Reliability of Pb-Free Solder Alloys in Demanding BGA and CSP Applications

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Abstract

Based on the electronics industry's move to lead-free soldering, and increasing popularity of portable electronics, new concerns about solder joint reliability have emerged. Consequently, there is a resulting industry-wide effort to develop and understand new lead-free alloys for improved solder joint reliability. Until now, most of the work has focused on improving drop shock reliability which is a critical attribute for portable electronics. Significant work has been done to reduce the silver level in common SnAgCu Pb-free alloys, which lowers the bulk alloy modulus. Also, this work has focused on further modification of the characteristics of these "low-Ag" alloys using various micro-alloy additives. The net result of micro-additive addition is to either 1) alter the bulk alloy characteristics by changing the bulk microstructure and altering the formation and growth of intermetallics in the solder itself, or 2) control the interfacial intermetallic layer(s). Alloy microstructure can also be altered by thermal history of the solder. Therefore process conditions play an equally important role in determining the overall solder joint reliability. The alloy composition, both the Ag-level and presence of certain micro-additives, can have a profound effect on both drop-shock and temperature cycling reliability. At Cookson Electronics, we have an aggressive program to develop and study new alloys for BGA and CSP applications. We have investigated a wide range of low-Ag SnAgCu alloys with a broad selection of alloy additives. This paper examines the effect of micro-alloy additives on solder joint reliability and microstructure. Solder joint reliability as measured by drop-shock, high-speed ball pull, and temperature cycling tests is discussed in terms of the micro-structural characteristics.

Introduction

During the transition to lead-free, SnAgCu alloys were adopted as the standard, with alloys like SAC305 and SAC405 being the most common. These "high-Ag" alloys showed performance comparable to or in some cases better than the SnPb eutectic. For example, these alloys are believed to provide higher strength and better resistance to temperature cycling. While the industry has moved forward to remove lead from electronics assemblies, portable electronic device popularity has increased at an extremely rapid pace. Mobile hand-held devices brought in new failure mechanisms under high strain rate situations like drop shock. To improve the drop shock performance of these devices, solder joints must be made robust enough to withstand high-impact mechanical shock. This has led to development of a new set of alloys that are more compliant than SAC305/405. Most of this work has focused on low-Ag alloys with or without additional micro-alloy additives [1]. Alloys with silver level as low as 0.3% or lower have been evaluated for various applications. Many of these alloys exhibit a significant improvement in drop-shock performance compared to their high-Ag predecessors. However, it has been recognized that this improvement in drop-shock performance can come with a degradation of temperature cycling reliability. As a result, most semiconductor package assemblers are forced to utilize multiple lead-free alloys depending on desired performance attributes, package requirements, and end-customer specifications. Today, most component assemblers are using at least two (and in many cases even more) lead-free solder sphere alloys to meet various package requirements.

Technical Approach

Much like the rest of the Industry, Cookson Electronics had taken the initial approach of optimizing drop-shock reliability only, with little focus on temperature cycling performance. Recently, this development effort has shifted to include optimization of both drop-shock reliability and temperature cycling performance from a single alloy. The results of this development approach are material recommendations for both 1) an alloy tailored for maximum drop-shock performance, and 2) an alloy optimized to balance drop-shock performance with excellent temperature cycling reliability.

Experimental Details

This section defines the high-speed ball pull, drop-shock, and temperature cycling tests used for this study.

High-speed Ball Pull Test Details

As reported earlier [2,3], the high-speed ball pull test can be used to predict drop shock reliability of the solder joints. The experimental work was conducted on Dage 4000HS high-speed Ball Pull and Ball Shear systems. The Dage 4000HS machine is capable of performing ball pull test at speeds up to 1000 mm/sec. All the tests were carried out using 12 mil (300 μm) spheres assembled on CABGA84 substrates with NiAu pad finish. Spheres were assembled using a water soluble paste flux (Alpha WS9180-M3) that was stencil printed on the substrates. Spheres were placed using a simple stencil alignment assembly and reflowed in air, using a seven-zone convection reflow oven. Samples were aged at room temperature for five days before performing the test. Two low silver SnAgCu base alloys (Sn1.0Ag0.5Cu and Sn0.3Ag0.7Cu) along SAC305 for reference were studied with a range of micro-additives. Ball pull failure modes were categorized as shown in Figure 1.

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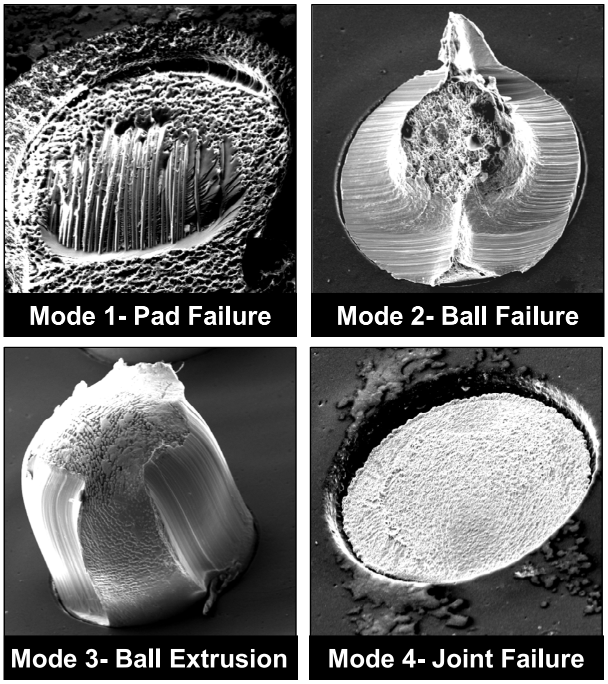

Figure 1. SEM pictures of ball pull failure modes

Mode 1 – Pad failure:
The whole pad comes off the substrate indicative of a board or substrate quality problem.

Mode 2 – Ball Failure / Neck Break:
Failure occurs in the bulk of the solder material indicative of a ductile failure. This is the preferred failure mode.

Mode 3 – Ball Extrusion:
This occurs because of improper placement of the pull tool or a solder that is too soft.

Mode 4 – Joint failure /IMC failure:
Failure occurs at the solder pad interface. This failure may have a larger peak force and is predominantly a brittle failure.

Drop Shock Test Details

Drop shock tests were performed following the JEDEC JESD22-B111 procedure [4]. Details of the test are shown in Figure 2. Our test vehicle is designed to accommodate fifteen CABGA84 components with 12 mil (300µm) spheres on NiAu pad finish. Components were mounted per JEDEC specifications on the test board. The pad finish on test boards was Cu-OSP and components were assembled using a water soluble BGA flux (Alpha WS9180-M3). All components were individually daisy-chained to facilitate in-situ monitoring. After assembly boards were aged at room temperature for five days before performing the test. A multi-channel event monitor was used for data acquisition. Failures were defined per JEDEC specifications.

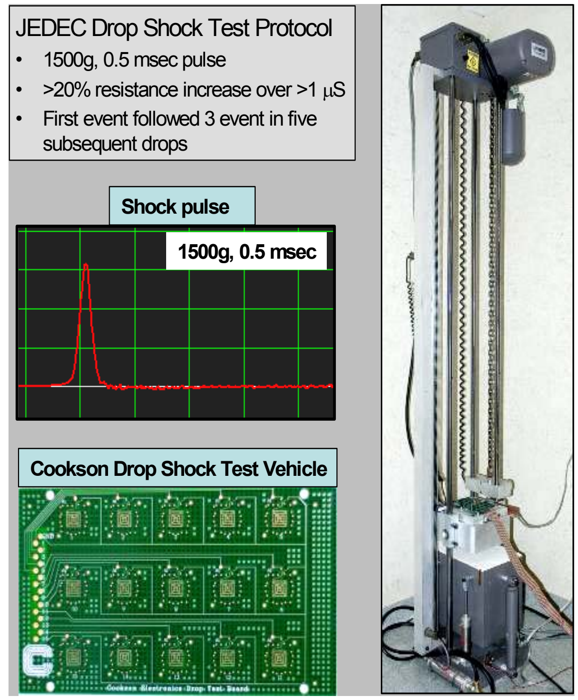

Figure 2. Drop shock test setup, test vehicle and JEDEC test protocol.

Temperature Cycling Test Details

Selected samples were subjected to temperature cycling test. Temperature cycling conditions were -55°C to +125°C with 10 min dwell on each end. Transition time on each side is approximately 5 mins. The test vehicle is the same as that used for drop shock testing.

Results and Discussion

The drop shock test data for SAC105, SAC105+Ni and SAC105+Ni+Cr is shown in Figure 3. It appears that Ni addition has little effect on drop shock performance but addition of both Ni and Cr shows a significant improvement. In all testing to date, the Ni+Cr additive combination in low-Ag alloys has displayed the best overall drop-shock performance.

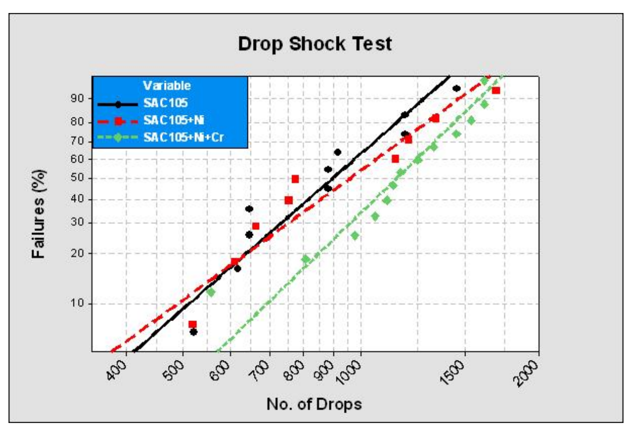

Figure 3. Drop shock test: Effect of Ni and Cr addition to SAC105.

The effect of Bismuth addition to lead-free solders has been a focus of several investigations in the past [1, 5-7]. As reported in these publications the effect of Bi addition is either to lower the solidus temperature, improve the strength of the bulk solder through precipitation hardening or to suppress the formation of large Ag_3Sn intermetallics in the bulk solder. The effect of Bi addition is also reported to improve wetting and spread of the solder alloy on common substrates. Segregation of Bi, or other additives, to the solder surface during the liquid state improves solder spread, possibly by decreasing the surface tension of the molten solder. Similar to the behavior of Pb, Bi also doesn't form intermetallic compounds with common substrate metals, but it does have an impact on the IMC layer formation.

Under certain conditions, Bismuth has actually been shown to degrade the solder joints due to its segregation to the Cu-IMC interface. [6]. As reported in our previous work [1], the net effect of Bi addition to SnAgCu on drop shock performance can be positive or negative depending on alloy composition. This net effect of Bi is a combination of the following: effect of enhancing wetting/spread, thickness of IMC formation, and strengthening of the solder matrix. In general, Bismuth's net effect in low-Ag alloys is an improvement to drop-shock and ball pull/shear performance. Therefore, in this work we limited to study the effect of Bi addition only to low-Ag alloys. However, the effect of Bi in high-Ag alloys is expected to improve the temperature cycling performance as shown by the evolving solder microstructure.

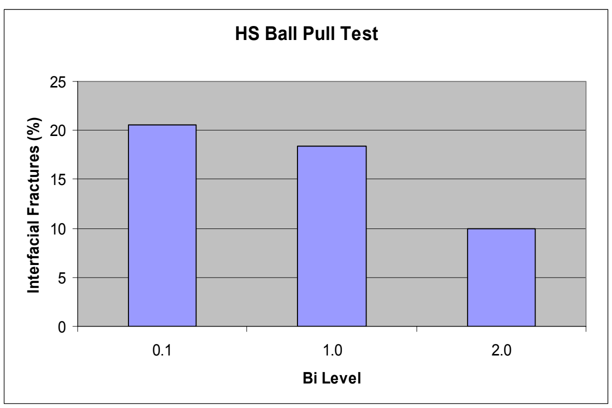

Figure 4. Effect of different levels of Bi addition to SAC0307 on high-speed ball pull.

Figure 4 shows the effect of different levels of Bi addition to SAC0307. This figure shows the fraction of interfacial fractures (mode 4 failures) in high speed ball pull test. The test speed in all ball pull tests shown here was 1000 mm/sec. As the Bi level increases, the fraction of interfacial fractures decreases. This is due to the effect of improved wetting with higher Bi level and reduced interfacial IMC layer thickness.

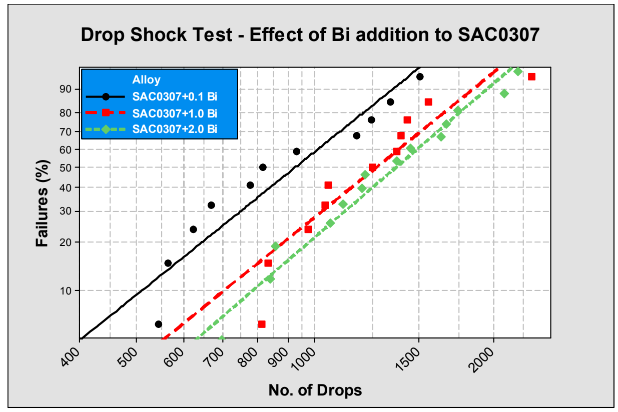

Figure 5. Effect of different levels of Bi addition to SAC0307 on drop shock performance.

Figure 5 shows drop shock performance of the SAC0307 alloy with 0.1, 1.0 and 2.0 % Bi addition. As expected from ball pull results, alloys with higher Bi level last longer in drop shock test. That is despite the fact that Bi addition increases the solder strength, an undesired attribute for drop shock performance. To verify that solder strength really increases with Bi addition, we show the peak breaking force in ball pull test in figure 6 below. Ideally, one could run bulk solder stress-strain tests, but peak breaking force in ball pull can also be used as a qualitative comparison of bulk mechanical strength. To eliminate the effect of interfacial IMC layer and poorly formed joints, we have included data for only the joints that failed in the bulk (mode 2 failure).

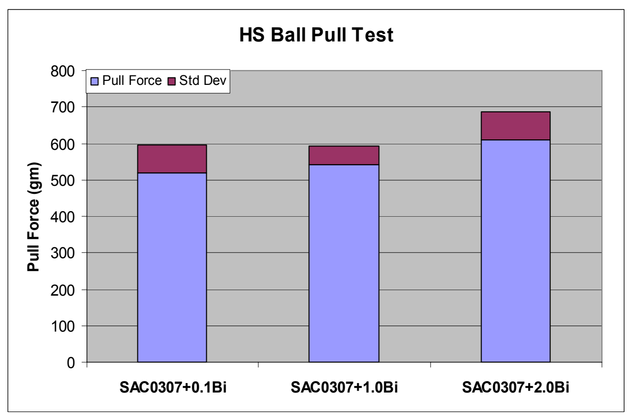

Figure 6. Peak breaking force of 12 mil spheres attached to NiAu pad on CABGA84 substrates. Pull speed was 1000 mm/sec. Data shown is average of 25 solder balls that failed in the bulk (mode 2).

Although the data above suggest that higher Bi content provides the best reliability, one must be careful when selecting a Bi level. There can be reliability concerns attributed to high levels of Bismuth in tin-based alloys. Tin and Bismuth can form an undesired lower temperature eutectic phase. Although our data suggest that at low levels of Bi addition, there is minimal risk of introducing such a low melt phase, it should be understood that long term aging at elevated temperatures or temperature cycling may exacerbate this phenomenon. Also, there are reports that at high levels of Bi, the Bi can segregate to the solder-pad interface, thus making Cu pads brittle. Therefore, selecting an optimum level of Bi addition is very important.

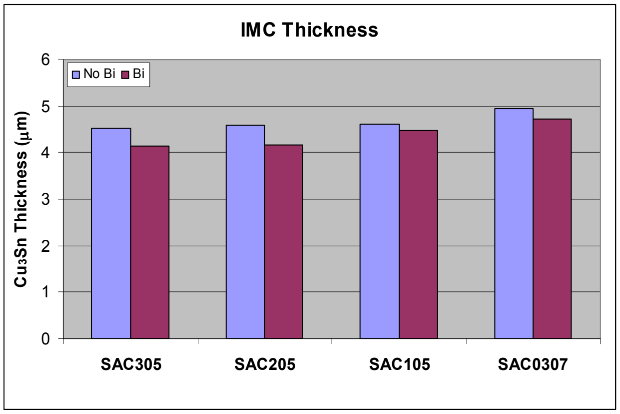

Figure 7. Effect of Bi addition on IMC thickness. Thickness of the first IMC layer (Cu_3Sn) after 1000 Hrs aging at 150°C is shown.

The effect of Bi addition to SAC305, SAC205, SAC105 and SAC0307 on interfacial IMC thickness is shown in figure 7. Solder performs were soldered to Cu-OSP pads on FR4 laminate substrates using a water soluble BGA flux (Alpha WSX). The samples were reflowed in air with peak temperature 255°C and 50 sec time above liquidus (TAL). After reflow, the samples were cleaned in water at 50°C and then aged at 150°C for up to 1,000 hours. Shown in Figure 7 is the average thickness of the first intermetallic layer (Cu_3Sn) after 1,000 hours aging. Because it is very difficult to see Cu_3Sn layer in fresh soldered samples, it can be measured only after aging the samples at elevated temperature. Measurements taken at other aging times as well also show similar thicknesses. It is obvious from these results that addition of Bi to all the solders reduces the thickness of the IMC layer. Since IMC's are brittle in nature, any reduction in the interfacial IMC layer would lead to an improvement of the solder joint in drop shock performance provided everything else remains the same. Our experience with Bi addition shows that this effect should be viewed along with its other effects, especially its effect on strengthening the solder matrix through precipitation hardening.

Since the main objective of this study was to find an alloy that performs well in both high strain rate tests such as drop shock and in temperature cycling test, we also ran temperature cycling tests on alloys that appeared promising. This test is still ongoing today. The test results to date are shown in figure 8.

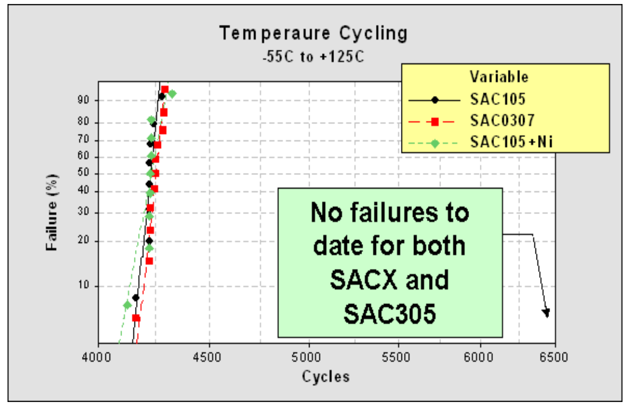

Figure 8. Temperature cycling test of SAC alloys. All common low-Ag SAC alloys fail around 4,000 cycles. However, SACX and SAC305 show no failure up to 6,500 cycles.

Most of the low-Ag alloys such as SAC0307 and SAC105 fail around 4,000 cycles. However, high silver alloys (SAC305) used as control has shown no failure until 6,500 cycles. Also, the SACX alloy (Cookson Electronics' Bi-containing SAC0307 alloy) has not shown any failure so far. SAC0307 without Bi has failed around 4,000 cycles just like all other low-Ag SAC alloys.

In addition to exhibiting exceptional temperature cycling performance, drop-shock results of the SACX alloy have also been confirmed. Figure 9 shows the relative performance of the SACX alloy compared to SAC305 and SAC105.

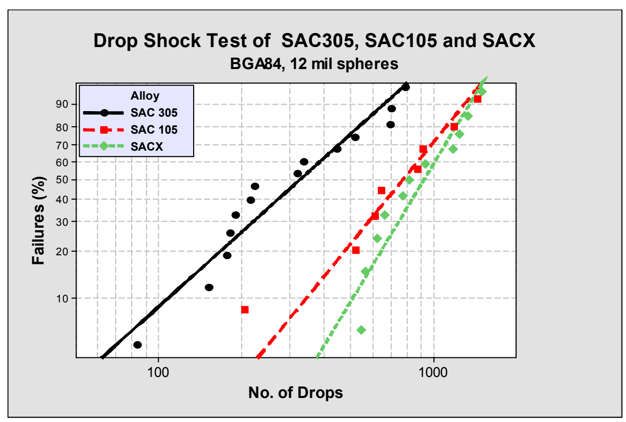

Figure 9. Drop shock results for SACX, SAC105, and SAC305

To understand how alloy additives affect drop shock and temperature cycling performance, it is important understand their effect on bulk alloy properties. Comparing the alloy microstructure [8-10] is one tool to understand how these alloys will behave in actual performance tests. Representative alloy samples were micro-sectioned and SEM images recorded. In some cases, EDAX was used map the element distribution.

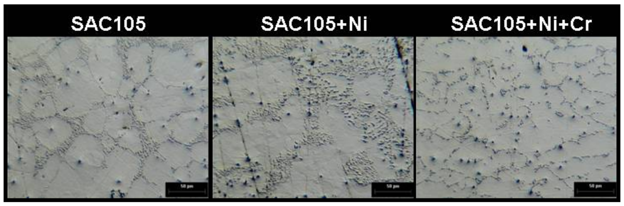

Figure 10. Effect of Ni and Cr addition on the microstructure of SAC105.

The effect of Ni and Cr addition to SAC105 on the bulk alloy microstructure is shown in figure 10. Ni is one of most common additives to low-silver SAC alloys and has been studied extensively. Ni addition has very little effect on microstructure. Therefore, one would not expect much difference in bulk alloy mechanical properties. That would explain why the effect of Ni addition to SAC105 has minimal effect on drop shock performance (see results in figure 3). However, there are other reports that show an improvement in drop shock performance of SAC105 with Ni addition when soldered to Cu-OSP pads. Ni addition does have an impact on Cu_3Sn IMC growth [1]. Since the component side pad finish is NiAu in the present study, addition of small amount of Ni to the solder will make little difference to the interfacial IMC formation.

On the other hand, addition of Ni and Cr appears to make a big difference in the microstructure as shown in figures 10 and 11. Cr has practically no solubility in Sn, however it does react with Cu. It appears this reaction reduces the formation and growth of Cu_6Sn_5 in the bulk of the solder, which would decrease solder stiffness and thus improve drop shock performance.

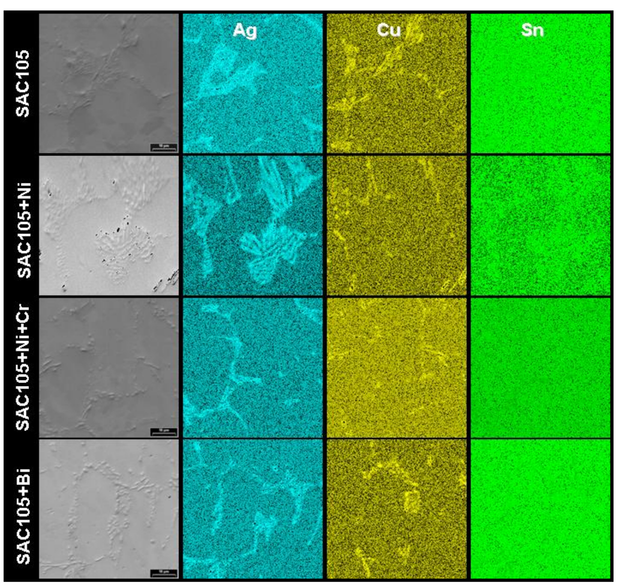

Figure 11. SEM pictures of the bulk alloy cross section and element mapping of SAC105 with different micro-additives.

In order to understand the role Bi plays, elemental analysis was performed on micro-sectioned bulk alloys. This analysis helps to display how Bi affects microstructure and how it contributes to the thermo-mechanical properties of these solder alloys

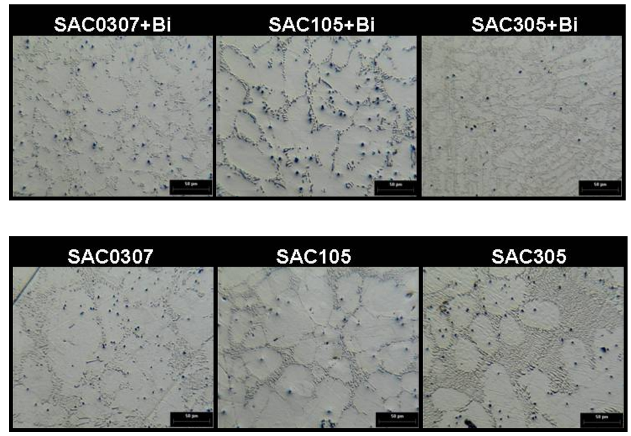

Figure 12. Effect of Bi addition on the microstructure of SAC alloys

Figure 12 shows cross section of the bulk solder. Alloy samples were prepared under identical conditions. Samples of SAC0307, SAC105 and SAC305 alloys and same three alloys with Bi addition were prepared in air and cooled down at ambient temperature. Special care was taken to make sure that all samples were subjected to identical cooling rate, because cooling rate can impact the microstructure. It is clear from these images that Bi contributes to a refinement of grain structure in SnAgCu alloys. This means that during temperature cycling there will less chance of stress buildup at the grain boundaries. Also, since the starting grain sizes are smaller, overall impact of grain coarsening will be small. Both of these would result in improved temperature cycling performance.

Conclusions

SAC105 and SACX with different additives have been studied to compare their performance in high strain rate mechanical tests and temperature cycling tests. Results have been interpreted in terms of bulk solder microstructure and interfacial IMC thickness. The data presented leads to the following conclusions:

- Common low-Ag SAC alloys show good drop shock performance but generally perform poorly in temperature cycling.
- Addition of Ni+Cr exhibits optimal drop shock reliability in low-Ag alloys.
- Addition of Ni has no effect on microstructure of SAC105
- Bi addition shows improved drop shock performance in low-Ag alloys because of its effect to control interfacial IMC in SAC0307, even though it acts to strengthen the solder matrix.
- Bi addition has significant grain refining effect that improves the temperature cycling performance.
- SACX shows optimal performance in both drop shock and temperature cycling.

Acknowledgments

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