

Effect of vibration on lead-free solder joint reliability under temperature changes for automotive electronics

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ABSTRACT

The reliability of lead-free solder balls of Sn-3.5Ag, Sn-0.7Cu and Sn5.0Sb was evaluated by vibration tests under temperature changes. The materials were used to fabricate BGA test chips, and those are assembled with daisy chain circuit board to prepare the test module. Random vibration was applied under temperature cycle, and the resistance of the solder ball was monitored during the test. Shear strength and microstructure with respect to IMCs morphologies and thickness were also analyzed. A numerical simulation to obtain the natural frequency and corresponding modes were performed to estimate the frequency range effect of the random vibration on the test module. It was found that Sn-0.7Cu exhibited superior mechanical properties among the investigated solder materials in the present test method.

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

INTRODUCTION

Recent global environment regulation leads to utilize various lead-free solder materials for interconnection joining materials. Not only the electronic industry but automotive industry requires substituting lead solder materials for lead-free solder materials. For instance, the exemption of ELV legislation for vehicle electronics will be expired in January 1st, 2011. Thus, it is imperative to find pertinent lead-free solder materials to replace the conventional lead containing solder materials. Since automotive electronics near engine or under-hood undergoes severe vibration and high temperature during the operation of vehicles, the investigation of their effects on the reliability is very important. A number of studies have been reported on the temperature reliability test and vibration test independently. However, reliability test combining temperature with vibration at the same time has yet researched so far, although they are closely related in actual automotive environment. Few literatures are available for this subject. Among them, Delphi Delco Electronic System recently published the typical continuous maximum temperatures as stated 140 degree Celsius on engine and transmission with the vibration level up to 10 Grms [1].

In the present study, a preliminary investigation of the random vibration effect under temperature change on

the reliability of Sn3.5Ag, Sn0.7Cu and Sn5.0Sb solders was performed. BGA test chips with daisy chains were fabricated using the solder materials, and the chips were assembled on a circuit board to monitor resistance changes during the test process. Random vibration was applied under temperature change. Microstructure evolution and interface structure changes after the tests were examined and correlated with the solder ball shear strength and failure modes. The data was compared, and used to evaluate the reliability of the solder materials.

FABRICATION OF THE TEST MODULE

Several BGA test chips with daisy chain were prepared, and CT x-ray image of the chip is shown in Figure 1. A silicon die with daisy chain was encapsulated in the molding compounds. Cu pad of the BGA chip was finished with ENIG. The pad diameter was 300 μ m, and their pitch was 0.8 mm. The net shape in the Figure is an extra Cu reinforcing the BT substrate structure under the silicon chip.

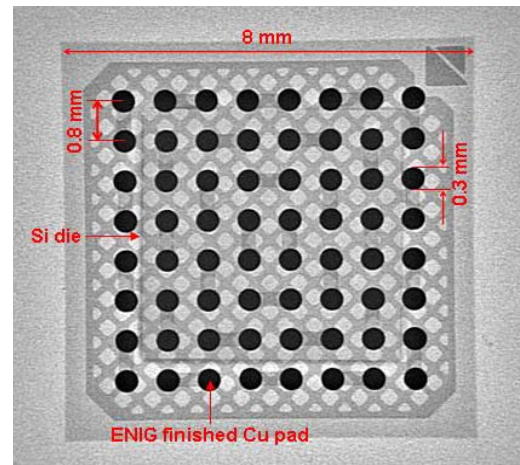


Fig. 1. CT x-ray image of BGA test chip

For the solder ball formation on the chip, the ENIG pad was dispersed with flux, and each solder ball was mounted on the pad and bonded by reflow process. The total number of the solder balls was 64. Then, this BGA chip specimen was mounted on the daisy chain circuit board again and reflowed. The material of the daisy chain board was FR4 and Cu pad was treated with organic

surface preservative (OSP) finished. Figure 2 shows the schematic illustration of the solder joint, and Figure 3 shows the fabricated test module and the daisy chain.

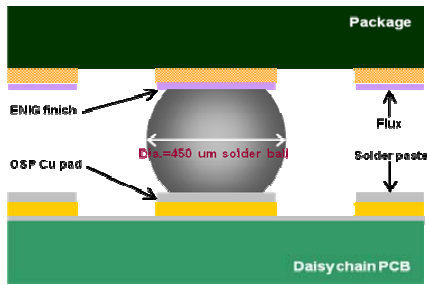


Fig. 2. Schematic illustration of the solder joint

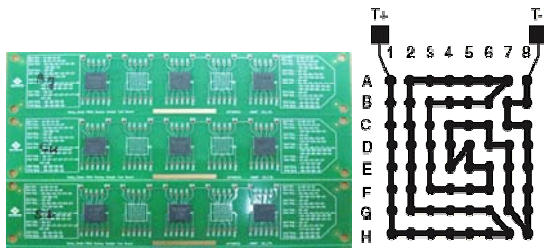


Fig. 3. Fabricated chip module (left) and daisy chain (right)

TESTS

The vibration tests were performed by Shinken G-0120V. The test modules were attached on top of the vibrating plate with a Teflon tape. During the test, the resistance change was continuously monitored by MultiMeter 3700 (Keithley co. Ltd.). Detecting time for resistance was every 2 minute. The schematic illustration of resistance measurement and the test module installation on the vibration plate are shown in the Figure 4. After the test module installation, two types of accelerometer were attached. One accelerometer was attached on the vibration plate, which monitored the frequency that transmitted to the plate. And the other accelerometer was attached on the daisy chain circuit board to detect the frequency that transmitted to the board. The reason that the accelerometers were employed is that the plate and the interior vibrator were bolted together, thus, resonant frequency was occurred. The accelerometers prevented the possible errors from the discrepancy of the frequencies of the plate and the test module. Hence, accurate value of frequency applied to the test module could be monitored by the accelerometers.

The vibration was randomly applied in the frequency range of 10 Hz ~1,000 Hz with 3G force. The total test time was 20 hours. Vibration profile is exhibited in Figure 5, and the temperature profile applied during the vibration is shown in Figure 6. In the initial stage, the temperature was decreased to -40°C , then increased to 150°C , then returned to room temperature.

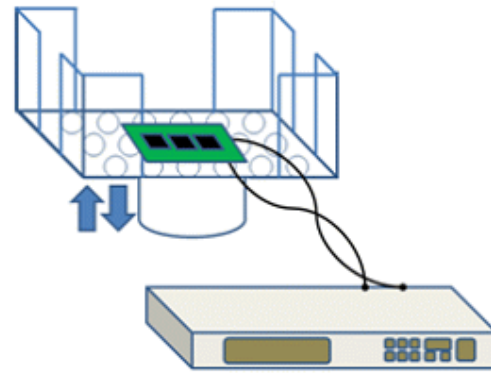


Fig. 4(a). Schematic illustration of resistance measurement

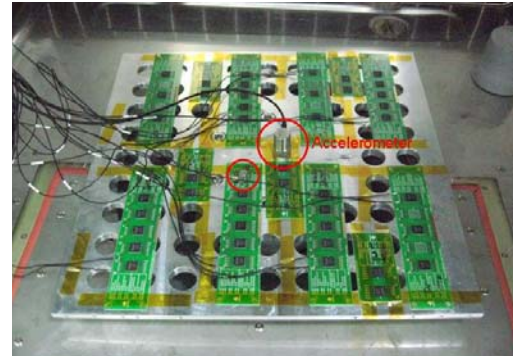


Fig. 4(b). Image of resistance measurement

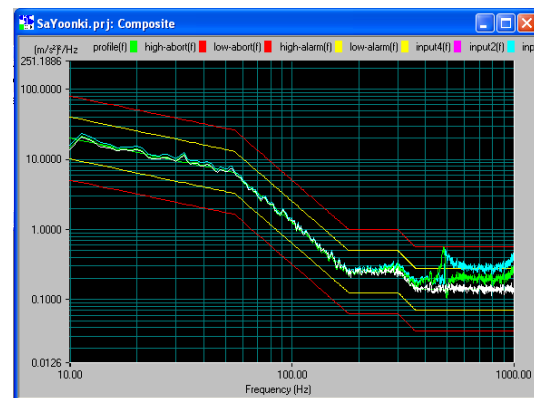


Fig. 5. Vibration profile

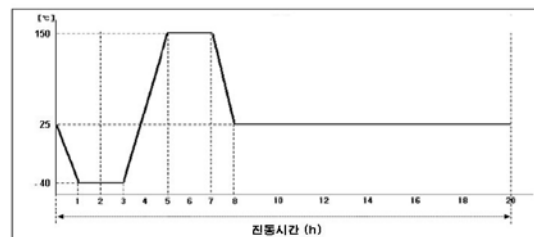


Fig. 6 Temperature profile

The test was performed according to the profiles to z-axis (out of the plane to the vibration plate). The resistance changes during the test are illustrated in Figure 7. The resistance change profiles of the materials are similar. As the temperature was decreased, the resistance values were declined, and as the temperature was increased, the resistance was also increased. However,

peak resistance values had a slight difference among the solder materials. Sn-0.7Cu was lower than other solder materials. After 20 hour test to z-axis, the tests to x-axis and y-axis were conducted consecutively, until any fracture was observed. Figure 8 represents the resistance variations of the materials. After 120 hour, the resistance value of Sn-3.5Ag was increased about 38 %. The resistance values of Sn-0.7Cu and Sn-5.0Sb were also increased, but not as much as Sn-3.5Ag. Figure 7 and Figure 8 indicate Sn-0.7Cu and Sn-5.0Sb were more stable than Sn-3.5Ag in this test.

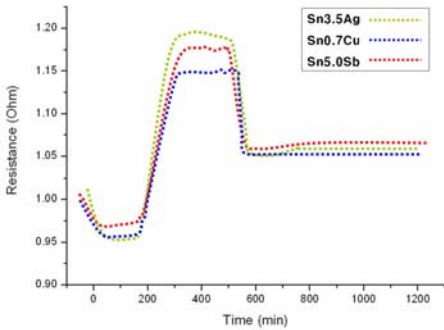


Fig. 7. Variation plots of resistance at real-time for the first 20 hours.

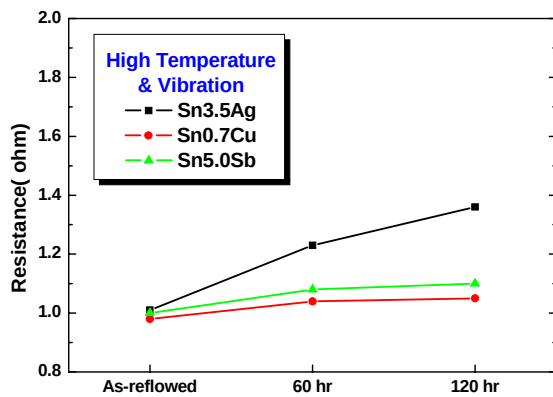


Fig. 8. Variation plots of the resistances

JOINING STRENGTH

Joining strengths were measured by shear tests and compared. The results are illustrated in Figure 9. Initial strength of as-reflowed solder joints were 29.2 kg_f for Sn-5.0Sb, 28.1 kg_f for Sn-3.5Ag and 23.1 kg_f for Sn-0.7Cu, respectively. However, joining strength of Sn-3.5Ag was sharply dropped as the reliability test was carried out. Similar decrease was observed from Sn-5.0Sb in the beginning stage, and then showed a tendency to be saturated. In case of Sn-0.7Cu, the joining strength remained relatively stable.

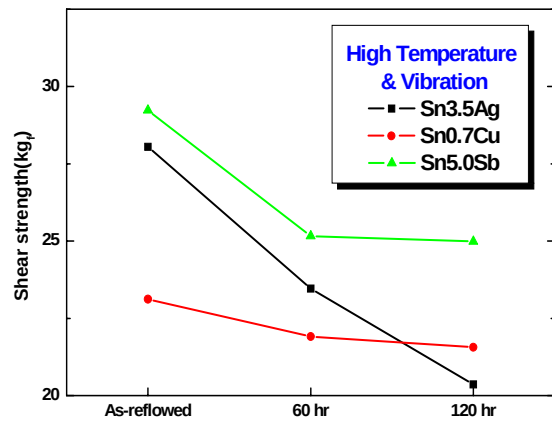


Fig. 9. Variation plots of joining strength

MICROSTRUCTURES

The change of microstructures was observed and espoused to the results of joining strength. Cross section and IMC morphologies of each solder material were shown in Figure 10.

In the case of Sn-3.5Ag, the cross section was not significantly changed after the test. However, the thickness of the intermetallic compounds (IMCs) was increased from 4.14 μm to 4.61 μm , and Ag₃Sn particles were observed in the solder. Presumably, as the thickness change was small, it may not be the main reason of the joining strength drop. The reason intermetallic compounds change was small might be assumed that IMC layer encountered coarsened Ag₃Sn particles in the solder. The Ag₃Sn particles acted as physical barriers to the IMC growth [2]. Also, exposure to high temperature was not sufficiently long enough to accelerate the growth of IMC because IMC growth is a function of the exposure time to high temperature. Nevertheless, growth rate of Sn-3.5Ag was not fast, joining strength was significantly decreased. Decrease of joint strength might be resulted from brittle IMC formation of Ag₃Sn inside the solder. Large plate growth of Ag₃Sn was considered to be formed and crack might be initiated and propagated along the IMCs due to accumulated fatigue come from vibration and high temperature cycle.

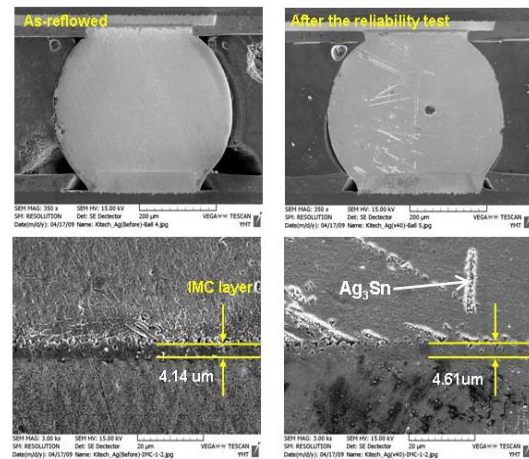


Fig. 10(a). Cross section of Sn-3.5Ag and IMC morphology

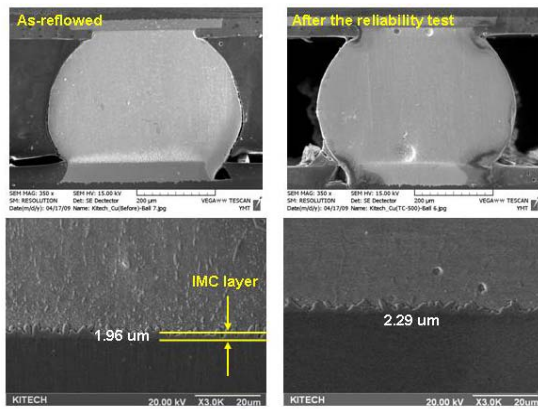


Fig. 10(b). Cross section of Sn-0.7Cu and IMC morphology

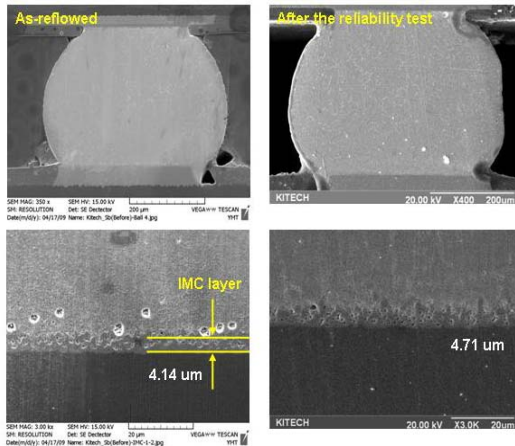


Fig. 10(c). Cross section of Sn-5.0Sb and IMC morphology

Initial IMC thicknesses of Sn-0.7Cu and Sn-5.0Sb were measured as 1.96 μm and 4.14 μm, respectively, and were gradually grown up to 2.29 μm and 4.71 μm. Evidentially, the IMC thickness of Sn-0.7Cu was the thinnest among the three solder materials. It is assumed that 0.7 wt. % of Cu lessened the concentration gradient, so diffusion driving force that is necessary for growth of IMC was decreased. In addition, morphology of IMC layer of Sn-0.7Cu was relatively regular compared with the other two solder materials. This could explain why the joining strength and resistance of Sn-0.7Cu were relatively stable.

The joint strength test data for Sn-5.0Sb indicates that the IMC growth mainly occurred during the initial stage of the test, then the grow rate was gradually inhibited and saturated. Thus, joining strength showed a sharp drop for the first 60 hour of the test and then, slightly decreased.

The fracture surfaces were examined with SEM and shown in Figure 11. From EDS analysis, Sn, Ag, Cu, and Sb were detected on the failure surface, indicating that the fractures were occurred inside the solders, not at the interfaces. It was found that brittle fracture was dominant for all the lead-free solders. Dimple structure was partially observed in Sn-0.7Cu solder material. The picture of the dimple structure and the EDS results are shown in Figure 12.

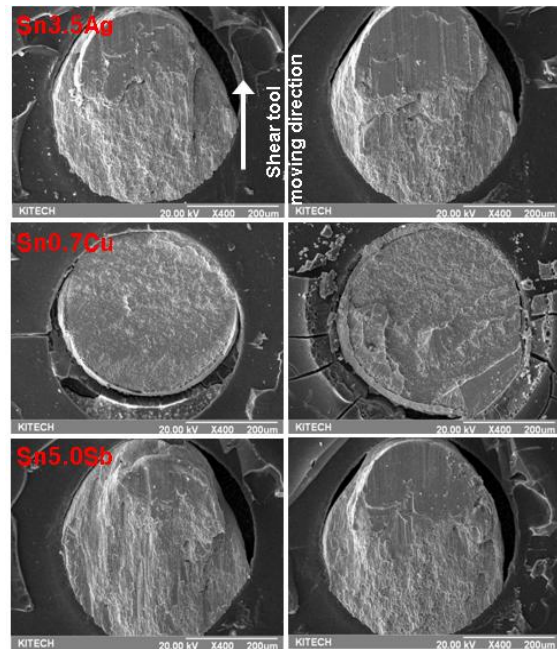
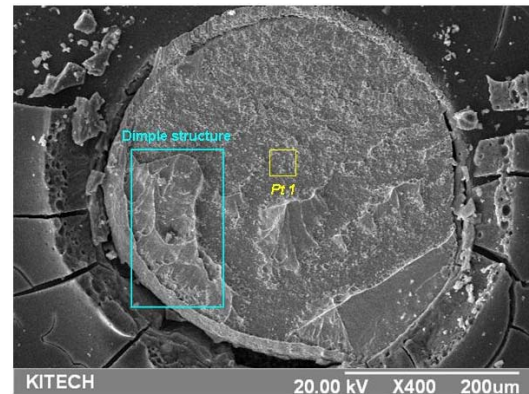


Fig. 11. SEM analyses of fracture planes



Weight %		
	Cu	Sn
Base(9)_pt1	36.47	63.53

Fig. 12. Fracture images and EDS analysis

NATURAL MODE ANALYSES OF THE SAMPLE

Predicting the correct fundamental frequencies and corresponding mode shapes is critical in estimating the frequency effect on the solder joint damage. To estimate the vibration frequency effect, the natural mode of the test module was analyzed by numerical method. To calculate the natural frequency and corresponding modes, ANSYS was employed for the modeling. The sample size and the installed chip location are shown in Fig. 13. As was explained previously, the samples were located on the vibration plate by fixing the two edges by a Teflon tape as shown in Figure 6(b) and Figure 14. Therefore, the edge condition might be similar to the mixture of simply supported (displacement to x and z directions were fixed at both ends) and clamped boundaries (displacements and rotations are fixed at both ends). Therefore, the natural frequencies of the both boundary conditions were

calculated. The weights of the circuit board, silicon chip and the solder balls were carefully measured to obtain the mass. The calculations were particularly focused on the natural frequencies existed in the random frequency range of 10 Hz ~ 1000 Hz. The results are listed in Table 1. There are 5 natural frequencies for the simply supported case, and 2 for the clamped case. The lowest frequency is 170 Hz, and the highest one is 831 Hz. The first natural modes of the simply supported case and the clamped case are illustrated in Figure 15. Clearly, the natural mode may effect on the chip reliability due to the different deformation depending on the frequency. Further study is planned for the frequency effect.

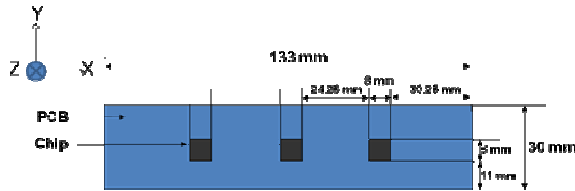


Fig. 13. Test coupon geometry.

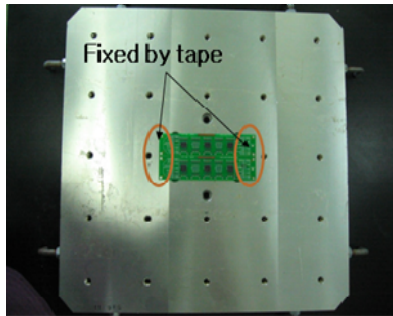


Fig. 14. Sample installation on the vibration plate

	Simply supported					Clamped	
Mode	1 st	2 nd	3 rd	4 th	5 th	1 st	2 nd
Hz	170	560	725	779	871	531	831

Table 1. The natural frequencies of the sample.

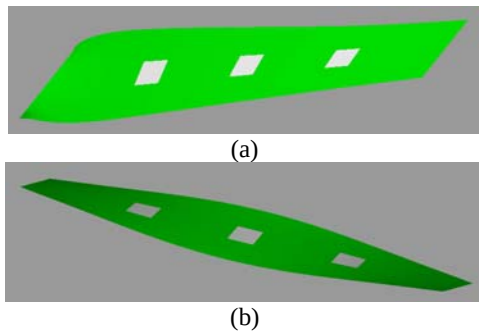


Fig. 15. The first natural mode of the sample: (a) simply supported case (b) clamped case.

Based on the data, it was observed that the reliability of Sn-0.7Cu was superior to the other two materials. A further investigation on the detail effect of the temperature changes with different cycle pattern, and the relationship with the vibration are under process.

CONCLUSION

The influence of the vibration under temperature changes on the joint of lead-free solder materials was examined. To analyze the resistance data monitored during the tests, the joint strength tests and the intermetallic section investigations were also performed. The results showed that, among the lead-free solder joint materials considered in this study, Sn-0.7Cu was the most reliable material against the random vibration test combined with the temperature change in the range from -40 °C to 150 °C. Further investigation is needed to understand the detail understanding of the failure mechanism, which is under progress.

ACKNOWLEDGEMENTS

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