Effect of rapid thermal shock cycle on the thermomechanical reliability of 20Sn-80Pb solder bumps

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Abstract. The influence of rapid thermal shock(RTS) cycles on 20Sn-80Pb solder bumps was studied. In the study, 20Sn-80Pb solder bumps were prepared by desktop nitrogen lead-free reflow soldering machine. The prepared 20Sn-80Pb solder bumps were used for RTS test in the temperature rang of 0℃ ~ 150℃. One cycle of RTS is 24 seconds, and the temperature rise and fall rate of RTS is 12.5 ℃/s. The result indicated that when the cycle of RTS reached 1500T (here T is cycle, the same below), the shear strength of Sn-80Pb solder bump dropped drastically 48.6%. Whereas, when the cycle of RTS reached 5500T, 20Sn-80Pb solder bumps’ shear strength decreased to 18.35 MPa, which increased by 7.5% compared with that of 16.97 MPa at 4500T. With the increase of RTS cycles, 20Sn-80Pb solder bumps’ shear strength was a decreasing trend and the fracture mechanism changed from ductile fracture to ductile-brittle mixed fracture, which could be subject to the thickening of the interfacial IMCs and the stress concentration caused by the growth of interfacial IMCs. To understand the changes of the mechanical properties of 20Sn-80Pb solder bumps, the influences of RTS on the crack and interfacial IMC of 20Sn-80Pb solder bumps were studied in details.

1. Introduction

Although people are trying to seek the right lead-free solders to replace traditional lead-based solder, there has not been found to be able to completely replace the lead-based solder[1]. Additionally, Jiang et al[2]. emphasized the dependability problems of Pb-free solder alloys in electronic applications, and pointed out some elements that lead-free solders still had challenges in many application fields. Although considerable researched has been done on lead-free solder alloys, there was currently no alternative to achieve characteristics of high-lead solder[3-5]. Hang et al.[6] made it clear that Pb-based solder alloys still existed in many fields, especially in the aerospace field without considering its related environmental concerns. In addition, high Sn-Pb solder is used in many high temperature applications[7,8] because of its resistance to formation of intermetallic compounds, high melting temperature, low cost, excellent long-term reliability and high thermal fatigue temperature[9,10]. During deep space exploration, electronic components must withstand extreme temperature changes[11]. Solder joints’ integrity play a crucial role in the overall function of electronic components owing to solder joints providing mechanical, thermal and electrical contiunity.
of electronic components[12]. Hence, it is a matter of urgency to research the thermomechanical dependability of high Sn-Pb solder bumps under extreme temperature variations. In this study, the influence of RTS cycle on 20Sn-80Pb solder bumps was studied.

2. Experimental methods
A ball grid array with dimensions of 6 mm x 6 mm x 1 mm containing 25 20Sn-80Pb solder bumps is the material used in this experiment, which had a diameter of 600 μm. 20Sn-80Pb solder bumps were prepared by desktop nitrogen lead-free reflow soldering machine. The peak reflow temperature for 20Sn-80Pb solder bumps was 357℃, and the duration above liquids (273℃) was about 120s. The prepared 20Sn-80Pb solder bumps were used for RTS test in the temperature range of 0℃ ~ 150℃. RTS equipment mainly included heating system and cooling system, and heating system consisted of induction coil and sample placement table, and cooling system was comprised of sample placement table cooling fluid as shown in Figure 1. One cycle of RTS is 24 seconds, and the temperature rise and fall rate of RTS is 12.5 ℃/s in Figure 2. The RTS cycles included 1500T, 2500T, 3500T, 4500T and 5500T, respectively (here T is cycle, the same below). Optical metalloscope(OM) and scanning electron microscope(SEM) were used to analyze the microstructures of interface. The thickness of the interfacial IMCs layer was measured using ‘Image-J’ software. The average shear strength of several joints (the shear velocity was 0.05 mm/sec) were identified by the PTR-1102 bonding tester.
3. Results and discussion

3.1 Microstructure of 20Sn-80Pb solder bumps after RTS

Microstructure morphology of overall of 20Sn-80Pb solder bumps after different RTS cycles could be seen from Figure 3, which showed that the Sn-rich appeared in the 20Sn-80Pb solders matrix. When the period of RTS reached 1500T, the Sn-rich phases in the 20Sn-80Pb solders matrix increased and distributed uniformly in the solder matrix. Whereas, as the period of RTS continued to increase, the number of Sn-rich phases in the solder matrix did not change significantly. In general, the microstructures of the high-Pb solder were stable and there was no significant change in the microstructure during thermal shock[13]. This stability, combined with the lack of brittle IMCs in the matrix, enabled a wide range of applications for high-lead solder.

Figure 3. Overall of 20Sn-80Pb solder bumps after different RTS cycles.(a.0T, b.1500T, c.2500T, d.3500T, e.4500T, f.5500T).

3.2 Internal cracks of 20Sn-80Pb solder bumps after RTS

Figure 4 showed the corners of solder bumps after different RTS. It was obvious that no cracks appeared at the interface of solder bumps at 0T. When the cycle of RTS reached 1500T, a crack was found at the lower left of solder bumps. Cracks were formed gradually at the lower corners of solder bumps as the increase of RTS cycle, and the width and depth of the cracks kept increasing. The phenomenon could be explain by the fact that the stress concentration between the solder and IMCs continued to occur, which made cracks form here and eventually continued to expand with the continuous increase of RTS cycles. In the RTS process, solder bumps were hastily heated and cooled in a wide temperature range (0℃ to 150℃) in this study, and the coefficient of thermal expansion (CTE) values of the lead, Cu₃Sn, copper were 29.3 x 10⁻⁶, 0.067, 0.059 ppm/K, respectively, so there was a difference in CTE between lead and Cu₃Sn, which was significantly greater than the difference in CTE between lead and copper. Hence, the mismatch of CTE led to the concentration of shear stress at the interface of the solder/IMCs layer. Additionally, Cu₃Sn IMCs would shrink in volume during the growth process[14,15], which would also enhance the stress concentration between the solder and IMCs layer interface.
Figure 4. The corners of solder bumps after different RTS cycles. (b1.b2:1500T, c1.c2:2500T, d1.d2:3500T, e1.e2:4500T, f1.f2:5500T).

3.3 Interfacial IMCs of 20Sn-80Pb solder bumps after RTS

Figure 5 presented interfacial IMCs of solder bumps after different RTS cycles. It was noticed that the original morphology of IMCs at the solder bumps interface was plane-type, but after rapid thermal shock, the morphology of IMCs changed from plane-type to scallop-type. The empirical power-law equation was used to elucidate the mechanism of IMCs layer growth, and the formula was used as follows[16].

$$ W = W_0 + At^n $$

Where $W$ is the IMCs layer thickness at time $t$, $W_0$ is the IMCs layer thickness in the as-soldered condition, $A$ is growth constant and $n$ is the time index. The value of the time index $n$ is considered to be an indicator of the IMCs growth mechanism[17,18]. If $n$ is closer to 0.33, the control mechanism for IMCs growth is considered to be grain-boundary diffusion[19,20]. The research determined the value of $n$ by appropriate nonlinear regression analysis fitting to experimental results. The values of Cu-Sn IMCs layer time index $n$ and related factor $R^2$ were shown in Table 1. The results indicated that
the control mechanism of Cu-Sn IMCs growth was grain-boundary diffusion.

Table 1. Time index (n) of the IMC layers at solder bumps/Cu interface

| IMC layer | n   | $R^2$ | IMCs Growth Mechanism       |
|-----------|-----|-------|----------------------------|
| Cu-Sn     | 0.28| 0.41  | Grain-Boundary Diffusion    |

The calculation formula for the thickness of IMCs was as follows:

$$LIMC = \left( \frac{NIMC}{NSEM} \right) \times LSEM$$  \hspace{1cm} (2)

Figure 6 showed that the thickness of interfacial IMCs of bumps after different RTS cycles, revealing that the thickness of interfacial IMCs of solder bumps generally went up as the increase of RTS cycles. Whereas, when RTS cycle reached 3500T, the thickness of interfacial IMCs of solder bumps dropped to 2.68 $\mu$m compared to the thickness of interfacial IMCs of solder bumps at 2500T. Additionally, the thickness of interfacial IMCs of solder bumps dropped to 3.59 $\mu$m at 5500T compared to the thickness of interfacial IMCs of solder bumps at 4500T. This was due to the formation of interfacial cracks in the solder/IMCs layer led to the further diffusion of Cu and Sn atoms to form the gaps, which hindered the growth of the interface IMCs layer [21]. The crack length of solder bumps interface at 3500T was obviously longer than that at 2500T as showed in the Figure 5, explaining that the thickness of interfacial IMCs of bumps at 3500T was lower than that at 2500T. Similarly, the thickness of interfacial IMCs of bumps at 5500T was lower than that at 4500T.

Figure 5. Interfacial IMCs of bumps after different RTS cycles.(a.0T, b.1500T, c.2500T, d.3500T, e.4500T, f.5500T).
3.4 The shear strength and fracture morphology of 20Sn-80Pb solder bumps after RTS

The effect of RTS on the shear strength of 20Sn-80Pb solder joints was studied through shear tests. The results were showed Figure 7, which presented solder bumps’ shear strength after different RTS cycles. Before RTS, the initial solder bumps’ shear strength was as high as 50.18MPa. Solder bumps’ shear strength generally showed a downward trend as the increase of cycles of RTS. However, whilst the cycle of RTS reached only 1500T, solder bumps’ shear strength was extremely reduced to 25.81MPa, which was 48.57% lower than that at 0T. As the cycle of RTS continued to increase, solder bumps’ shear strength decreased slowly. Solder bumps’ shear strength even reduced by approximately 63.43% (18.35MPa) at 5500T. Fracture morphology of solder bumps after RTS could be seen from Figure 8, the fracture mainly occurred in the solder. The fracture was a parabolic dimple, and its orientation was the same as the shear orientation. As the growth of interfacial IMCs and the thickening of Cu$_3$Sn IMCs layer led to stress concentration near the interface, cracks propagated more easily through Cu$_3$Sn IMCs layer. Therefore, the fracture mode of solder bumps changed from the inside of solder matrix to the mixed fracture mode of solder matrix and Cu$_3$Sn IMC layer as the increase of RTS.
4. Conclusions

(1) The microstructures of 20Sn-80Pb solder bumps were stable and there was no significant change in the microstructure during RTS due to the stability of high-lead content solders. When the cycle of RTS reached 1500T, a crack was found at the lower left of solder bumps. Cracks were formed gradually at the lower corners of solder bumps, and the width and depth of the cracks kept increasing as the increase of RTS cycle.

(2) The thickness of interfacial IMCs of solder bumps generally went up as the increase of RTS cycles. Whereas, when the RTS cycle reached 3500T, the thickness of interfacial IMCs of solder bumps dropped to 2.68 μm compared to the thickness of interfacial IMCs of solder bumps at 2500T.
Additionally, the thickness of interfacial IMCs of solder bumps dropped to 3.59 μm at 5500T compared to the thickness of interfacial IMCs of solder bumps at 4500T.

(3) Solder bumps’ shear strength generally showed a downward trend as the increase of cycles of RTS. However, whilst the cycle of RTS reached only 1500T, solder bumps’ shear strength was extremely reduced to 25.81MPa, which was 48.57% lower than that at 0T. As the cycle of RTS continued to increase, solder bumps’ shear strength decreased slowly. Solder bumps’ shear strength even reduced by approximately 63.43% (18.35MPa) at 5500T.

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