Microelectronics Reliability 86 (2018) 66–71

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Joint reliability of various Pb-free solders under harsh vibration conditions for automotive electronics

Kyeonggon Choi[a,b], Dong-Youl Yu[b], Sungdo Ahn[b], Kyoung-Ho Kim[b], Jung-Hwan Bang[b], Yong-Ho Ko[b,*]

[a] Department of Materials Science and Engineering, Inha University, 100, Inha-ro, Nam-gu, Incheon 22212, Republic of Korea
[b] Joining R&D Group, Korea Institute of Industrial Technology (KITECH), 156, Gaetbeol-ro, Yeonsu-gu, Incheon 21999, Republic of Korea

ARTICLE INFO

Keywords:
Pb-free solder
Automotive electronics
Combined vibration test
Intermetallic compound (IMC)
Reliability

ABSTRACT

These days, realization of technology for automotive electronics is important for convenience and safety in automobile industries. Although technology development is continuously progressing, various problems associated with the reliability of automotive electronics have arisen. In this study, combined vibration tests were performed to determine the reliability of various solders under harsh environments: Sn-3.0Ag-0.5Cu (SAC305), Sn0.7Cu and Sn-0.5Cu-0.01Al-0.005Si-0.008Ge (SnCuAl(Si)) solder (in wt%). The Pb-free solder balls were used on electroplating nickel finished Cu pads of a fine ball grid array (FBGA) package. The BGA packages mounted with solder balls were set up on electroless nickel-immersion gold (ENIG) finished Cu pads of a daisy-chained printed circuit board (PCB). The combined random vibration test was performed under 2.5 G_{rms} in the range of 400 to 2000 Hz in the temperature range of −45 to 125 °C and was continued until 500 cycles. The reliability of the solder joint was determined by measuring the electrical resistance using a multi-meter. The resistance gradually increased and finally approached infinity. In addition, the IMC thicknesses increased during the combined random vibration test, which affected the fracture behavior. To determine the reliability of the solders, the number of failures of solders and the crack morphology and propagation in each solder were evaluated. Among the three solders, the SnCuAl(Si) solder demonstrated the best reliability.

1. Introduction

In the past, Pb-solder alloys were used for electronic packaging because of several advantages such as a low melting temperature, good wettability, and good reliability. In particular, for electronic packages used at high temperatures, more than 85% Pb-containing Sn-Pb alloys have been used [1–4]. However, the use of Pb-solder alloys has become limited after the legislation on environmental regulations such as Restriction of Hazardous Substances (RoHS), Waste Electrical and Electronic Equipment (WEEE), and End of Life Vehicle (ELV) as Pb is harmful for human body and environmental preservation. Therefore, Pb-free solders have been issued in packaging industry as an alternative to Pb solders. Sn-Ag-Cu (SAC) alloys are one of the representatives as a replacement for previously used Sn-Pb solder alloys because of its good wettability, thermal shock reliability and creep resistance [5–7]. Various researches are still reported for Pb-free solders [8–11].

Nowadays, automobiles are composed of many electronic components for convenience and safety. Automotive electronics are lightweight, high-integration, and multi-functional devices. However, many problems are associated with the mechanical reliabilities of automotive electronic components. In case of electronic packaging, failures or fractures of the solder joint occur due to delamination and fatigue induced by thermal deformation and external environmental factors [12–14]. As a result, improving the joint reliability by various packaging technologies is necessary because the failure of solder joint can degrade the electrical functioning of electronic devices. Generally, automotive electronic components are often exposed to harsh environments than other electrical and electronic devices are. According to Johnson [15], the typical continuous maximum temperature of an engine is 125 °C and the vibration level is up to 10 G_{rms}. Thus, the environment of an automobile engine room is too harsh to maintain the reliability of the solder. Therefore, the reliability of automotive electronics in severe environments such as high temperature and vibration needs to be evaluated. Many automobile companies have test methods and standards to assess the reliability of solder joints in automotive electronics such as thermal cycle, thermal shock, and vibration tests.

In the area of random vibration fatigue, Yu et al. [16] reported the fatigue life of SAC305 (Sn96.5-Ag3.0-Cu0.5) and SAC405 (Sn95.5-

* Corresponding author.
E-mail address: yonghoko@kitech.re.kr (Y.-H. Ko).

https://doi.org/10.1016/j.microrel.2018.05.006
Received 13 October 2017; Received in revised form 10 May 2018; Accepted 10 May 2018

Ag4.0-Cu0.5) by combining both finite element analysis (FEA) and vibration test under an ordinary temperature. They focused on the fatigue failure of Pb-free solder joint and analyzed the S-N (stress-life) curve determined from the FEA model and the rain-flow counting method. In case of thermal cycling fatigue, Hokka et al. [17,18] demonstrated the effects of thermal cycle using a SAC solder. They verified the reliability of the solder joint under various conditions, such as difference between the maximum and minimum temperature, dwelling time and ramping rate, which can affect the lifetime of the solder joint. In addition, they also investigated the failure mechanism and microstructural changes from the thermal cycle profiles under various accelerated conditions. Although many vibration and thermal cycle tests have been reported [19–21], studies on combined vibration tests in harsh conditions and solders used in high temperatures for automobile engines are still limited. Therefore, additional studies are still required to enhance the reliability of solder under harsh conditions and high temperatures, as well as to solve problems and to develop Pb-free solders. In this study, the reliability of a Sn-0.5Cu-0.01Al-0.005(Si)-0.008Ge (SnCuAl(Si)) solder was evaluated and compared with that of other conventional solders, SAC305 and Sn0.7Cu, under combined vibration conditions. The melting point of SnCuAl(Si) solder was approximately 230 °C. In addition, as mentioned earlier, the typical temperature of an engine room is 125 °C [15]. Thus, the solder was developed for application in automobile engine room components at over 230 °C, which is higher than the melting point of conventional Pb-free solder (SAC305: 217 °C, Sn0.7Cu: 227 °C) [22]. Therefore, the reliability of SnCuAl(Si) solder based in harsh environment was demonstrated through a combined vibration test and compared with that of other conventional solders SAC305 or Sn0.7Cu. Furthermore, the morphologies of the solder joints and the thicknesses of intermetallic compounds (IMC) were verified using a field-emission scanning electron microscope (FE-SEM).

2. Experimental procedure

In this experiment, three kinds of solder pastes and solder balls were used: SAC305, Sn0.7Cu, and SnCuAl(Si). The schematic diagram of a fine ball grid array (FBGA) structure is shown in Fig. 1. A standard FBGA consisting of 64 solder balls and an FR-4 printed circuit board (PCB) were used in this experiment. The FBGA test packages were finished with electroplating nickel surface treatment. The pad pitch was 0.8 mm with a 450 μm diameter solder ball on a pad with dimensions of 8 × 8 mm. The PCB was also treated with electroless nickel-immersion gold (ENIG) on Cu pad. For the surface mounting of FBGA package on PCB, solder pastes were firstly printed on the ENIG of the PCB using a screen-printing machine and the package was mounted using a high-speed chip mounter. After mounting, the samples were reflow soldered in a reflow oven for 50 s above 217, 227, and 230 °C for SAC305, Sn0.7Cu and SnCuAl(Si) solders, respectively. The specific reflow profiles are shown in Table 1.

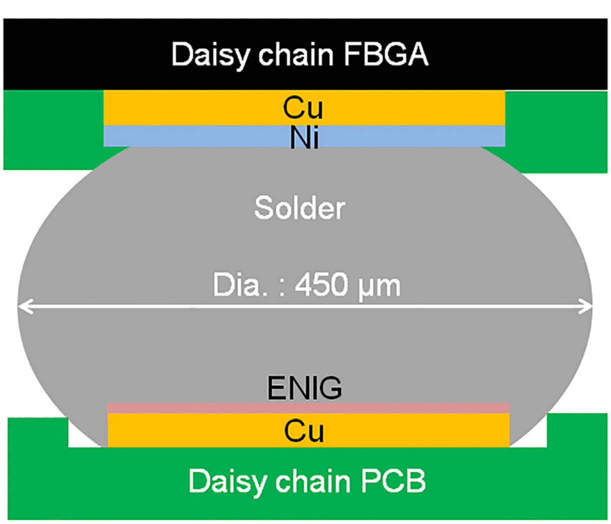

Fig. 1. Schematic diagram of FBGA.

Table 1
Detailed information of specific reflow profiles.

Solder components	Pre-heating	Reflow	
	Time	Max. peak temp.	Dwelled time over melting point
SAC305	107 s	250 °C	50 s
Sn0.7Cu	73 s	255 °C	50 s
SnCuAl(Si)	73 s	260.5 °C	50 s

Fig. 2 shows the schematic diagram of side and top views of the combined vibration test and an image of the loaded test samples on a vibration jig. The total number of loaded samples on the vibration jig was 42, and the same number of samples were tested.

After the test samples were fabricated, they were placed on a jig connected to a vibrator (G-0120N & PVL-3KPH; Hielkema Co., Japan). All the samples were standoff to facilitate quick development of fracture, and the standoff gap between the jig and PCB was 4.56 mm. Thermal cycling was carried out in the temperature range of −45 to 125 °C, with a dwell time of 210 min for one cycle. The thermal cycle profile and its detailed information are shown in Fig. 3 and Table 2. Random vibration was performed at the root mean square (RMS) values of acceleration, 2.5 G_{rms} in the frequency range of 400–2000 Hz. Only z-axis vibration was applied to the test samples. Moreover, the vibration test was performed during thermal cycle until 500 cycles. After the combined vibration test, the samples were polished with a SiC paper and Al_2O_3 powder, and, etched with a solution consisting of 95% C_2H_5OH, 3% HNO_3 and 2% HCl (in vol%). After etching, the cross-sectional images and interfaces of the solder joints were observed to evaluate the reliability of the Pb-free solders by using a FE-SEM (Inspect F, FEI) and an energy-dispersive X-ray spectroscope (EDS; 8825B-1DUS-SN, Thermo Electron Co.)

3. Results and discussion

To identify the failures of each solder, the changes in electrical resistance were measured at every 10 cycles using a multi meter. It is one of the simplest methods to measure the reliability of solder [23,24]. The initial electrical resistance of each solder varied from 0.3 to 0.4 Ω. During the combined vibration test, it gradually increased to approximately 1.0 kΩ. Finally, the signal of the electrical resistance of the solder indicated zero value, which implied that the resistance approached infinity. A zero signal of electrical resistance indicates the failure of the solder joint. Fig. 4 shows the accumulated number of failure for each solder during the combined vibration test with increasing number of cycles. As shown in Fig. 4, the SnCuAl(Si) solder exhibited the lowest number of failure among the three solders. The total number of sample was 14, and the number of failures was 8, 6, and 4 for SAC305, Sn0.7Cu, and SnCuAl(Si) solders, respectively; that is, the failure percentage was 57.14%, 42.86%, and 28.57%, respectively. Overall, most of the failures appeared at the PCB side than at the FBGA side. It is assumed that the increase in the thickness of the IMC due to thermal cycling affects the failure of the solder joint during the combined vibration test, which results in increased electrical resistance. Therefore, we assumed that SAC305 had the thickest IMC than the others did and measured the IMC thickness of each solder.

The IMC thicknesses of FBGA package side (top) and PCB side (bottom) of the as-reflowed solder samples and samples subjected to 500 cycles of random vibration are shown in Fig. 5. The initial IMC thicknesses of the solders were 2.18, 1.38 and 1.32 μm at the top side and 2.10, 1.369 and 1.34 μm at the bottom side for SAC305, Sn0.7Cu