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Low-Silver BGA Assembly
Phase II – Reliability Assessment
Fifth Report: Preliminary Thermal Cycling Results

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Abstract
Some ball grid array suppliers are migrating their sphere alloys from SAC305 (3% Ag) or SAC405 (4% Ag) to alloys with lower silver contents. There are numerous perceived reliability benefits to this move, but process compatibility and thermal fatigue reliability have yet to be fully demonstrated.

The current study has been undertaken to characterize the influence of alloy type and reflow parameters on low-silver SAC spheres assembled with backward and forward compatible pastes and reflow profiles. This study combines low-silver sphere materials with tin-lead and lead-free SAC305 solder pastes under varied reflow conditions. Solder joint formation and reliability are assessed to provide a basis for developing practical reflow processing guidelines and to assist in solder joint reliability assessments.

This is the fifth report in a series being published as results become available, and presents the preliminary results of the thermal cycling portion of the test program. Thermal cycling conditions include both 0 to 100°C and -40 to 125°C, with 10 minute dwell times.

Key Words: Lead-free, low silver, mixed metals, BGA reliability, thermal cycling

Introduction

The introduction of low-silver SAC spheres into printed circuit assemblies (PCAs) raises processes compatibility and thermal fatigue reliability concerns. The process concerns, which could manifest as reliability issues, stem from the fact that the low-silver SAC replacement alloys have higher melting temperatures than SAC305, approximately 227°C as compared to 221°C. Certain families of electronic assemblies, such as consumer portables, are often heat-sensitive and are reflowed in the low end of the established lead-free peak reflow temperature range, typically 230-235°C. The temperature difference between the spheres' melting temperature and the peak reflow temperature raises questions about the reliability of the solder joints that are formed under this tight thermal margin. These are similar to the concerns raised with the backward compatibility of SAC305/405 spheres with tin-lead solder processes. Some of the solutions identified in the lead-free ball/tin-lead paste scenario may apply to the low-silver SAC ball/SAC305 paste combination, but they require review for their applicability with this new set of mixed metals. The fatigue reliability concerns stem from early studies showing low Ag alloys may be less reliable than the SAC compositions with 3 – 4% Ag [1]. Further, the reliability performance of mixed SnPb/Pb-free joints using these low Ag BGA ball alloys has not been established.

The study was divided into four phases. The first phase focused on the development of reflow profiles and their influence on mixing of the low silver SAC spheres with the tin-lead or SAC305 solder [2 – 5]. The second, third, and fourth phases assess thermal fatigue performance, drop shock resistance, and vibration performance of the mixed assemblies, respectively. This report focuses on the second phase of the study.

Experimental Design

The objective of the overall study is to define the minimum reflow requirements for low silver BGA spheres in board-level assembly, and to understand the thermal and mechanical reliability of the joints that are formed. Four low-silver sphere alloys were tested. They were:

- SAC 105 – Sn-1.0Ag-0.5Cu
- SAC 205 – Sn-2.0Ag-0.5Cu
- SACX 0307 – Sn-0.3Ag-0.7Cu+ Bi+X
- LF35 – Sn-1.2Ag-0.5Cu + Ni

Eutectic tin-lead spheres were also used to provide a baseline for comparison. Solder pastes included:

- Eutectic Sn-Pb together with components balled with Eutectic Sn-Pb spheres
- Eutectic Sn-Pb together with components balled with Pb-free spheres
- SAC305 together with components balled with Pb-free spheres

Four different BGA package types were used:

- 1.27mm SuperBGA, 600 I/O
- 1.0mm Plastic BGA, 324 I/O
- 0.8mm ChipArray BGA, 288 I/O
- 0.5mm ChipArray Thin Core BGA, 132 I/O

Each package was used three times per test vehicle assembly.

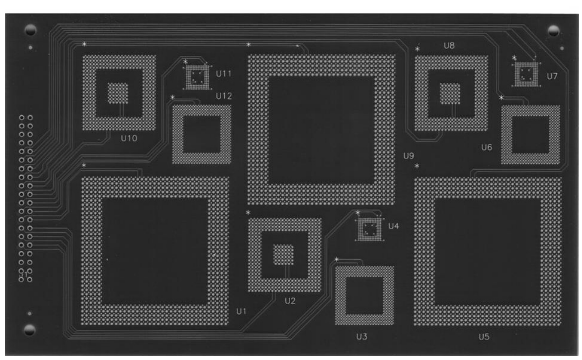

Figure 1 – Test vehicle designed by iNEMI mixed metals BGA team [6] and used in this study.

The test board chosen for this study is shown in Figure 1. It was designed by the iNEMI mixed metals BGA team to study assemblies with SAC305 or 405 BGA spheres and tin-lead soldering processes [6]. Because the two studies are analogous in nature, duplication of the assembly test vehicle allows for easier comparison between the findings of both investigations. It should be noted that although the studies both address similar phenomena of mixed metallurgy in BGA joints, the actual experiments differ in their structures, as they assess different combinations of mixed metals systems. Test board characteristics are provided in Table 1.

Table 1. Test board characteristics.

Test Vehicle PCB Characteristics	
Thickness	0.093”
Finish	OSP
No. Cu Layers	2 Ground (1 oz.) layers 6 Signal (1/2 oz.) layers
Pad definition	Non-Solder Mask Defined
Laminate T_g	170°C
Laminate T_d	340°C

Common to all test assemblies are:

- PCB pad finish: Organic Solderability Preservative (OSP)
- Device pad finish: (electrolytic)Nickel-Gold
- Reflow atmosphere: air

Varied are:

- Ball alloy (see list above)
- Peak Temperatures: 215°C, 220°C, and 235°C as given in Table 2

Test Vehicle Assembly

The PCAs were assembled at Jabil’s Advanced Manufacturing Technology Laboratory in San Jose, California, USA. Details of the assembly methods have been described in earlier reports [2 – 5]. Table 2 gives the key assembly characteristics for each “cell” of the phase 2 test program. Unlike earlier phases, a single time-above-liquidus (TAL) value of 60 seconds was used for all assemblies.

Table 2. PCA assembly characteristics

Paste Alloy	Sphere Alloy	Peak Reflow Temp (°C)	Board Count	
			Sn-Pb Paste	SAC305 Paste
Sn-Pb	Sn-Pb	215	**21**	0
Sn-Pb	SAC305	215	**21**	0
SAC305	SAC305	235	0	**21**
Sn-Pb	SAC105	215	**21**	0
Sn-Pb	SAC105	220	**21**	0
SAC305	SAC105	235	0	**21**
Sn-Pb	SACX	215	**21**	0
SAC305	SACX	235	0	**21**
Sn-Pb	LF35	215	**14**	0
SAC305	LF35	235	0	**21**
SAC305	SAC205	235	0	**21**
		Total	119	105

Typical microstructures for the mixed SnPb/Pb-free joints are given in Figure 2. As discussed in previous reports [2 – 5], the level of mixing between the SnPb paste and the Pb-free ball is a function of ball size (which varies with pitch) and alloy. For the Pb-free joints, any mixing of the ball alloy with the SAC305 paste alloy is not discernable, either optically or with SEM, and “mixing” does not have meaning the way it does for mixed SnPb/Pb-free joints. Microstructures for these joints are typical of Pb-free joints for packages of the type used in this study.

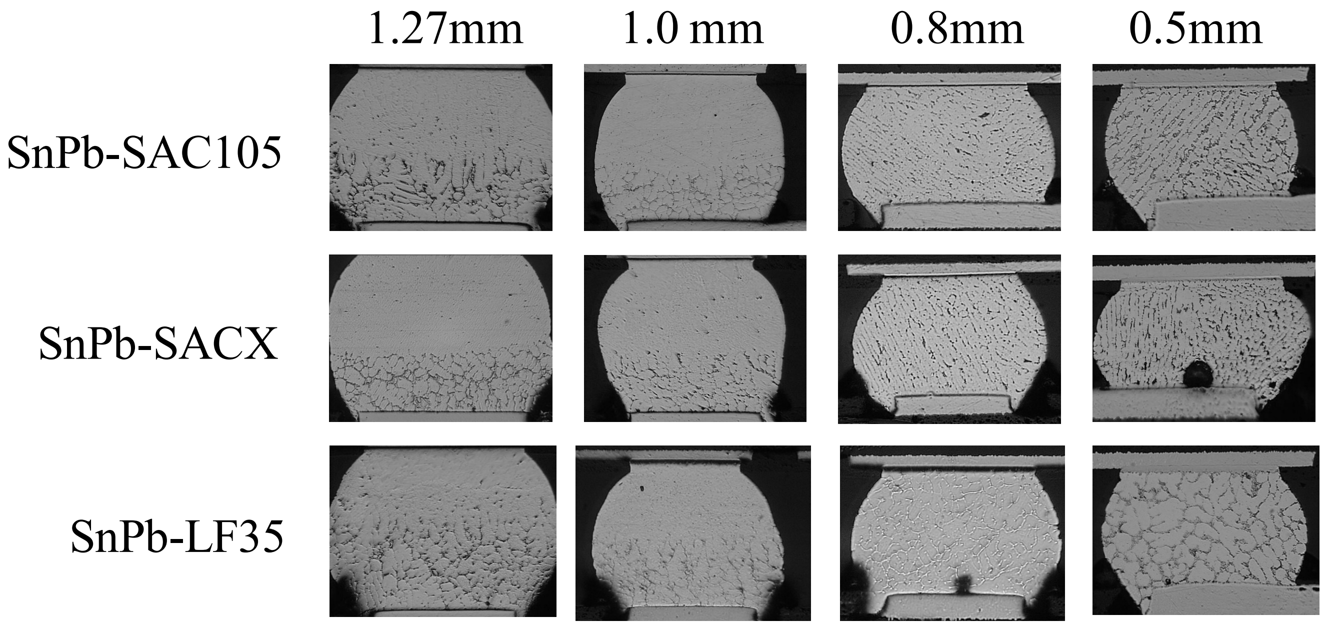

Figure 2 – Typical microstructures for mixed SnPb/Pb-free solder joints tested in this study. Such joints were reflowed at peak temperatures of 215 ^{o}C to produce partial mixing on the larger packages (joints shown were formed in phase 1B [4]).

ATC Testing Procedure

Two target ATC profiles were selected for this study:

- IPC-9701A condition TC1: 0°C to 100°C with 10 minute ramps and dwells (40 minute total cycle time)
- IPC-9701A condition TC3: -40°C to 125°C with 16.5 minute ramps and 10 minute dwells (53 minute total cycle time).

The actual temperature profiles are shown in Figure 3, which includes data from multiple thermocouples attached to different test boards. The thermal profiles were relatively uniform at different locations within the oven. The actual cycles were as summarized in Table 3.

Table 3. Actual thermal cycle parameters.

Nominal Profile	0/100^{o}C	-40/+125^{o}C
Range of Max. Temp. (^{o}C)	101 to 104	126 to 129
Range of Min. Temp. (^{o}C)	-4 to -1	-40.5 to -38.5
Range of High Temp. Dwell (min.)	10.5 to 12.0	10.5 to 13.5
Range of Low Temp. Dwell (min.)	8.5 to 10.5	9.0 to 11.5
Total Cycle Time (min.)	46.0 to 46.5	58

Solder joint interconnect integrity was monitored using one daisy-chain net for each package. Continuous in-situ monitoring of daisy-chain resistance was conducted throughout ATC testing. The data acquisition software "flagged" a daisy-chain net as failed using the IPC-9701A standard criterion of a 20% resistance rise. Since the resistance (R) is a function of temperature (T), measured R(T) values at any point during the test were compared against those measured on the first thermal cycle at an equivalent T. A "failure" was recorded once the following condition was met:

$$R(T) > 1.2 \cdot R_o(T) \quad , \tag{1}$$

where $R_o(T)$ represents the resistance measured during the first cycle at temperature T. This method compares the net resistance at all temperatures, not at a single reference temperature. For the data presented here, the tenth incidence of resistance reaching the failure criterion was used for plotting. This approach minimized the chance of plotting spurious signals rather than actual failures.

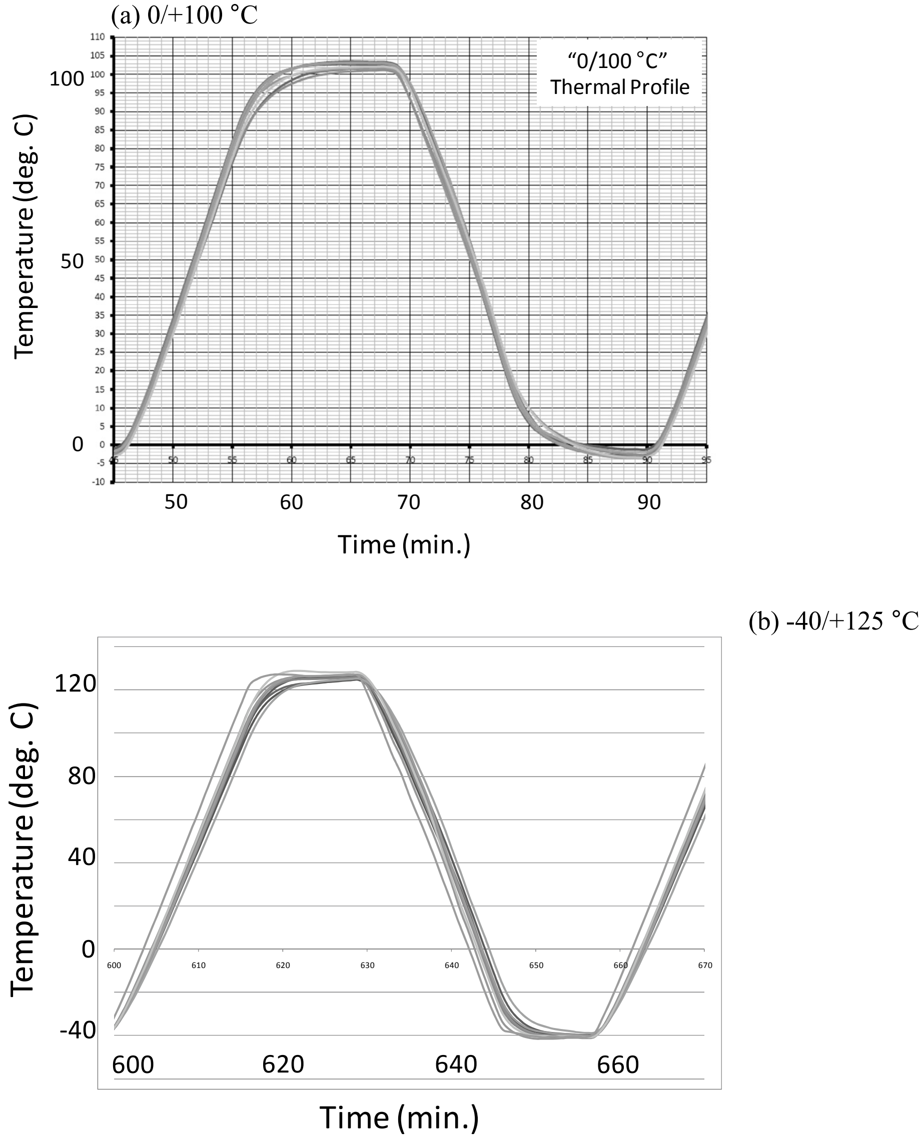

Figure 3 – Thermal profile as measured on test boards at multiple locations.

Preliminary Results and Discussion

Thermal cycling continues as of the writing of this paper. Data from the -40 to +125°C test, which was begun after the 0 to 100°C test, is just beginning to become available, so there are insufficient failures to present at this time. For the 0 to 100°C test, 2280 cycles have been accumulated and preliminary findings are discussed in this section.

Figure 4 presents data for joints made using eutectic Sn-Pb solder balls with eutectic Sn-Pb solder paste. As has been mentioned previously [7 – 9], direct comparison of thermal fatigue performance for low-Ag SAC alloys with the historical Sn-Pb eutectic solder has been lacking. The current study fills this gap using two different thermal cycle profiles and four different package types.

The data in Figure 4 demonstrate high Weibull slopes (β) and good correlation coefficients (ρ), suggesting that the joints were well manufactured and that no major problems occurred during test execution. Characteristic lives (η) range from about 1100 cycles to almost 2100 cycles. As expected, the accelerated thermal cycle performance depends on package type. The 0.8mm pitch parts consistently fail first, and the 0.5mm pitch parts are the next least reliable under the conditions tested. This trend has been repeated for other solder combinations in the data collected so far.

Figure 5 compares the accelerated thermal cycle performance for the baseline SnPb-SnPb joints with those of the mixed SnPb-SAC joints for 0.8mm pitch parts. Insufficient data have been obtained to date to make similar comparisons for the other package types. Again, all data are for the nominal 0 to 100°C profile.

Data for the 0.8mm pitch packages again demonstrate relatively high ρ values, except for the SnPb-SACX joints. The reason for the unusual SnPb-SACX data is still under investigation. The Weibull slopes for the mixed metallurgy joints are below that of the SnPb-SnPb joints, which is not uncommon. This result may suggest greater variability in mixed solder joints than for those consisting of a single alloy.

The data collected so far show that the mixed SnPb-SACX joints show significantly lower projected life at 1% failure than SnPb-SnPb, even though η is higher for the mixed joint compared to SnPb-SnPb. As stated earlier, the reason for the low β value for the mixed SnPb-SACX joints is still under investigation. The mixed SnPb-SAC105 joints show approximately the same 1% failure life as SnPb-SnPb, though a somewhat higher characteristic life. The exact reason for the low β value of these mixed joints relative to SnPb-SnPb joints is not known at this time, but such behavior of mixed SnPb-SAC joints is not uncommon. Finally, the mixed SnPb-SAC305 joints show significantly greater reliability than the SnPb-SnPb joints, both at the 1% failure level and the (projected) characteristic life. This finding suggests that the mixed joints are well formed and that good mixing has taken place using the profile listed in Table 2.

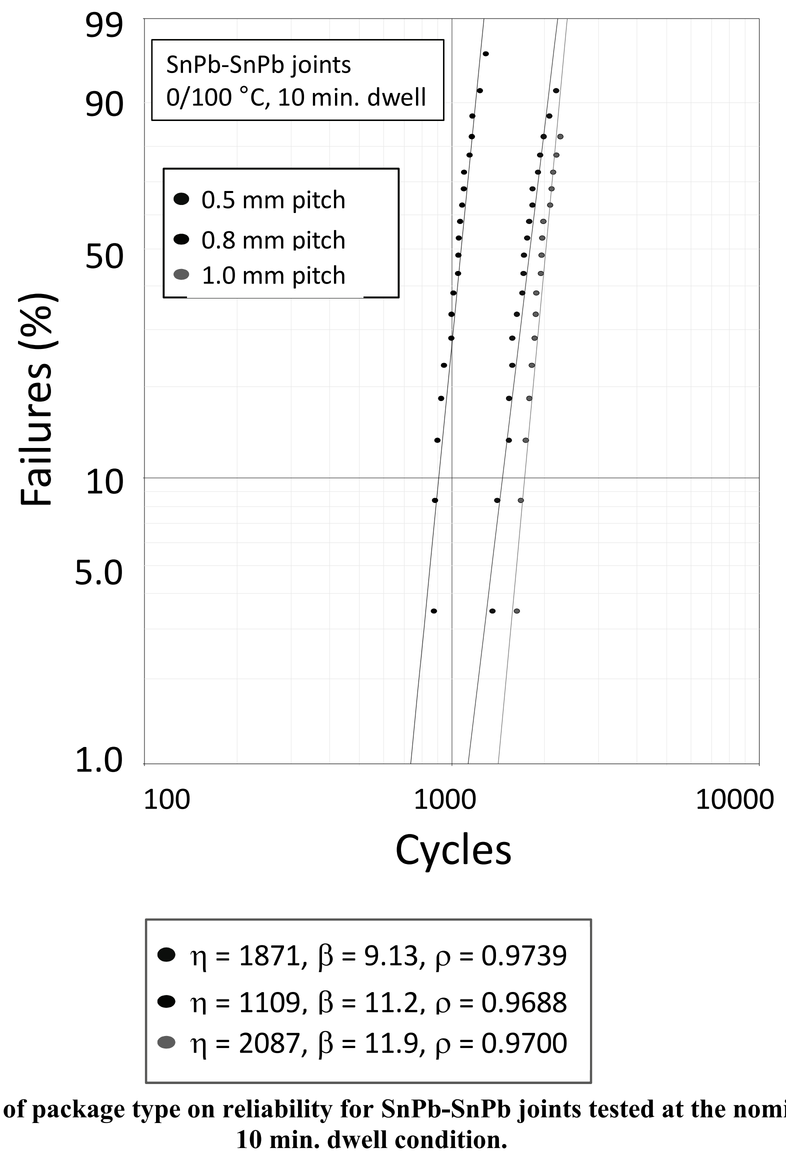

Figure 4 – Effect of package type on reliability for SnPb-SnPb joints tested at the nominal 0/100 °C, 10 min. dwell condition.

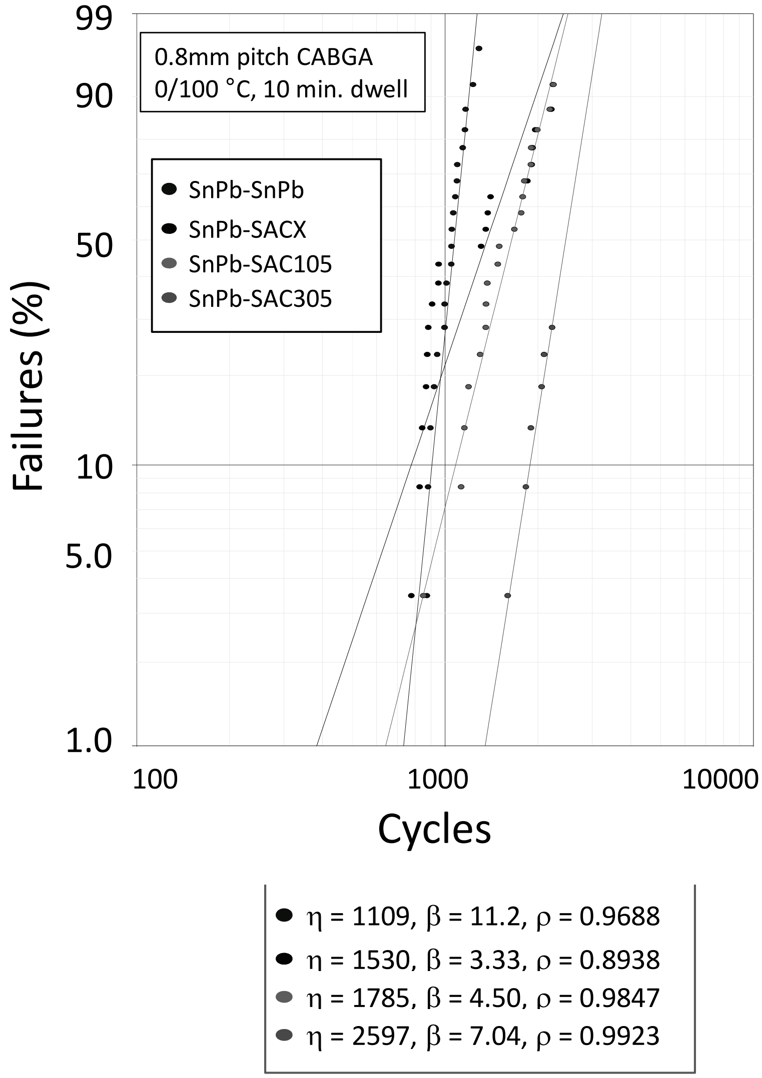

Figure 5 – Effect of solder joint composition on reliability for 0.8mm pitch CABGA components tested at the nominal 0/100 °C, 10 min. dwell condition – mixed SnPb-Pb-free joints

Comparison of the accelerated thermal cycle performance (nominal 0 to 100°C profile) for the baseline SnPb-SnPb joints with those of the Pb-free joints for 0.8mm pitch parts is given in Figure 6. Insufficient data have been obtained to date to make similar comparisons for the other package types.

Data for the 0.8mm pitch packages again demonstrate relatively high ρ and β values, suggesting well formed joints and that no major problems occurred during test execution. In this case, the Weibull slopes for the mixed Pb-free metallurgy joints are both above and below that of the SnPb-SnPb baseline, depending on the Pb-free ball alloy. Still, the lowest β in this group is 7.65, suggesting that there were no significant issues with the manufacture of the mixed metallurgy joints.

Perhaps the key finding of the study so far is that all the Pb-free joints perform better in thermal cycling than the SnPb-SnPb baseline at the nominal 0 to 100°C condition. As mentioned earlier, this has been a major question regarding the performance of new low Ag alloys [7 – 9]. Figure 6 shows that the joints with SAC105 and SACX solder balls have very similar reliability (essentially the same within statistical confidence). The Ag concentrations for these two alloys are 1.0% and 0.3%, respectively. Perhaps the other alloy additions in the SACX alloy are making up for the lower Ag concentration, given that thermal cycle performance usually scales directly with Ag content [1, 7, 10]. Consistent with this general observation, the Pb-free joints with SAC205 balls have yet higher reliability and those with SAC305 balls show no failures at this time. Again, these results are consistent with the trend of increasing reliability with increasing Ag content.

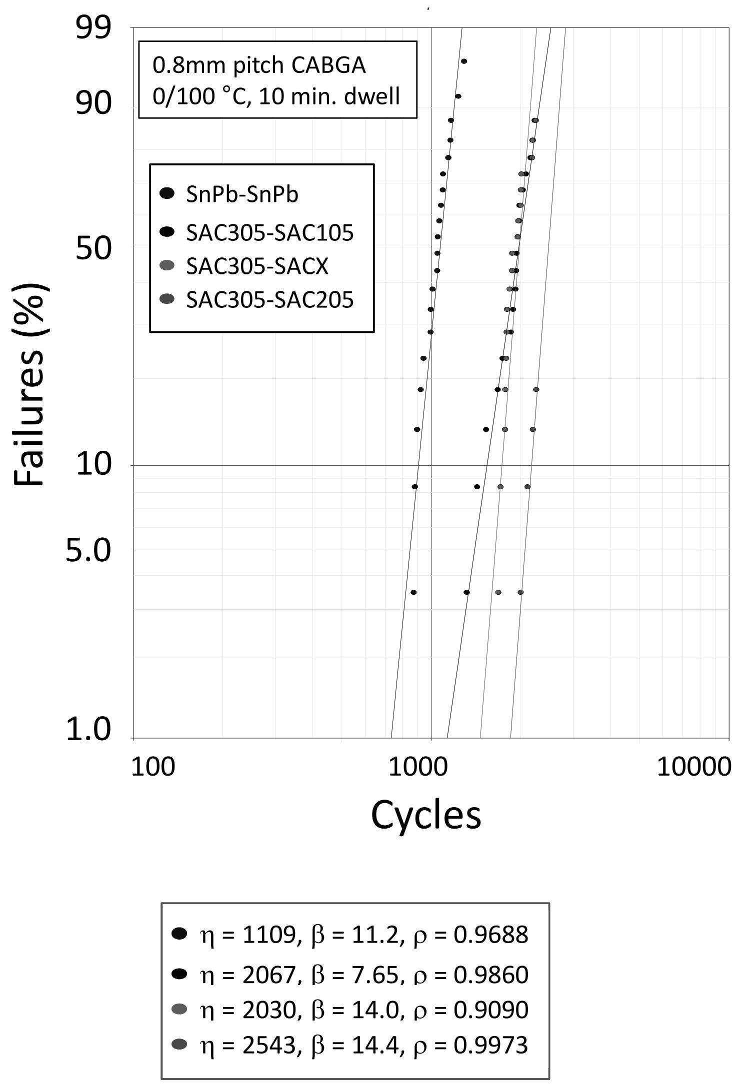

Figure 6 – Effect of solder joint composition on reliability for 0.8mm pitch CABGA components tested at the nominal 0/100 °C, 10 min. dwell condition – SnPb vs. Pb-free.

Table 4. Summary of Thermal Cycling Results for 0.8mm BGA, 0/100 °C, 10 minute Dwell

Paste Alloy	Sphere Alloy	Characteristic Life (η)	Weibull Slope (β)	Correlation Coefficient (ρ)
Sn-Pb	Sn-Pb	1109	11.2	0.9688
SnPb	SACX	1530	3.33	0.8938
SnPb	SAC105	1785	4.50	0.9847
SnPb	SAC305	2597	7.04	0.9923
SAC305	SACX	2030	14.0	0.9090
SAC305	SAC105	2067	7.65	0.9860
SAC305	SAC305	2543	14.4	0.9973

Table 4 summarizes the thermal fatigue data collected so far for the 0 to 100°C profile. The baseline SnPb-SnPb joints have the lowest characteristic life. This finding may be of some comfort for those faced with designing products using low Ag Pb-free BGAs soldered with either Pb-free SAC305 or (if properly manufactured) eutectic SnPb paste. (Of course, a validated acceleration model would be required to quantitatively assess reliability performance for field conditions.) Next in order are the Pb-free BGAs soldered with eutectic SnPb solder paste. For these, the characteristic life increases as the Ag concentration in the ball alloy increases. Finally, the 100% Pb-free joints perform consistently better than the SnPb-SnPb joints, again with the trend of increasing characteristic life with increasing Ag concentration.

Continuing Work and Preliminary Conclusions

The investigation reported here continues as the test boards continue to cycle under both profiles. The goal is to reach complete failure, or at least enough failures to reach the characteristic life, for all combinations of solder joint composition, assembly conditions, and package type. Results will be published as they become available.

It is risky to make firm conclusions at this point in the experiment, the but following tentative conclusions can be put forward at this time.

1. 100% Sn-Pb joints are less reliable under the 0/100°C test conditions than either the mixed SnPb/Pb-free joints or 100% Pb-free joints. For mixed SnPb/Pb-free joints, this conclusion is limited to the reflow conditions used in this study, which produce joints with relatively good mixing of Pb throughout. The only exception to this finding is for SnPb-SACX joints, which have a low projected 1% failure life and low β, possibly due to problems with proper solder joint formation.
2. Under 0/100°C test conditions, low Ag BGAs soldered with SAC305 paste are more reliable than corresponding 100% SnPb joints. This finding suggests that the risk of using low Ag BGAs in environments that induce solder joint thermal fatigue may be manageable in many applications.

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