

Reliability evaluation of lead-free solders for automotive applications

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ABSTRACT

Thermal shock and thermal cycle tests in the temperature range from -40 °C to +150 °C was performed to understand the joint reliability of Sn3.5Ag, Sn0.7Cu and Sn5.0Sb. For the thermal tests, the solder balls of the BGA test chips were fabricated using the materials. The chips are assembled to a daisy chain PCB. Thermal shock tests as well as thermal cycle tests were performed, and the resistance of the solder joints was monitored during the test. To analyze the failure, microstructure with respect to IMCs morphologies and thickness was analyzed and compared. The shear strength was also measured depending on the thermal cycles. A preliminary stress analyses was also conducted by numerical simulation. It was found that Sn0.7Cu exhibited superior mechanical properties among the investigated solder materials in the present test method.

Key words: lead-free solder, high temperature reliability, joint properties, automotive, thermal cycle

INTRODUCTION

A number of lead-free solder materials for interconnects have been studied and evaluated to cope with recent global environment regulation. The lead-free solder materials should fulfill the technical demands in the electronic packaging area as well as the environmental concerns. Fortunately, much advance has been achieved and plenty of accomplishments and results have been reported. However, those accomplishments and results focused on relatively mild environmental situation under temperature of 85 °C for commercial electronics devices. Recently, lead-free solder materials have been widely applied to automotive electronics due to ELV (End of Life Vehicle) legislation. Thereby, high temperature solders have been adopted to manage high temperature environments of automotive engine room and transmission. However, the methods to evaluate the solder materials have not sufficiently developed to satisfy the technical requirements because the usage surroundings are totally different from the conventional ones. Delphi Delco Electronic System recently published the typical continuous maximum temperatures as stated 140 °C on engine and transmission [1]. In this temperature level, there exist many engineering issues which could not be observed in the lower temperature, therefore proper evaluation of the reliability should be conducted.

In the present research, thermal shock and thermal cycle test with the temperature range from -40 °C to 150 °C was performed. This condition was assumed to be sufficiently similar with automotive environment under operation. Three different lead-free materials of Sn3.5Ag, Sn0.7Cu and Sn5.0Sb solders were used, and the effects of thermal cycling on the materials were investigated by measuring resistance changes. Microstructure evolution and interface structure change after the thermal reliability test were microscopically observed and correlated with the solder ball shear strength and failure modes.

FABRICATION OF BGA CHIP MODULE

BGA test chips with the size of 8 x 8 mm and the thickness of 0.7 mm were prepared. The BGA test chip has a daisy chain to measure the resistance during the test. Cu pad of the BGA test chip was finished with ENIG. Pad diameter was 300 μ m, and the pitch was 0.8 mm. Scanning acoustic micrometer (SAM) image of BGA test chip is shown in Figure 1. As seen, a silicon die is encapsulated in the molding compounds, and signal detected in the area of x1 (left image of Figure 2) indicated the phase was not converted, which informed no defect between silicon die and mold compound.

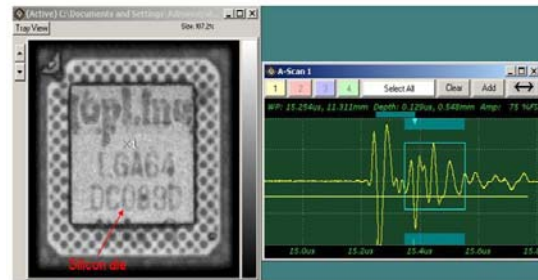


Fig. 1. SAM image of BGA test chip

The lead-free materials of Sn3.5Ag, Sn0.7Cu and Sn5.0Sb were prepared for the solder balls, and were reflowed by solder pastes of the corresponding composition to the base solder ball materials. Each solder ball was mounted on the ENIG pad dispersed with flux and bonded by reflow process. The reflow temperature profile is shown in Figure 2. Thereby, BGA chip specimen with 64 solder ball was fabricated. And then, this BGA chip specimen was mounted on the daisy chain PCB again and reflowed. The material of the PCB was FR4, and Cu pad was treated with organic surface

preservative (OSP) finished. Figure 3 showed the schematic illustration of BGA chip module and Figure 4 showed the fabricated BGA test module and daisy chain.

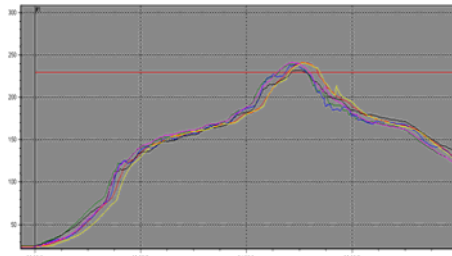


Fig. 2. Reflow profile for the lead-free materials

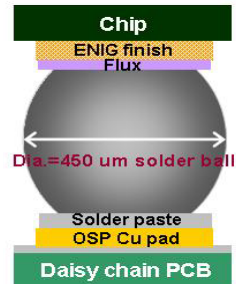


Fig. 3. Schematic illustration of test module

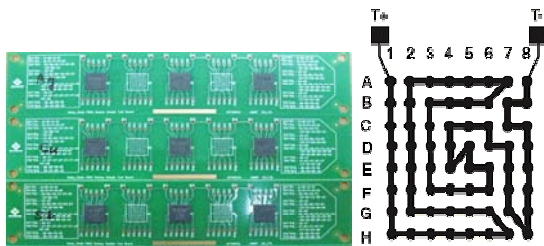


Fig. 4. Fabricated chip module (left) and daisy chain (right)



Fig. 5. Thermal shock and cycle tester

TESTS

Thermal shock test and thermal cycle test were performed by VT 7012 S2 and VTS made by Votsch co. Ltd., German. In the thermal shock tests, the specimens in the chamber move reciprocally between the hot and cold chambers by a elevator type sample mover. On the other hand, the thermal cycle tester has only one chamber, which can control the heating rate and cooling rate. Thermal shock and thermal cycle tester are shown in Figure 5.

Test temperature range was set from -40 to +150 °C to simulate the actual automotive operation environment.

Dwell time with respect to each temperature was 10 minutes and one cycle was approximately 25 minutes as shown in Figure 6. The 10 min dwell period begins when the specimen is within 3 °C difference from the target temperature. The thermal reliability test was carried on up to 1500 cycles.

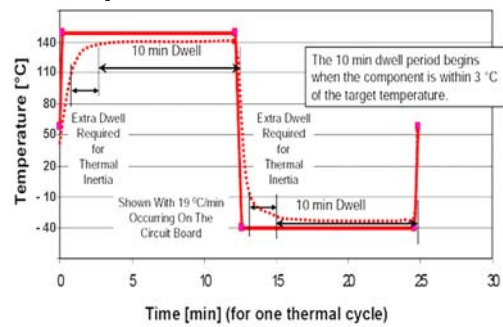


Fig. 6. Thermal shock profile

During the reliability test, the variation of the resistance was monitored and measured at real-time. MultiMeter 3700 made in Keithley co. Ltd. was used for the measurement of the resistance change. Detecting time for the resistance was every 30 minute.

The plots of the resistance variations by the thermal shock test are shown in Figure 7(a). Depending on the materials, the profiles of the resistance increase exhibited different patterns as the number of cycle was increased. A similar tendency was observed in case of Sn0.7Cu and Sn5.0Sb. As the number of cycle was increased, the resistance was gradually increased. Final resistance after 1500 cycles of the test was found to be 25% more than the initial resistance. However, in case of Sn3.5Ag, resistance was drastically increased during the test.

The resistance variation profiles by the thermal cycle tests are illustrated in Figure 7(b). Again, sharp increase of the resistance was observed for Sn3.5Ag. In this case the resistance was increased continuously through the whole test duration in the thermal cycle test, while the sharp increase was observed after 750 cycles in thermal shock test. For Sn0.7Cu and Sn5.0Sb cases, the resistance increased very similar to that of the thermal shock. These plots indicated that Sn0.7Cu and Sn5.0Sb were more stable than Sn3.5Ag.

JOINING STRENGTH

Joining strength was measured by a shear tester, and the results were compared. The plots of joining strength and comparison were exhibited in Figure 8(a) for the thermal shock tests, and Figure 8(b) for the thermal cycle tests. Initial strength of as-reflowed showed different values among the three types of materials. That of Sn5.0Sb was measured at 29.2 kg_f and Sn3.5Ag, Sn0.7Cu were measured at 28.1 kg_f and 23.1 kg_f, respectively. The joining strengths of Sn3.5Ag and Sn5.0Sb were sharply dropped after 250 cycles of the test while Sn0.7Cu exhibited relatively gradual decrease. However, after 750 cycles, all the materials showed fast decrease.

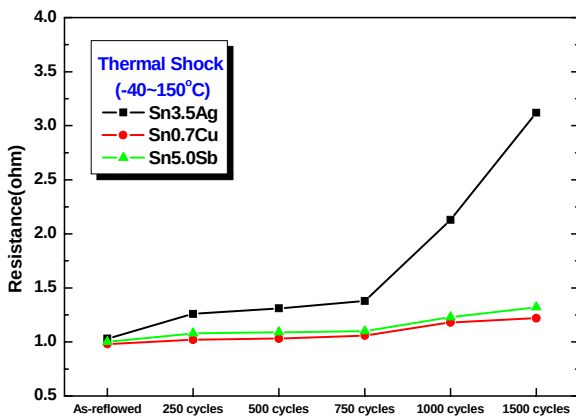


Fig. 7(a). Variation plots of resistance at real-time in thermal shock test

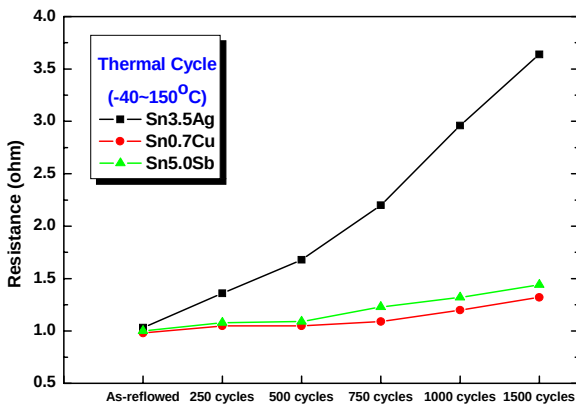


Fig. 7(b). Variation plots of resistance at real-time in thermal cycle test

The trends of the rapid resistance changes and the strength changes are similar for Sn3.5Ag, however, the data of the other two materials provided little relationship between the resistance change and the strength change. The test results represented that Sn0.7Cu showed relatively stable variation of the strength, and its final strength value was the highest compared with the other two materials. In general, the joining strengths of the lead-free solders were strongly affected by the thermal tests.

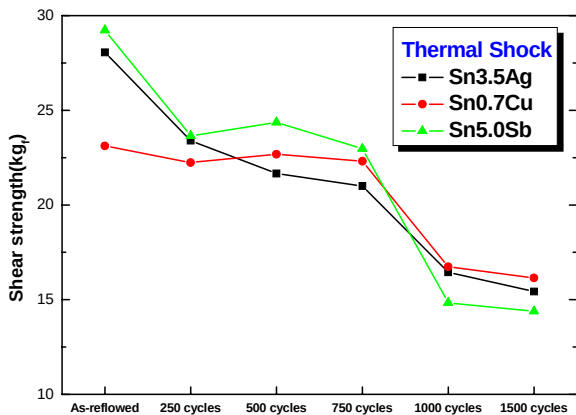


Fig. 8(a). Variation plots of joining strength in thermal shock test

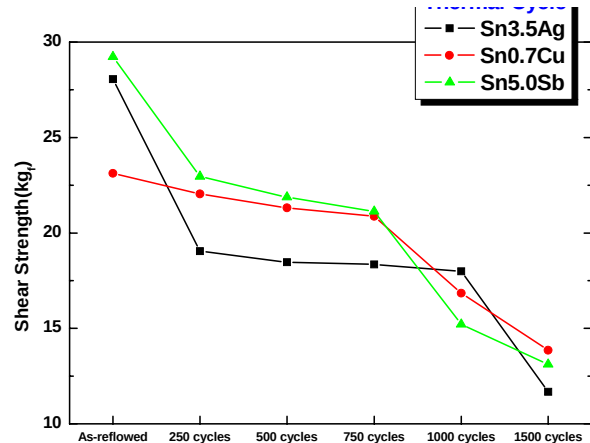


Fig. 8(b). Variation plots of joining strength in thermal cycle test

MICROSTRUCTURES

As was mentioned previously, the fabricated BGA test module has two different interfaces: one is between ENIC finished Cu pad in the chip side, the other is OSP finished Cu pad in PCB side as shown in Figure 4. The change of microstructures was observed and espoused to the results of joining strength, particularly focused on the IMC morphologies. The IMC morphologies of the each solder were shown in Figure 9.

In case of Sn3.5Ag, IMC was grown very irregularly in both chip side and PCB side after the thermal test. And also, the spalled Cu_6Sn_5 IMCs were observed at the interface in PCB side, which could be detrimental in the reliability of the solder joints. After 1500 cycles of the thermal test, the thickness of the IMC was about 6.1 μm .

In case of Sn0.7Cu, initial thickness as well as final thickness of IMC was fairly thin compared with those of Sn3.5Ag and Sn5.0Sb. Probably, 0.7 wt. % of Cu lessened the concentration gradient, so diffusion driving force that is necessary for the growth of IMC was decreased. Another possibility for the thin IMC layer stems from the higher activation energy of Sn0.7Cu than those of Sn3.5Ag and Sn5.0Sb [2,3]. And, initially, IMC morphologies of Sn0.7Cu was irregular, like column structure. After the test, the shape has been transformed into flat-like morphologies. Initial IMC thickness of Sn0.7Cu was measured at 1.96 μm and IMC was grown up to 2.34 μm after the test.

In case of Sn5.0Sb, initial IMC thickness was measured at 4.14 μm and grown up to 6.81 μm . The IMC of Sn5.0Sb was the thickest among the materials used in this study. However, IMC morphologies were more uniform than those of Sn3.5Ag.

The fracture surface was observed with SEM and shown in Fig. 10. From EDS analysis, Sn, Ag, Cu, and Sb were detected on the failure surface. Therefore, the fracture occurred inside solders, not at the interface. It was found that the main mechanism of the Sn3.5Ag solder joint failures was brittle fracture, as seen in Figure 11. On the other hand, ductile fracture was dominant for Sn0.7Cu, and the mixture of the brittle and ductile fracture was found for Sn5.0Sb.

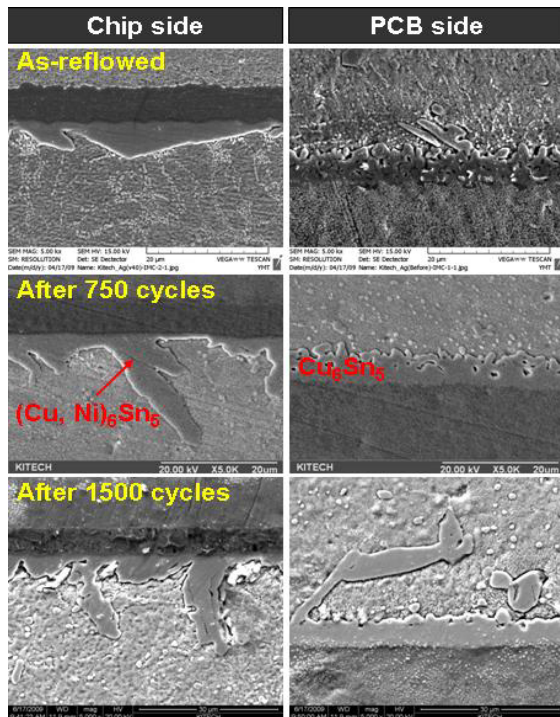


Fig. 9(a). IMC morphologies of Sn3.5Ag in both side of chip and PCB.

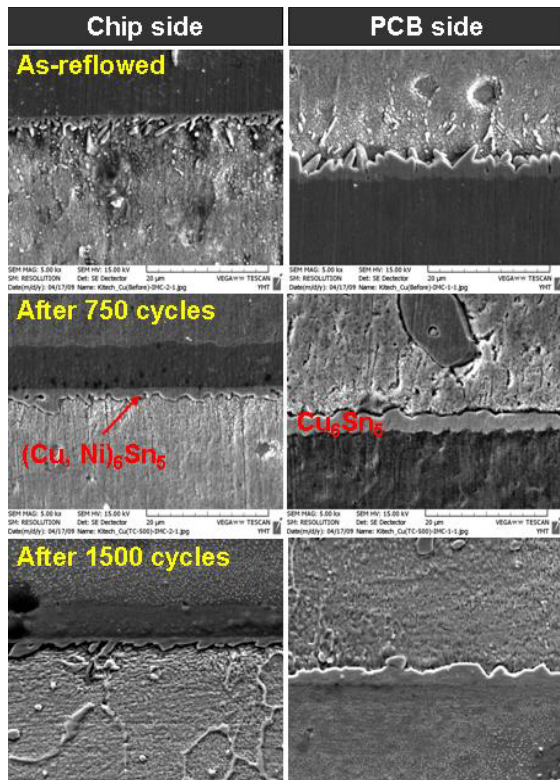


Fig. 9(b). IMC morphologies of Sn0.7Cu in both side of chip and PCB

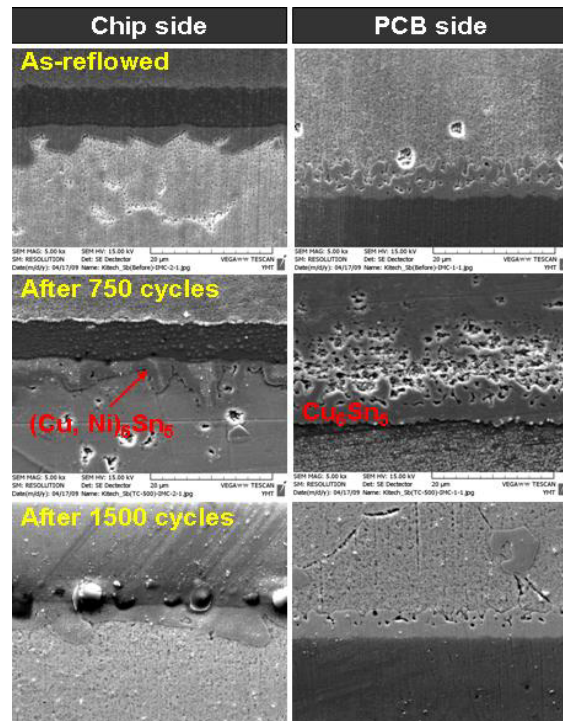


Fig. 9(c). IMC morphologies of Sn5.0Sb in both side of chip and PCB

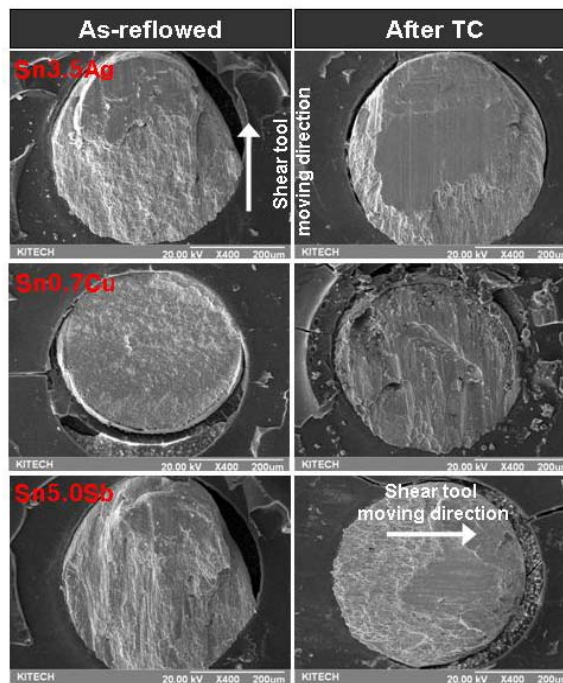


Fig. 10. SEM analyses of fracture planes

STRESS ANALYSES ON THE SOLDER INTERCONNECTS

In addition to the solder materials characteristics, the packaging structure geometry is also important to understand the failure mechanism. Depending on the geometry, the stress development and the critical locations favorable to the failure may vary. In this section,

preliminary analyses of the stress development on the solder interconnects are performed. A program was written for ANSYS to simulate the stress generation during the accelerated thermal cycle tests. The material properties used in the simulation is listed in Table 1. The section geometry of the chip is represented in Figure 11. A strip type FEM model was employed, and the modeling is shown in Figure 12. The stress free temperature was assumed at 255°C, where the solder was reflowed to the PCB, and the temperature was dropped to -40 °C. Von-mises stresses in the solder joints were calculated, and plotted as shown in Figure 13. Numbers are assigned to the solder ball from the center of the chip. As seen, the maximum stress is generated in the no. 3 solder ball joint to the chip side (ENIG interface), which is located at the end of the silicon chip.

	PCB	Si	EMC	BT substrate	Solder	Cu pad
E (GPa)	12.5	160	20	21	35.8	121
Poisson's ratio	0.28	0.3	0.25	0.26	0.4	0.35
CTE (ppm)	13.6	2.3	15	11	21	16

Table 1. Material properties of the component materials of the test module

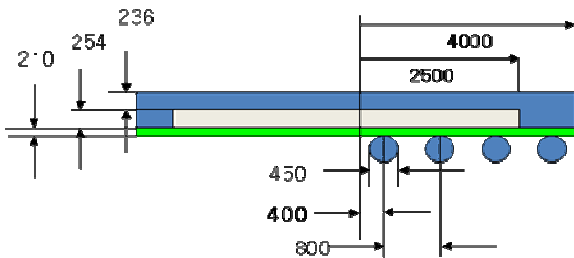


Fig. 11. Chip section geometry (unit: mm)

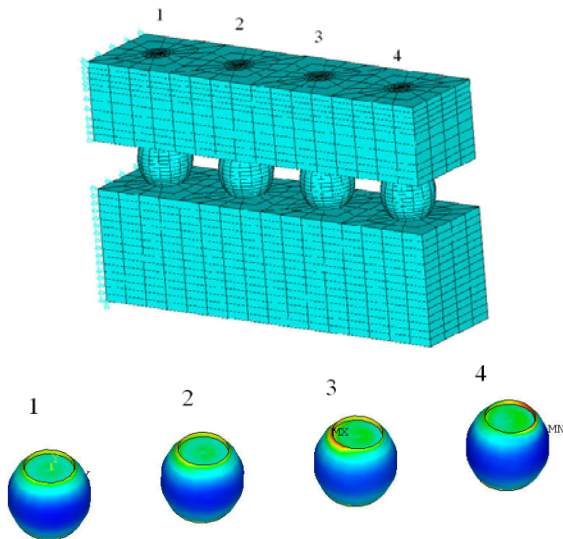


Fig. 12. Strip type finite element modeling and the von-mises stress in the solder balls

The thermal tests with the temperature range of -40 °C ~+150 °C on the three different types of the lead-free solder materials were conducted. The resistance changes, IMC layers and the shear strengths were examined to evaluate the reliability. Sn0.7Cu and Sn5.0Sb showed relatively small increase of the resistance, while the resistance of Sn3.5Ag rapidly changed. Regarding the shear strength, all the materials exhibited the sharp decrease, showing the strong influence of the temperature on the strength. The IMC investigation revealed that the IMC of Sn0.7Cu showed the least growth, resulting in the thinnest thickness. The data demonstrated that Sn0.7Cu was the most reliable material under the temperature cycling. Further studies considering potentially influencing factors such as the packaging geometry are under progress.

ACKNOWLEDGEMENTS

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CONCLUSION