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Brittle Failure and Effect of Thermal Aging on Pb-free Solder Flip Chip Using Electroless Ni-P UBM

Yong-Min Kwon*, Young-Doo Jeon, Kyung-Wook Paik, Jung-Do Kim[1], and Jin-woo Lee[1]

Dept. of Materials Science and Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-701, Korea
[1]Samsung Techwin Co., LTD., Yongin 449-712, Korea

Electroless Ni plating is a cost effective process for manufacturing the under bump metallurgy (UBM) in a solder bump flip chip. However, Pb-free solder joints using electroless Ni UBM are prone to brittle failure during reflow and underfill processes. Hence, application of electroless Ni UBM to a Pb-free solder flip chip is restricted by low assembly yield. In order to analyze the causes of brittle failure, thermal cycling tests were performed with various solder flip chips. In the thermal cycling tests, a eutectic PbSn solder flip chip before underfill shows no brittle failure, even after 5 cycles. On the other hand, most Pb-free solder flip chips before underfill failed less than 5 cycles because of brittle failure such as Si cratering and delamination on the electroless Ni-P/Al interface. Consequently, the flip chip assembly using Pb-free solder and electroless Ni-P UBM shows low yield problem during the flip chip assembly cooling process due to the thermo-mechanical stress build at the UBM/solder joint. To reduce stress on the solder joints, the effects of additional aging after reflowing were investigated. SnAgCu solder flip chips before underfilling were aged for various times and temperatures immediately after the solder reflow process. The results showed that the yield of the assembly process was increased by about 30 percent by additional aging. Furthermore, SnAgCu solder joints aged for longer time showed better reliability in thermal cycling tests before underfilling. Measurement of the flip chip warpage reveals that the additional aging processes cause creep deformation in the solder bumps and result in smaller flip chip warpage in comparison with directly air-cooled flip chips.

Keywords: electroless Ni-P, Pb-free, brittle failure, reliability

1. INTRODUCTION

Flip chip technology is a promising chip interconnection due to its small size, high I/O density, and good electrical performance. However, flip chip interconnections on organic substrates have reliability concerns because of the large differences in the coefficients of thermal expansion (CTE) between Si and organic materials. In a flip chip package without underfill, solder joints suffer high stress, resulting in failures during the assembly process. In order to improve the thermal reliability of flip chip joints on organic substrates, underfill materials are employed to fill the gap between the chip and the substrate. In underfilled flip chip joints, solder joints usually fail as a result of fatigue failure[7].

Electroless Ni-P under bump metallurgy (UBM) has low cost and good wettability with Sn based solder bumps[1]. However, solder joints using electroless Ni-P UBM are known to have a brittle Ni-P layer[2]. Brittle failure such as cracking of the Ni-P layer, Si cratering, and delamination of the UBM/solder interface have been reported for electroless Ni UBM and solder interfaces[3-4]. Further, the assembly yield of Pb-free solder flip chips using electroless Ni-P UBM is reduced by these failures.

In flip chip joints using Pb-free solders, higher reflow temperature can induce larger thermal expansion mismatch. Therefore, Ni-P UBM combined with Pb-free solders suffer higher stress than Pb containing solders before underfilling because less stress relaxation occurs in Pb-free solders.

As a result of this thermal stress before underfilling, flip chip joints employing Pb-free solders and electroless Ni-P UBM are prone to brittle failure. In the present study, the effects of varying UBM thickness and assembly process parameters were investigated in an effort to improve the reliability of Pb-free solders flip chip using electroless Ni-P UBM on organic substrates.

2. EXPERIMENTS

10 mm×10 mm size Si chips with peripherally distributed 144 Al I/Os were prepared. The distance from the neutral

*Corresponding author: Okita@kaist.ac.kr

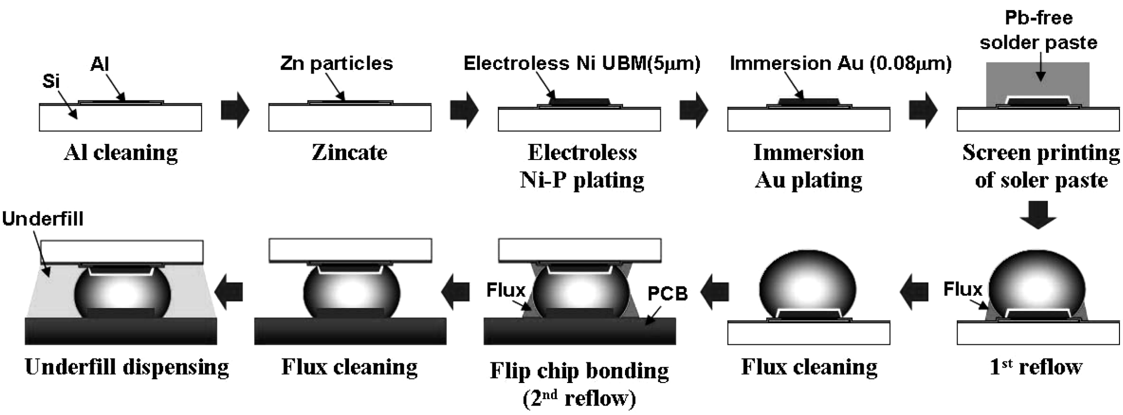

Fig. 1. Flip chip fabrication and assembly process.

point (DNP) of the outmost solder bump was 6.37 mm. After acid cleaning and zincate treatment, electroless Ni-P/Au UBMs were plated on each Al I/Os. Pb63Sn, Sn3.5Ag, and Sn3.0Ag0.5Cu solder pastes were then screen printed, and subsequently reflowed. The diameter of the solder bumps was about 120 μm.

For the flip chip interconnection, 0.5 mm thick FR-4 PCBs with Cu/Ni/Au metal pads were prepared. Si chips and PCB substrates were aligned using a flip chip bonder followed by reflowing. After flux activation at 150 °C for 1 min, the solder bumps were reflowed at 210 °C for Pb63Sn and 250 °C for Sn3.5Ag and Sn3.0Ag0.5Cu for 2 min, respectively.

3. RESULTS AND DISCUSSION

3.1. Solder joint failure before underfilling

Flip chip joints experience temperature changes during the assembly process such as in the cooling process after solder reflow. Si chips and organic substrates are mechanically jointed through solder bumps, which have large difference of CTE between the chip and organic substrate. This leads to flip chip warpage, ultimately resulting in flip chip failure. In this experiment, electrical resistances of solder joints located at four corners of a Si chip were measured before and after underfill curing. Table 1 shows the failure percentages of flip chip joints with various solder alloys.

Eutectic PbSn solder joints did not show any failure during the assembly process. However, in Pb-free solder joints, a significant amount of failures was observed before underfilling. These failures did not increase after underfilling. Hence, in order to enhance the assembly yield of Pb-free solder flip chips using electroless Ni-P UBM, failures before underfilling should be reduced.

In order to determine the failure mechanism in the Pb-free solder joint, thermo-cycling tests on non-underfilled flip chips were performed. Through the thermo-cycling test, solder joint failures could be induced artificially. Figure 2 shows solder joint failures during a thermo-cycling test at 30 °C~120 °C for 30 minutes. SnAgCu and SnAg solder joints failed initially before the T/C test, and more than 50% of the specimens failed within 3 cycles. However, eutectic PbSn solder joints gradually failed after 15 cycles.

Table 1. Failure percentages of solder joints after reflowing before underfilling and after underfill curing

	Failure % of solder joint (%)	
	After interconnection reflow (Before underfill)	After underfill curing
Pb63Sn	0 %	0 %
Sn3.0Ag0.5Cu	6.3 %	6.3 %
Sn3.5Ag	62.5 %	62.5 %

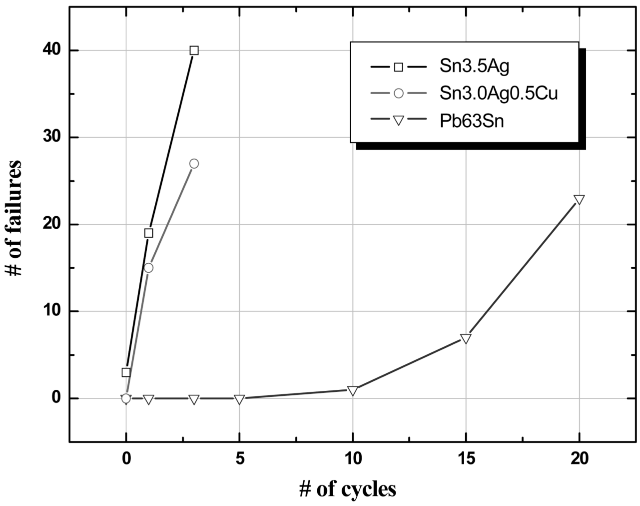

Fig. 2. Thermo-cycling reliability of various solder flip chip joints before underfilling.

Figure 3 shows cross-sectional images of solder joints that failed during the T/C test. After 20 cycles, SnPb solder joints located at both corners of the chip failed as a result of cracking inside the solder bumps near UBM. As temperature cycling increased, failure of SnPb solder joints increased due

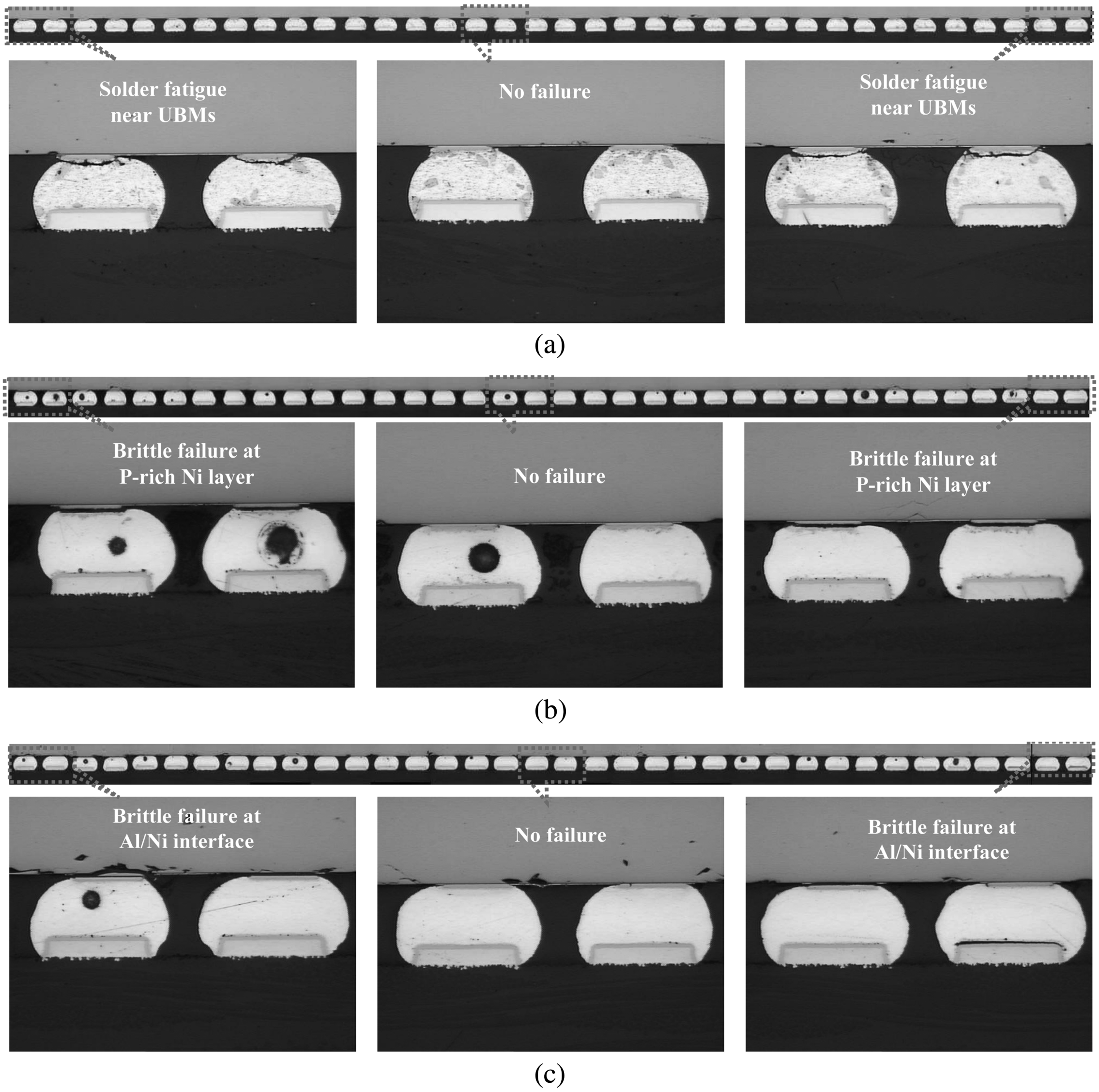

Fig. 3. Cross-sectional images of various solder joints after thermo-cyling test; (a) SnPb solder joints after 20 cycles, (b) Sn3.5Ag solder joints after 3 cycles, (c) Sn3.0Ag0.5Cu solder joints after 3 cycles.

to crack propagation through ductile solder bumps, representing typical fatigue failure. However, in the SnAg and SnAgCu solder joints, there was no fatigue failure. Brittle failure of the P-rich Ni layer and interfacial delamination of the Si chip and Ni-P UBM were observed after 3 cycles.

The different failure modes between PbSn and Pb-free solder joints resulted from the mechanical properties of the solder materials. Warpage of PbSn solder flip chip is relaxed by deformation of the solder joint, because PbSn solder has lower creep strength. However, SnAgCu solder shows a warpage difference between Si and the organic substrate because of its higher creep strength. Therefore, Pb-free solders are expected to have higher stresses due to this warpage difference, which in turn will cause brittle failure during the cooling process after reflowing[6].

3.2. Effects of thermal aging on Pb-free solder joint reliability

The stress is induced by warpage of the flip chip joints due to the large CTE mismatch between Si and the organic substrates. Therefore, brittle failure of solder joints can be prevented by reducing the warpage of the flip chip joints. Most failures in the underfilled flip chip are fatigue failures. In a typical flip chip assembly process, cooling of flip chip joints is immediately performed after solder reflow in order to enhance mechanical properties such as yield strength of solder joints, thereby resulting in better fatigue failure resistance[7-8]. However, flip chip joints using Pb-free solders and electroless Ni-P UBM show brittle failure after solder reflow. In Pb-free solder joints using electroless Ni-P UBM, rapid cooling can induce more failures, because Pb-free sol-

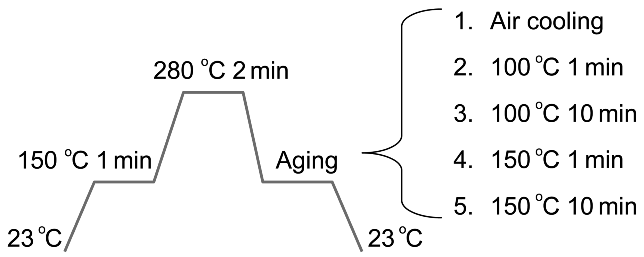

Fig. 4. Schematic reflow profile with additional thermal aging during cooling process.

ders have higher yield strength than Pb-Sn solders, resulting in less plastic deformation of solder bumps.

In order to investigate the effect of cooling rates, flip chips employing SnAg and SnAgCu solders were assembled using different reflow conditions, as shown in Fig. 4. Additional aging treatment was performed at 100 °C and 150 °C, respectively, for 1 and 10 minutes during the cooling stage of flip chip solder assembly. T/C tests were then performed in a temperature range of -30 °C ~120 °C for 30 minutes.

Figure 5 shows the failure rate of solder joints as a function of thermal cycles. In Fig. 5-(b), difference in the failure rates was observed in an early stage of the thermal cycling test. Over 20 percent of SnAgCu solder joints failed after 3 cycles in the direct cooling condition, whereas less than 10 percent of the solder joints failed in the cooling condition with additional aging treatment. Therefore, brittle failure of the solder joint can be reduced by additional thermal aging treatment. The effect of thermal aging was also observed in SnAg solder joints, as shown in Fig. 5-(c). Over 60 percent of the directly cooled solder joints failed immediately after reflow. However, in solder joints aged at 100 °C and 150 °C for 1 minute, the failure rates were significantly reduced, by about 20 percent. Furthermore, in solder joints aged at 100 °C and 150 °C for 10 min, no failure was detected immediately after reflow and prior to underfilling. Thermal cycling test results of SnAg solder joints showed that the assembly yield increased by about 30 percent as a result of additional aging treatment compared with the directly air-cooled flip chips. In addition, longer aging time yielded better thermal cycle reliability before underfilling.

Warpage of the flip chip assemblies was measured using a contact-type surface profiler with 0.2 μm resolution. Both the upper side of Si and the bottom of PCB were scanned along the diagonal direction. Fig. 6 shows the surface profiles of Si and PCBs. Regardless of the cooling conditions, the Si surfaces were flat immediately subsequent to reflow. However, convexly warped PCB surfaces were observed in all cooling conditions. The warpage of SnAgCu assembled PCB after directly air cooling was 21.8 μm. However, the PCB warpage was reduced to 16.4 μm after additional aging treatment at 100 °C for 10 minutes while the measured warpage of the SnAg assembled PCB at 100 °C for 10 min-

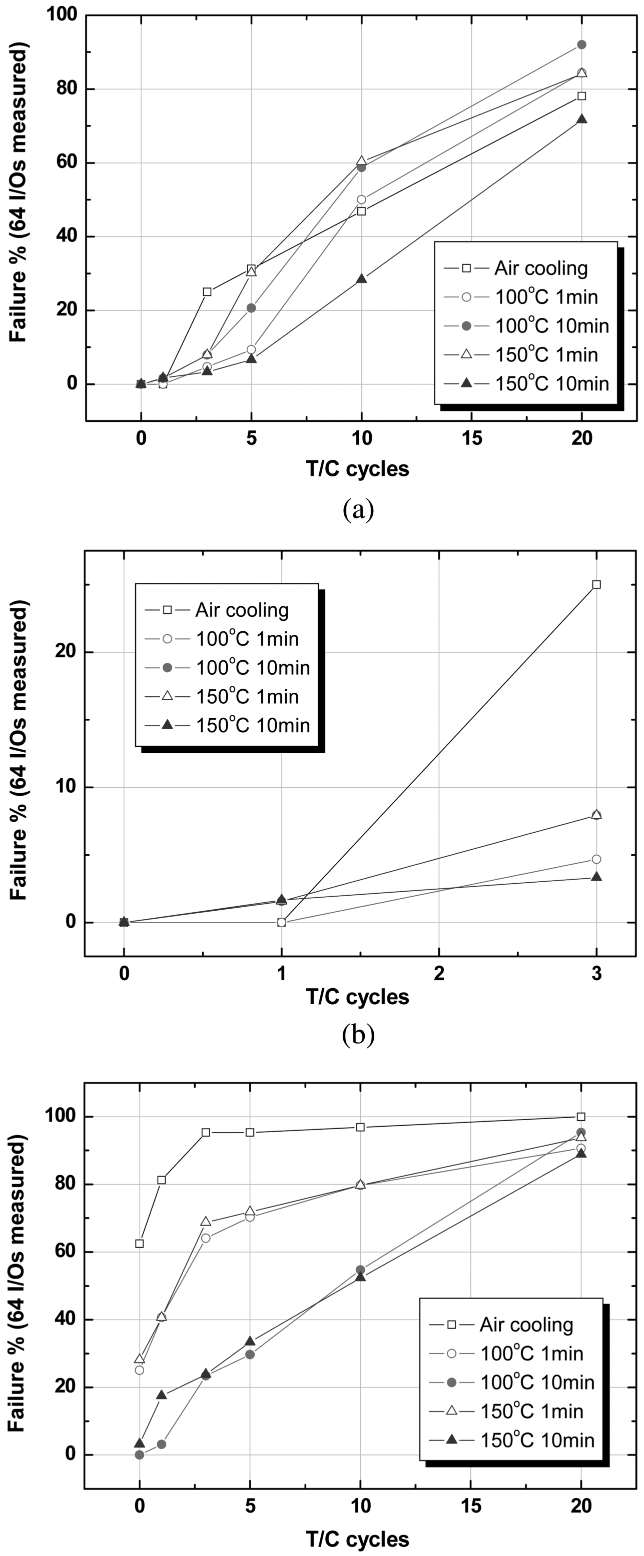

Fig. 5. Thermo-cycling reliability of flip chip joints before underfilling as a function of aging treatment during cooling processes after reflow. (a) SnAgCu solder joints (b) early stage of T/C test of SnAgCu solder joints (c) SnAg solder joints.

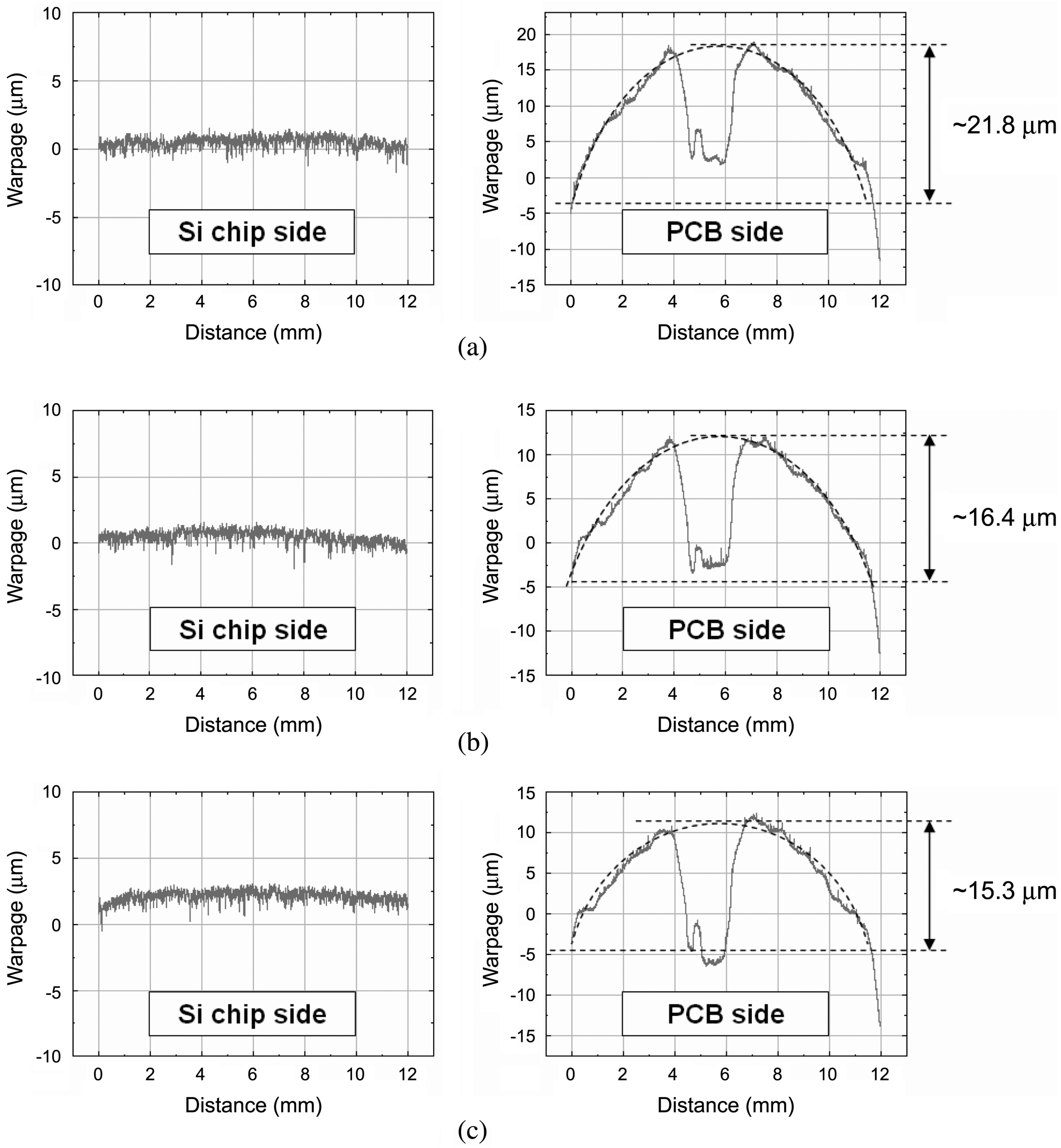

Fig. 6. Warpages of Si and PCB surface: (a) direct air cooled SnAgCu solder flip chip (b) SnAgCu solder flip chip joints aged at 100 °C for 10 min (c) SnAg solder flip chip joints aged at 100 °C for 10 min.

utes was 15.3 μm. The warpage relaxation caused by thermal aging clearly accounts for the higher assembly yield.

4. CONCLUSIONS

Failure mechanisms of non-underfilled flip chip joints with electroless Ni-P UBM/Pb-free solders were investigated using T/C tests. Fatigue failure of solder joints was observed in Pb-containing solder flip chips. However, in Pb-free solder flip chip joints, various types of brittle failure such as Si cratering, cracking of the P-rich Ni layer, and interface delamination between Si and PCB were observed. Flip chips using Pb-free solder have lower assembly yield due to these brittle failures.

In order to prevent brittle failure, thermal aging treatment was implemented during cooling after solder reflow. The results showed that the assembly yield increased by about 30 percent, because of additional thermal aging compared with directly air-cooled flip chip joints. In addition, longer aging time yielded better thermal reliability before underfilling.

Therefore, the assembly yield of flip chips using Pb-free solders and electroless Ni-P UBM can be increased by implementing thermal aging treatment during the cooling process after solder reflow.

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