Thermal cycling effect on the crack formation of solder joint in ball grid array package

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Abstract. Ball grid array (BGA) technology is one of the technologies used in surface mount technology (SMT). It provides many interconnection points via the solder ball and thus give advantages such as good heat dissipation, improved the PCB design, BGA package become robust and reliable. In electronic industry, the reliability of BGA package is being concerned. Thermal cycling test (TCT) is one of typical reliability test used to investigate the reliability of the BGA package. This study investigates on the thermal cycling effect on the crack formation of solder joint in ball grid array package. The BGA package was subjected to thermal cycle test with temperature cyclic of -40°C and 85°C for 500, 750 and 1000 cycles. The finding shows that the cracks were observed in solder joint in 750 and 1000 cycles. This shows that the BGA package is sensitive to the thermal cycling and effect its reliability. The package was modified with adding underfill materials and tested through the same cycles. Cross sectional and Dye and pry test show no crack formation and dye penetration for all thermal cycles in the BGA package with underfill.

1 Introduction

The performance of electronic devices depends on continuous improvement in miniaturization, application, technology, and cost. One of the most important advances that keeps electronics manufacturers constantly on their toes is the introduction of an extremely dense integrated circuit with higher reliability for various applications up to extreme conditions with finer pitch of solder joint interconnection [1-5]. When utilized in surface mount technology (SMT), interconnect technology such as ball grid array (BGA), offer a special advantage as they provide integrated circuit (IC) package technology, which makes devices with integrated circuits smaller, cheaper, and reduction in weight, with increased performance.

Since the year 1990, BGA had a substantial advantage over other technologies when it comes to manufacturing electronic products. Instead of utilizing lead solder to assemble IC packages, a new approach was implemented in which solder balls were used instead. BGA technology was found to have improved electrical performance due to a shorter printed circuit board (PCB) path [6]. In BGA technology, conventional material use as the solder ball are from Pb based solder materials. The Pb based solder materials are widely use in electronic packaging until 2006, and then the electronic market demand of the application of lead-free solder due to the Restriction of Hazardous Substance (RoHS). The restriction was due to lead, as it was identified as a toxic material that possess threat to environment and health to the worker in electronic manufacturing industries [7]. As a result of the restriction, lead-free solders were developed as replacement for the hazardous lead-based solders. Among several candidates, Tin-Silver-Copper (SAC) solder material was suggested as an electronic industry standard due to the properties such as low melting point, excellent wettability, and excellent mechanical properties [8]. The introduction of lead-free solder led to reliability concerns in electronic packages. Typically, solder joint integrity is significant to the reliability of the electronic packages.

Thermal changes induced by environmental condition combined with the mismatch of coefficient of thermal expansion (CTE) between the die and PCB lead to failure of the solder joint. Failure of the solder joint due to microstructural changes lead to crack formation in the bulk of solder joint [9]. This affects the reliability of the manufactured products. Dispensing underfill material to the BGA package was one of the methods used to overcome the crack occurrence in the solder joint [10]. Nevertheless, not much research focusses on a smaller BGA solder joint with solder ball size of below 400 µm. This paper focus on study the effect of thermal cycling to the crack formation in BGA package solder joint with average ball size of 330 µm. The BGA solder joint were prepared with and without underfill to suppress the crack formation.

2 Methodology

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2.1 Sample preparation

To study the thermal cycling effect on the crack formation of solder ball in BGA package, two samples of A and B (BGA without and with underfill) were manufactured. The BGA is a WLCSP component with solder ball size of 300 µm in width and 180 µm were mounted onto an Organic Solderability Preservative (OSP) surface finished printed circuit board (PCB) using Lead-free solder paste, Sn-3.0Ag-0.5Cu (SAC305) of type 5. Next, the sample was reflowed in a reflow oven (BTU Pyramax). An epoxy based underfill material was dispensed to the BGA package in a horizontal I pattern as illustrated in fig. 1 for sample B. Next, the sample B was cured at elevated temperature of 160 °C in a Vertical Curing Oven of model HCZ-400 for 10 minutes.

![Horizontal I pattern for underfilled sample B](image)

Fig. 1. Horizontal I pattern for underfilled sample B

2.2 Characterization

In this experiment, the BGA packages were evaluated via TCT in accordance with JESD22-A104 standard. The TCT was performed at temperatures ranging from -40 °C to 85 °C, with a ramp rate of 0.16 °C/s, with dwell times of 600 seconds at each extreme for 500, 750, and 1000 cycles. The TCT test was performed in a temperature cycle chamber (Espec EGNZ28-15NW). In fig. 2, the TCT profile used in this study is displayed. After TCT, samples were analysed through X-ray inspection, dye and pry (DNP) method and cross-sectional analysis. The shape and size of the solder ball joints were examined through Phoenix Microme 2D X-ray machine with the parameter setting of 80 kV and 50 µA. For DNP, the samples were tested as per IPC-TM-650 2.4.53 Dye and Pull Test standard method [11]. DNP involves cleaning the sample to remove debris and flux around the solder, followed by immersion in a red dye. The samples were then exposed to a vacuum environment to ensure the dye penetrated all cracks. After that, the samples were baked in an oven at 70°C for 3 hours and the dye was ensured to be completely dried. The samples were removed from oven and allowed to cool. To pry the component, Selleys Kneads IT epoxy was used to bond tee nut on top of the BGA surface component prior to pull using a Pull Tester instrument to separate the BGA and PCB. Once component removed, the solder ball was examined for any dye penetration using optical microscope and analysed using ImageJ software. Next, sample A without underfill and sample B with underfill cross-sections were made using metallographic techniques that included sample cutting, cold mounting, grinding, and polishing. In relation to the BGA package and PCB, the samples were laser cut perpendicularly. The samples were then placed in round molds with a 30 mm diameter. The epoxy resin and hardener mixture were then poured into the molds and allowed to set for 24 hours at room temperature. Both samples were ground with 240, 320, 600, 800, 1000, and 2000 grit Silicon Carbide paper with flowing water. Subsequently, diamond paste of 6, 3, and 1 micron was used to polish the surface, followed by oxide polishing for up to 60 seconds [1, 2]. The solder balls' microstructure was then examined using an optical microscope and evaluated with ImageJ software.
Fig. 2. TCT profile of -40°C to 85°C.

3 Results and Discussion

Both samples A and B were examined in an x-ray machine to determine the average diameter of the solder ball in the BGA package. Image of solder ball taken using x-ray was presented in fig. 3. Based on measurement, the solder balls with an average diameter of 337 µm for sample A and 335 µm for sample B were successfully manufactured. Hence, the solder ball diameter was identical in size in both conditions (without and with underfill). As a result, both samples were produced in a controlled environment, as shown by this finding. Having this condition is required in order to evaluate the thermal cycling effect on the crack formation of solder ball in ball grid array package.

In this study, both sample A without underfill and B with underfill were placed under thermal cycling test for up to 1000 cycles. Then, the samples were removed at each cycle of 500, 750 and 1000 and characterized in dye and pry (DNP) and cross-sectional analysis. Table 1 summarized the result of the characterization. Based on table 1, the result shows that there is dye penetration and crack formation in the samples A without underfill at cycle 750 and 1000 of TCT test while sample B exhibit none of the solder ball failure as indicated in sample A. Fig. 4 and 5 show the dye penetration images and crack formation respectively.

In samples A without underfill, at 500 cycles, there is no dye penetration on the pried solder ball as shown in fig. 4. (a). This indicate that the solder ball is still strong to endure any thermomechanical stress during the TCT test up until 500 cycles. However, the solder ball begins to fail at 750 cycles as indicated by fig. 4. (b). There is dye penetration in the solder ball approximately 20% of the solder ball area. This indicate that there is crack formation from the edge of the solder ball to the bulk of the solder ball center. At 1000 cycle, the crack in the bulk of solder ball is severe as indicated by fig. 4. (c). The severity of the crack formation throughout the solder ball caused the dye to penetrate almost 90% of the solder ball area. Cross sectional analysis was conducted to study the behavior of crack formation in the BGA package during the TCT test. From fig. 5. (a), at 500 cycle the solder ball is still intact without any formation of crack. This indicate that the solder ball is still able to endure the thermomechanical stress when the BGA was at 500 cycles. At 750 cycles, there is formation of crack of length 55 um observed in the solder ball. The crack appeared to be initiated from the left side of the solder ball as shown in fig. 5. (b), near the intermetallic compound (IMC) interface and propagated centripetally into the bulk of the solder ball. Fig. 5. (d) show the enlarged image of the crack formed at 750 cycles. The crack formation is more prominent at 1000 cycle. From fig. 5. (c), the crack of 292 µm formed completely throughout the bulk of the solder joint. The solder ball in the BGA package experience greater thermomechanical stress than previous cycle and as a result it completely fails the TCT test due to the crack formed throughout the solder ball. Fig. 5d and 5e show enlarged image of the crack at 750 and 1000 cycle respectively.

Table 1. A slightly more complex table with a narrow caption.

| Sample | TCT Cycles | Analysis Observation | Cross Section |
|--------|------------|----------------------|---------------|
| A      | 500        | No dye penetration   | No crack occurrence |
| A      | 750        | Dye penetrated       | Crack occurred |
| A      | 1000       | Dye penetrated       | Crack occurred |
| B      | 500        | No dye penetration   | No crack occurrence |
| B      | 750        | No dye penetration   | No crack occurrence |
| B      | 1000       | No dye penetration   | No crack occurrence |
In sample B with underfill, there is no solder ball failure indicated by the DNP and cross-sectional analysis. Fig. 6 show the cross-section image of solder ball after TCT test (a) at 500 cycles (b) at 750 cycles (c) at 1000 cycles. All solder ball of sample B with underfill survived TCT test without any crack formation occurred in the bulk of the solder joint. In sample A without underfill, the BGA packages failed temperature cycling experiments due to thermal fatigue and thermal shock. Mismatch of thermal expansion coefficients (CTE) between the silicon die and PCB substrate caused the solder joints to be thermally stressed when the ambient temperature changes during the cycle of -40 °C to 85 °C. The cyclic temperature changes caused solder ball to experience thermal fatigue. This fatigue led to the deformation of the solder ball which occurred due to creep [12, 13]. The result indicates that the solder ball in the BGA package is thermally stable at 500 cycles of TCT. This is shown by the dye penetration test and cross section result for sample A having no defect. However, the solder ball begins to fail at 750 cycles and failed severely at 1000 cycles as show by fig. 6. (a) and 6. (b) respectively. From the observation, the crack initiated at the outer layer of solder ball and then propagate to the center bulk of the solder ball. The crack spread initially near to the IMC and appeared to propagate with higher TCT cycle. With underfill, the solder ball in BGA package able to withstand the thermal stress caused by the temperature change and the TCT cycle. This prevents the thermal deformation in the solder that formed during TCT cycle.
4 Conclusion

This study has successfully investigated on the thermal cycling effect on crack formation in BGA package. Solder joint failure begin at TCT cycle of 750 as indicated by the dye penetration and crack formation in bulk of solder joint in the BGA package. TCT at 1000 cycles caused greatest crack formation throughout solder joint with length of 292 µm. Improvement on the BGA package to prevent solder ball cracking was conducted using underfill material and successfully prevented any failure throughout all TCT cycle.

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