Reliability of New SAC-Bi Solder Alloys in Thermal Cycling with Aging

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ABSTRACT

Drive towards lead-free electronics began in the early 2000s. Solder pastes based on tin (Sn), copper (Cu), and silver (Ag) were the initial replacement for the traditional SnPb solder. With the SAC alloys, several researches reported that one year of aging consumed more than 50% of the component life. Once the detrimental effects of aging were discovered, the industry started the search for better solder paste materials. The SAC based pastes were made better by adding elements such as Bismuth (Bi), Antimony (Sb), Nickel (Ni). Recently, all the leading manufacturers have introduced new solder materials that claim to have high reliability in harsh environments. Extensive tests are required to filter the best solder pastes. In the study, three high reliability solder materials from leading manufacturers have been selected and used for the test vehicle assembly. SAC305 paste is also included for comparison with the new materials. The test vehicle is a printed circuit board (PCB) of FR-4 laminate material with three CABGA208s (15x15mm) with SAC305 spheres, three LGA36s, and six SM resistors. Three surface finishes, namely electroless Nickel immersion Gold (ENIG), immersion Silver (ImAg), and organic solderability preserve (OSP), have been considered for the study. Immediately after assembly, all boards are aged for a period of twelve months at 125ºC. All the boards are then thermally cycled for 5000 cycles from -40ºC to +125ºC with a ramp time of 50 minutes and dwell times of 15 minutes at high and low temperatures.

Two parameters Weibull analysis is used to quantify the performance of the different alloy materials. ANOVA analysis involving the different composition and surface finish is also done in order to get insight into the most influential factors on the component reliability. Generally, all the new alloys were found to outperform SAC305 paste. Materials with a high content of Bi, Sb, and Ag performed the best in the lot. The microstructure analysis showed that bulk solder failure was the typical failure mode with the crack propagating in bulk along with the intermetallic compound layer on the component side.

KEY WORDS: BGA, Reliability, Thermal Cycling, Surface Finish, Solder Join

NOMENCLATURE

BGA	Ball Grid Array
QFN	Quad Flat No-lead
SMR	Surface Mount Resistors
CTE	Coefficient of Thermal Expansion, ppm/ºC
IMC	Intermetallic Compound
CABGA	Chip Array Ball Grid Array
PCB	Printed Circuit Board
ENIG	Electroless Nickel Immersion Gold
ImAg	Immersion Silver
OSP	Organic Solderabiltiy Preserve
FR4	Flame Retardant 4
SEM	Scanning Electron Microscope

Greek symbols

β	Shape parameter
η	Scale parameter, cycles

Symbols

Sn	Tin
Ag	Silver
Cu	Copper
Pb	Lead
Bi	Bismuth
Sb	Antimony
Ni	Nickel
Co	Cobalt

INTRODUCTION

SAC based solder alloys were thought to replace the traditional SnPb solder in electronics. Among them, SAC305 was the most popular candidate for harsh thermal cycling applications. But it was later found that after aging, the reliability degrades by more than 50%, which became a concern in the electronics industry, especially for military and automotive under the hood applications. This paved the way for micro-alloying new elements to the SAC based solder. Bi, Sb, Co, Ni, In are some of the micro-alloyed elements.

When the components are mounted on the boards in the reflow process at elevated temperatures, the IMC layer is formed at the interface of the solder sphere and Copper pad that is crucial for the electrical and mechanical bond. The diffusion of Cu from the pads to the bulk solder is responsible for this brittle IMC layer formation. Over time, the thickness of the IMC layer increases, which causes reliability concerns. Several reliability studies such as shock, vibration, thermal cycling, shear fatigue have been conducted on these new materials [1-10]. The fine IMC precipitates in the bulk solder get coarsened during aging, after which they are not effective in blocking the dislocation movement or the grain sliding. This results in decreased strength of the solder joint. In addition, from several studies based on simulation, it has been found that the stress developed due to the CTE mismatch is concentrated at the interface of the solder and the pad, where the IMC layer is located. This makes the situation worse as the IMC layer is brittle in nature [11]. There have been several studies on the effect of aging periods and temperatures on component reliability [12-15]. All the studies pointed in the same direction that the reliability deteriorated with aging duration and temperature.

Fig. 1 and Fig. 2 show the difference between SAC305 and micro-alloyed alloy in general. SAC305 has a uniform dendrite structure of IMC precipitates, whereas Innolot has a similar structure, but with Bi precipitates that makes the alloy more resistant to creep, thereby contributing to its improved reliability. Also, some of the Bi stays in the solid solution of Sn and could not be seen in the microscope. Similarly, there are several other elements such as Sb, Ni, Co, In that are added to improve the mechanical properties and thereby increase the life of solder joints [16-23].

Fig. 1 Microstructure of non-aged SAC305 solder alloy

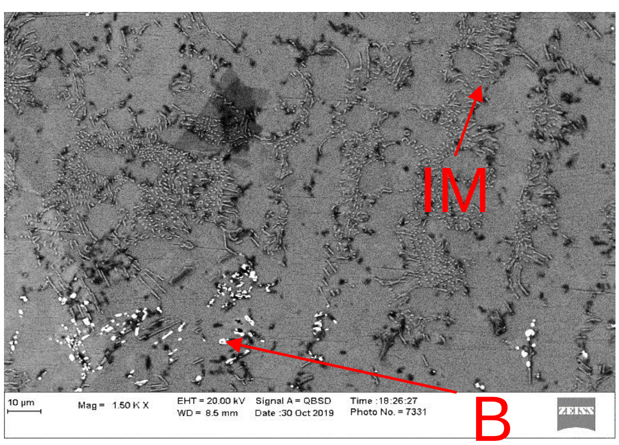

Fig. 2 Microstructure of non-aged Innolot alloy

In this study, the effect of micro-alloying is investigated with three solder pastes with three surface finishes and SAC305 solder spheres in harsh thermal cycling. SAC305 alloy is also included as a baseline to compare the micro-alloyed materials in the study.

EXPERIMENTAL SETUP AND PROCEDURE

The test board included in the study is shown in Fig. 3, which consists of CABGAs, QFNs, and SMRs on non-solder mask defined pads. The board consists of four layers of FR4-06 glass epoxy PCB with a glass transition temperature of 170ºC with dimensions of 4.0 x 5.0 x 0.062 inches.

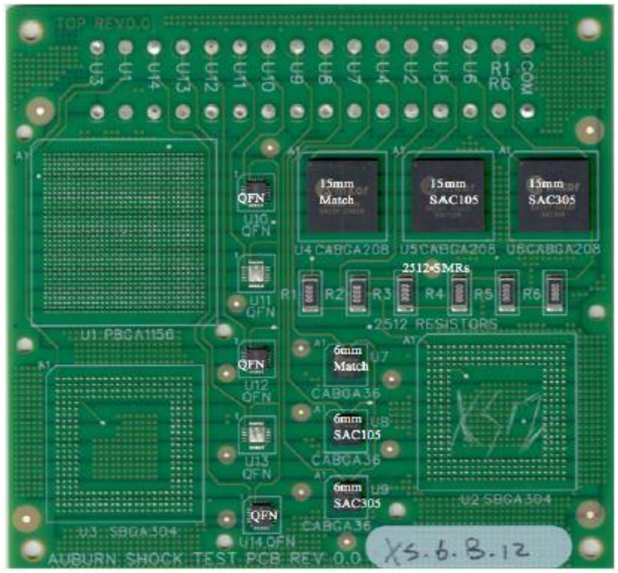

Fig. 3 Test vehicle used in the experiment

The reflow profile for assembly is selected such that the solder joints have the best wetting and least board damage. Fig. 4 shows the reflow profile used for the assembly.

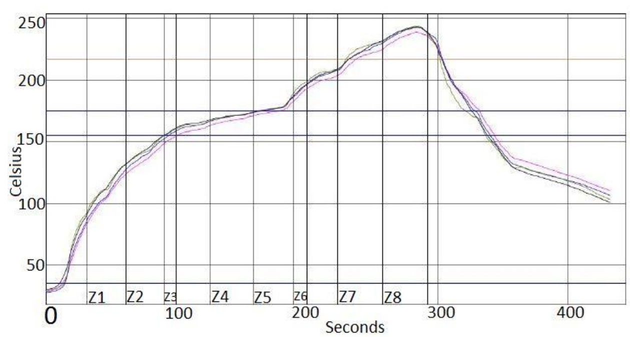

Fig. 4 Reflow profile

The composition of solder pastes included in the test is mentioned in Table 1. Solder alloys include the popular Innolot, SAC with Bi and SnCuBi. These are compared with the SAC305 solder material.

Table 1. Solder paste composition

Paste	Composition
Innolot	Sn-3.80Ag-0.70Cu-0.15Ni-1.40Sb -3.00Bi
SAC-Bi	Sn- 3.41Ag- 0.52Cu- 3.3Bi
SnCuBi	Sn-0.92Cu-2.46Bi
SAC305	Sn-3.0Ag-0.5Cu

BGAs are surface mounted using the popular SAC305 solder spheres. The BGAs are of size 15mm x15mm (CABGA 208) and 6mm x 6mm (CABGA 36) with a pitch size of 0.8mm. The SMRs are arranged in banks of six resistors placed in series.

The QFN package size is 5mm x 5mm, with a pitch size of 0.65mm. All the components are daisy-chained to ensure the passage of the signal through each solder joint.

Table 2. Test plan matrix

Component/sphere	Solder paste	Surface Finish
CABGA208/ SAC305	Innolot	ENIG
		ImAg
		OSP
	SAC-Bi	ENIG
		ImAg
		OSP
	SnCuBi	ENIG
		ImAg
		OSP
	SAC305	ENIG
		ImAg
		OSP

In the study, the effect of micro-alloying different elements on the characteristic life of solder joints is studied. In the case of each paste, only the popular SAC305 solder spheres are considered to minimize the variability, as described in table 2.

Upon assembly, all test boards were isothermally aged at a temperature of 125oC for a period of twelve months. The temperature of 125oC was chosen so that the packages undergo effective aging. After aging, the boards were subjected to thermal cycling using the profile given in Fig.5. The temperature range was from -40oC to +125oC. The up and down ramp times were 50 minutes each, and dwell times at maximum temperatures were 15 minutes. The boards were cycled for 5000 cycles.

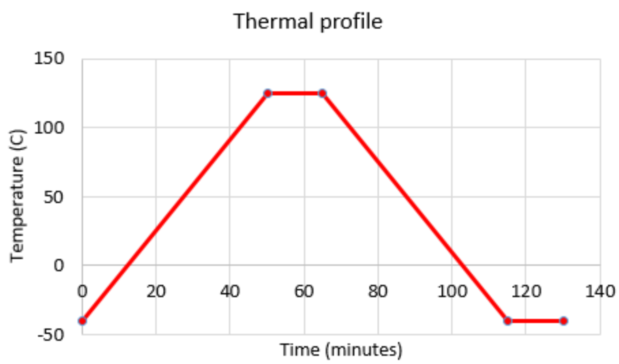

Fig. 5 Thermal cycling profile

The resistance in thermal cycling is continuously monitored by a system that includes a digital multimeter interfaced with a switch scanning system.

RESULTS AND DISCUSSION

The aged test boards were subjected to 5000 thermal cycles under continuous monitoring. Almost all the larger BGAs (15x15mm, CABGA 208) failed while there were only a few failures among other smaller components (CABGA 36, MLF 20, and SMR). So, only the data regarding CABGA 208 components are presented in the paper. In the study, three solder pastes with popular compositions using popular solder sphere, namely SAC305 and three surface finishes, ENIG, ImAg, and OSP, are used. Two parameters (β, η) Weibull plots were used to quantify the performance of different solder paste-sphere-surface finish combinations. The characteristic life (η) is the time (cycles in the study), at which 63.2% of the components are expected to fail, and the shape parameter (β) represents the slope of the Weibull plot.

Fig. 6(a) shows the Weibull analysis for different solder pastes for ENIG surface finish in comparison with SAC305 solder paste. The data has been summarized in Fig. 6(b). It could be seen that the characteristic life improves with doping. SAC305 paste has the least characteristic life. When Ag is removed, and Bi is added, there is a slight improvement. When Ag is added, and Bi content is increased to slightly above 3%, the fatigue life gets better. When other elements such as Sb and Ni are added as in Innolot, the reliability is the best in the case of ENIG surface finish. Fig. 6(c) shows the B10 life for all the alloys. B10 life follows the same trend as characteristic life except for SAC-Bi, which is due to the early failure that could be seen in the Weibull plot.

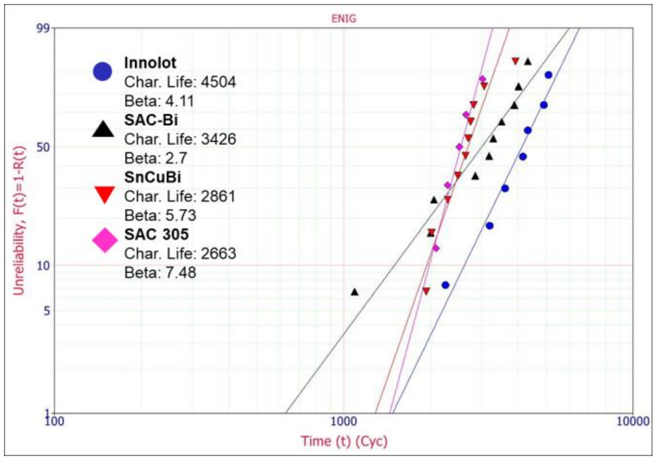

Fig. 6(a) Weibull analysis of different solder alloys with ENIG surface finish

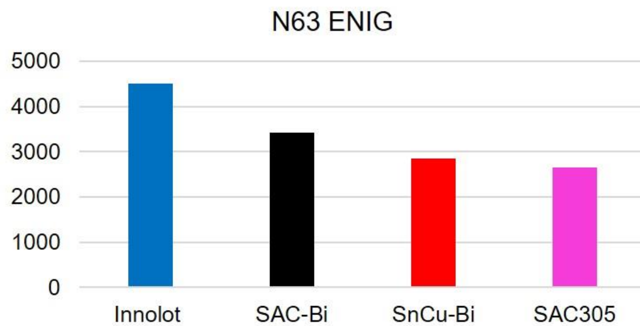

Fig. 6(b) Summary of characteristic life for ENIG finish

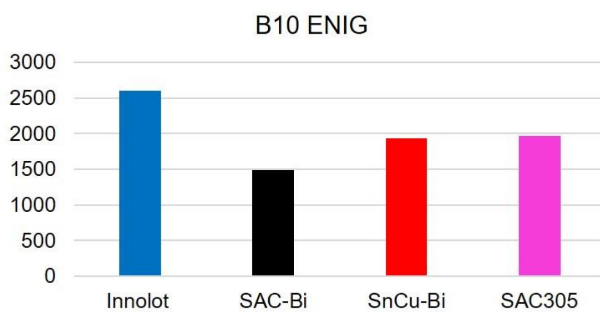

Fig. 6(c) B10 life for alloys with ENIG finish

Fig. 7(a) shows the Weibull plot for solder pastes with ImAg surface finish. Characteristic life follows a similar trend as in the case of ENIG finish. Data is summarized in Fig. 7(b) and Fig 7(c). It could also be observed that the difference in characteristic life between Innolot and SAC-Bi is not as large as in the case of ENIG finish. B10 life follows the same trend as in the case of characteristic life.

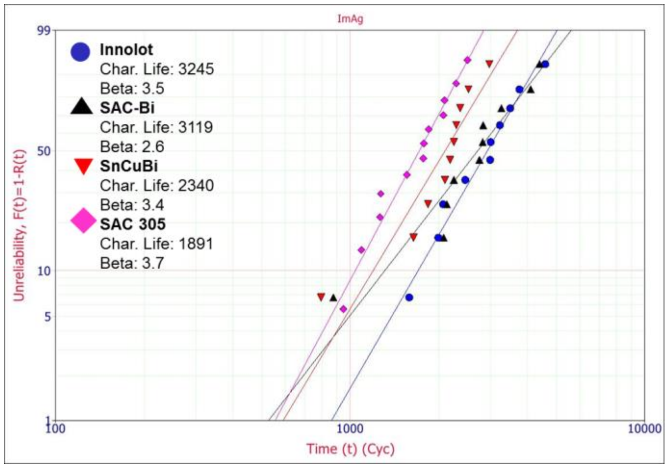

Fig. 7(a) Weibull analysis of different solder alloys with ImAg surface finish

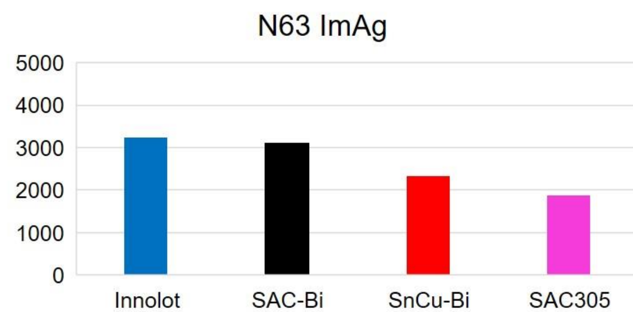

Fig. 7(b) Summary of characteristic life for ImAg finish

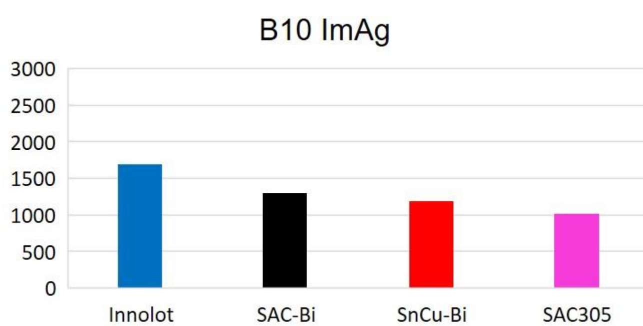

Fig. 7(c) B10 life for alloys with ImAg finish

Fig. 8(a) shows the Weibull analysis for solder pastes with OSP surface finish that is popular in the consumer electronics industry. Data is summarized in Fig. 8(b) and Fig 8(c). In this case, there is a noticeable difference in life between SAC305 and the other micro-alloyed pastes. It is also interesting to see that SAC-Bi alloy performs better than Innolot in the case of OSP finish, and this trend could be seen in the case of B10 life as well.

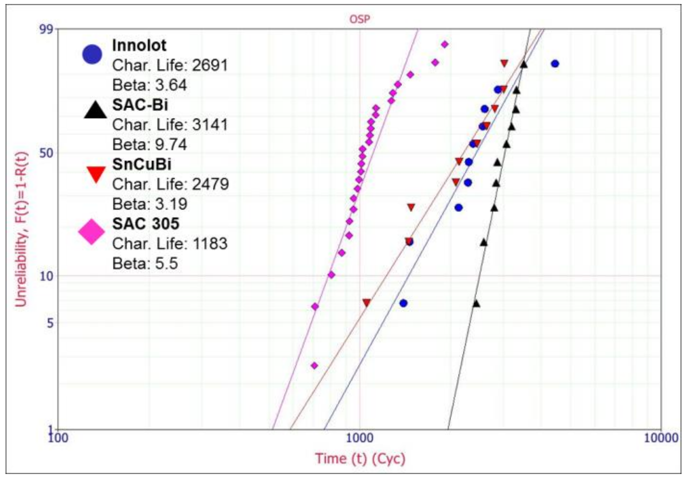

Fig. 8(a) Weibull analysis of different solder alloys with OSP surface finish

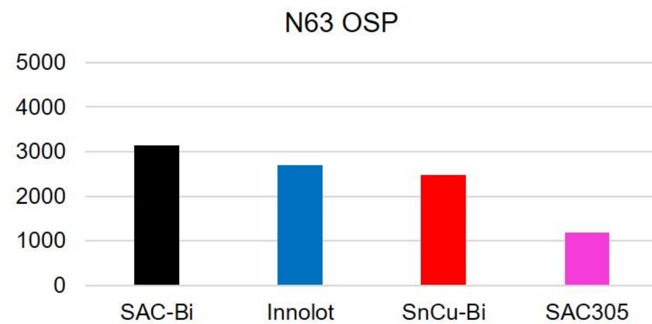

Fig. 8(b) Summary of characteristic life for OSP finish

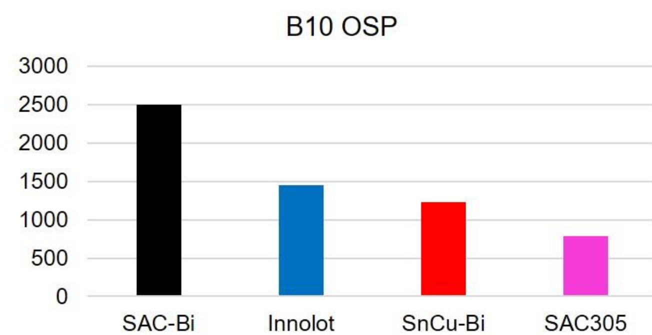

Fig. 8(c) B10 life for alloys with OSP finish

In all the three cases of ENIG, ImAg, and OSP, it could be seen that the alloys with more elements performed better. SAC305 was the best among SAC based pastes for thermal cycling. But when Bi is added, the creep resistance of the alloys is improved by solid solution strengthening effect of Bi precipitates [16,17]. Bi is also found to increase the reliability by decreasing the thickness of the brittle IMC layer as well as slowing down its growth [16]. Sb contributes to the reliability by solid solution hardening and particle hardening as found by Li et al. It was also found that since Sb has a higher affinity for Sn, it would form Sn-Sb compound, thereby reducing the driving force for Cu-Sn IMC layer formation [18]. Ni was found to suppress the growth of Cu3Sn[20], similar to Co[21]. In the case of all these micro-alloyed elements, it could be observed that the elements contributed positively to the reliability only if added in a certain proportion. Otherwise, it proved to be detrimental to the fatigue life of solder joints.

Fig. 9(a) and Fig. 9(b) show the main effects plot and the interaction effects plot, respectively. From the main effect plot, it is obvious that the micro-alloyed elements perform much better than the SAC305 alloy. Among the surface finishes, ENIG appears to be better than ImAg and OSP. ENIG finish has a Ni layer that acts as a barrier to the Cu diffusion from the pads to the bulk solder, as shown in Fig. 10, thereby decreasing the IMC layer growth. From the interaction plot, it could be seen that in certain cases, combinations of the paste with OSP finish is better than ImAg finish.

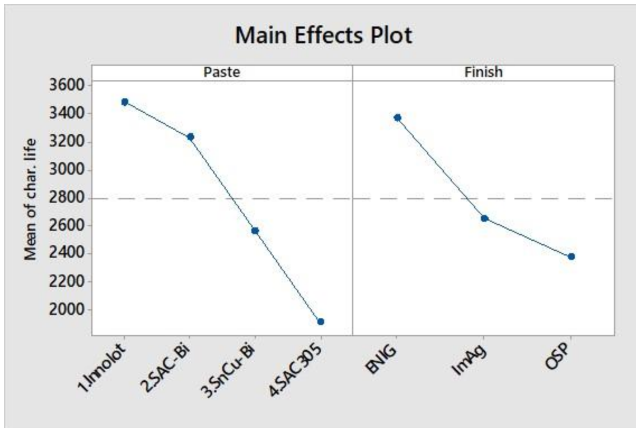

Fig. 9(a) Main effects plot for solder alloys and finishes

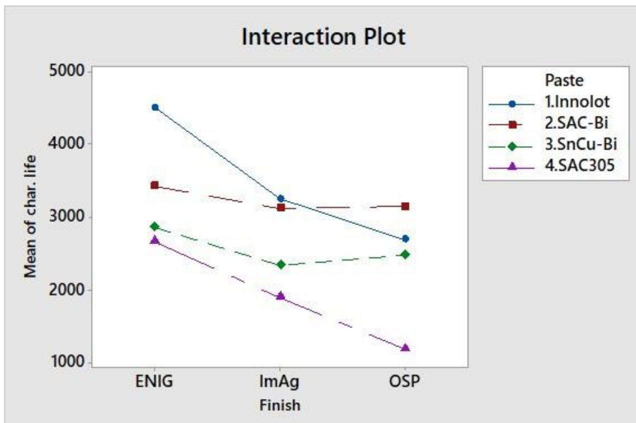

Fig. 9(b) Interaction plot for solder alloys and finishes

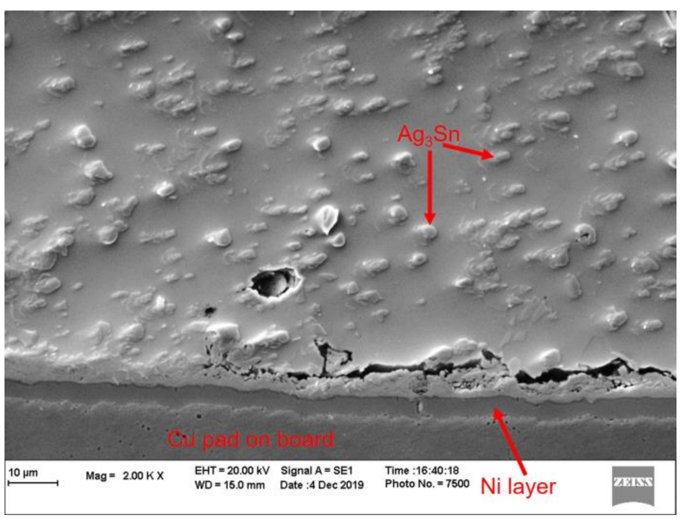

Fig. 10 Nickel layer for ENIG surface finish

Fig.11(a), Fig. 11(b), and Fig.11(c) show the cross-section images of Innolot, SAC-Bi, and SnCuBi alloys, respectively. It was observed that in most cases, failure was at the component side. Crack propagation was in the bulk solder along with the IMC layer. For Innolot and SAC-Bi pastes, Ag3Sn precipitates are seen to be distributed throughout the bulk, whereas in the case of SnCuBi, the number of precipitates was found to be less, which could be one of the reasons for comparatively lower characteristic life

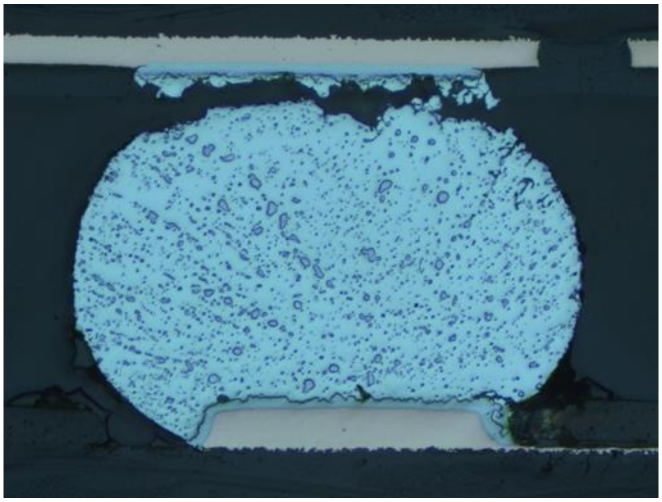

Fig. 11(a) Bright field image of cross section of a solder joint for Innolot alloy

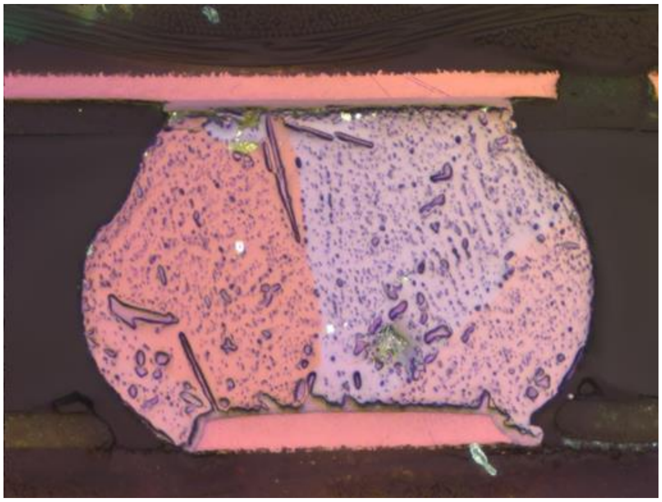

Fig. 11(b) Cross polarized image of cross section of a solder joint for SAC-Bi alloy

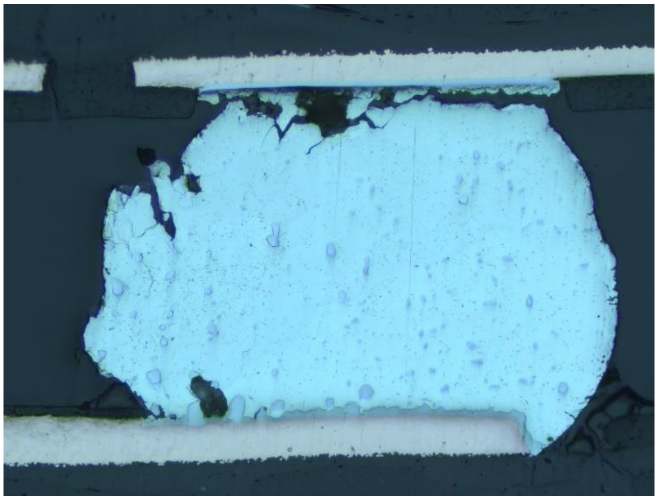

Fig. 11(c) Bright field image of cross section of a solder joint for SnCuBi alloy

SUMMARY AND CONCLUSION

In this paper, the effect of micro-alloying different elements to SAC based solder materials on component reliability was studied using 15mm x 15mm CABGA, considering various factors of solder paste and surface finish. For each surface finish, the alloys involved in the study were analyzed. It was observed that the new elements have positively contributed to the component reliability. The micro-alloyed solder pastes proved to be more reliable than SAC305 alloy. Adding elements such as Bi, Sb, Ni, and Co to the SnAgCu solder joint was found to improve the fatigue resistance and slows down the adverse effect of aging and thermal cycling on the component reliability.

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