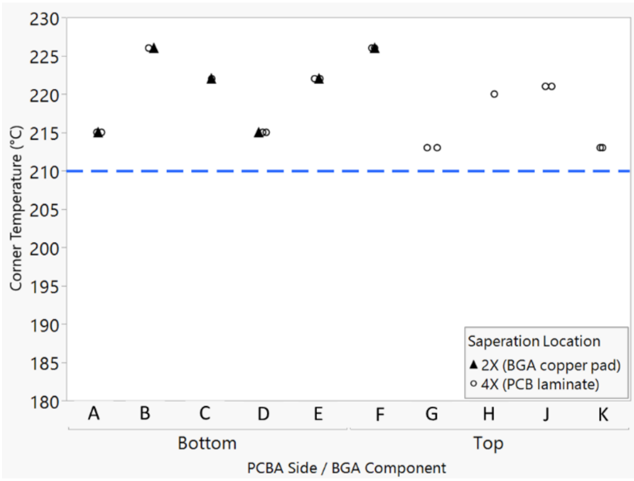


Figure 8 Dye penetration % with the effect of temperature differences at the BGA component area: (a) centre of the BGA components; (b) corner of the BGA components



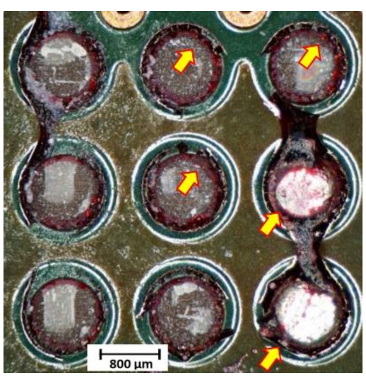
(a)



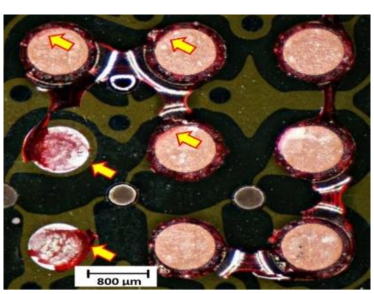
(b)

Figure 9 Separation location with the effect of temperature differences at the BGA component area: (a) centre of the BGA components; (b) corner of the BGA components

Figures 10 (a) and (b) show D&P test results for post hot air rework. The photos were taken from the top corner of the F BGA component section, which was located near the U1 rework component. This section focuses on nine of the 132 solder joints on a BGA component. The dye penetration coverage represented the affected solder joints because of the crack occurrence, according to the observations. Because of the hot air rework, five out of nine BGA solder joints were affected.



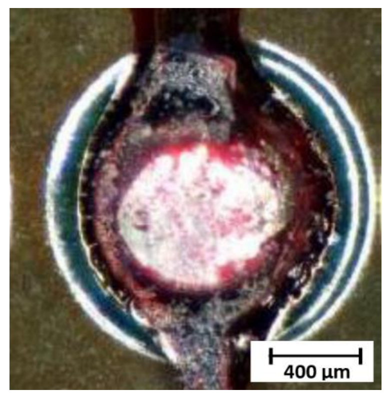
(a)



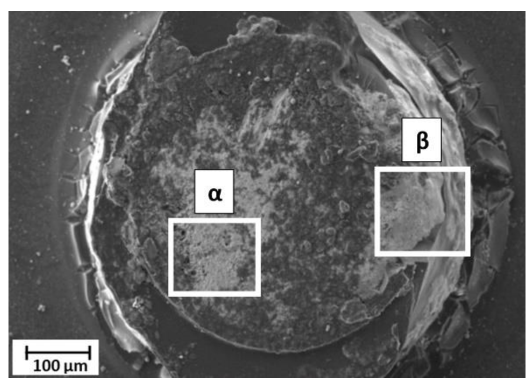
(b)

Figure 10 D&P result post hot air rework: (a) PCBA side; (b) BGA component side

Figures 11 (a-c) show solder joint separation locations at the PCBA side along with their SEM image. The rounded surface indicates a separation from the IMC layer (β), whereas the flat surface indicates a separation near the bulk solder (α). The SEM image shows two different surface topographies: an intergranular surface (β) with dye penetration and an elongated surface (α) fracture with no dye penetration as shown in Figures 11 (d) and (e). The image of the intergranular surface shows no signs of severe plastic deformation, indicating a brittle fracture that generates an unstable crack that quickly propagates, allowing the dye to penetrate. The elongated surface has spherical dimples, which are indicative of a ductile fracture. This is consistent with the findings of the Nourani and Spelt (2015) investigation, the brittle fracture surface was flatter and smoother, resulting in a progressive change in the crack route from the bulk solder to the brittle IMC.



(a)



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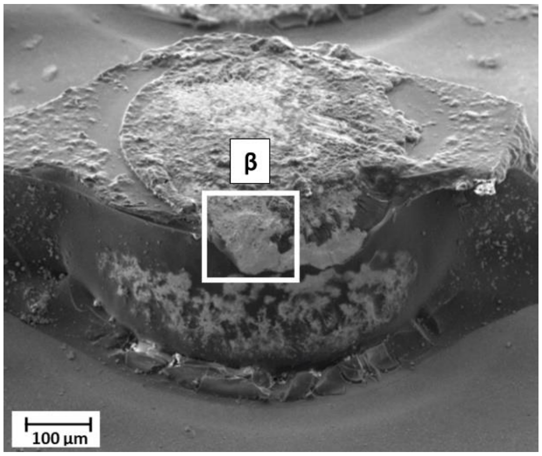
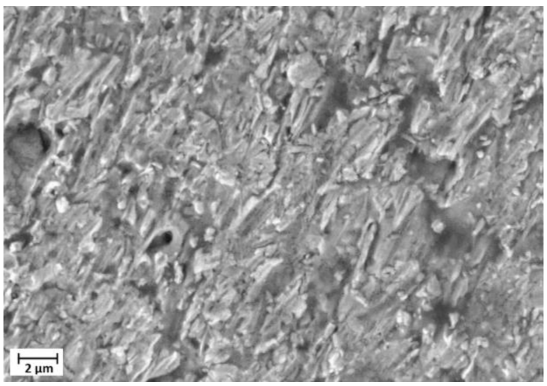
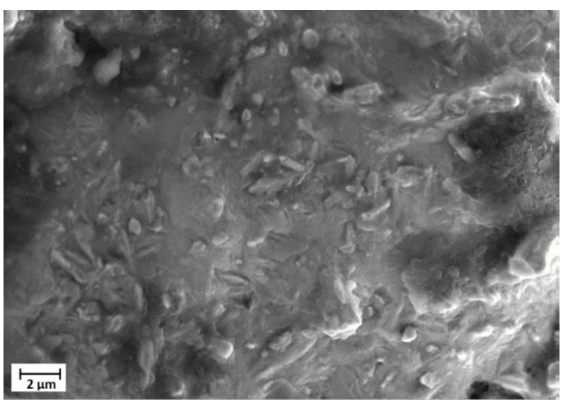


(c)



(d)



(e)

Figure 11 Close up look at PCBA side of dye penetration: (a) optical microscope image; (b) SEM image from top; (c) SEM image from isometric view; (d) elongated surface (α); (e) intergranular surface (β)

4.0 CONCLUSION

This study assessed the correlation between adjacent BGA component temperature and thermal-induced damage to their solder joints on the reworked PCBA top and bottom sides. Thermal assessment during the rework process was performed effectively with a combination of thermography imaging and TC wire temperature measurement. D&P test results showed the BGA component's solder joint crack was induced by the thermal damage. Dye penetration of 76 % or higher and solder joint separation locations at the copper pad on BGA occurred when the temperature exceeded 195°C and 210°C at the component's centre and corner, respectively. SEM analysis was able to inspect the solder joint surface topography of the post-D&P test.

Acknowledgement

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