Thermal Cycling Reliability of Alternative Low-Silver Tin-based Solders

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Abstract

Sn-3.0Ag-0.5Cu (SAC305) alloy is the most widely used solder in electronic assemblies. However, issues associated with cost and drop/shock durability have resulted in a continued search for alternative solder alloys. One approach to improve the drop/shock reliability has been to reduce the silver content in Sn-Ag-Cu alloys. Another approach is doping Sn-Ag-Cu solder with additional elements. Moreover, conflicting results have been reported in literature on the effects of aging on Sn-Ag-Cu alloys. In 2008, International Electronics Manufacturing Initiative (iNEMI) started the "Characterization of Pb-Free Alloy Alternatives" project to provide a comprehensive study of fifteen tin-based solder interconnect compositions benchmarked against the eutectic tin-lead solder. For this study, temperature cycle durability was the primary focus and solders were selected to study the effect of varying silver content, microalloy additions, and aging. This paper reports the preliminary findings from one of the test conditions conducted under the iNEMI project. The cycles to failure for a temperature cycling test condition from -15°C to 125°C, with dwell times of 60 minutes at both extremes are presented. The test assembly consisted of sixteen 192 I/O BGAs and sixteen 84 I/O BGAs soldered on to LG451HR laminate. Preliminary findings revealed that the reduction of silver resulted in a reduction in cycles to failure. In all cases, the fifteen tin-based solders were more durable than the eutectic SnPb solder. Aging did not affect the cycles to failure in SAC105 solder; however, the cycles to failure decreased with aging in SAC305 solder. In addition, aging resulted in a wider distribution of cycles to failure in 192 I/O BGAs.

Key words

Alternative solders, iNEMI characterization of Pb-Free alloy alternatives project, Low silver lead-free solder, Thermal cycling reliability.

I. Introduction

The adoption of lead-free legislations has resulted in the proliferation of alternatives to eutectic tin-lead solder. Near-eutectic Sn-Ag-Cu (SAC) alloys were initially recommended by National Center for Manufacturing Center (NCMS) and International Electronics Manufacturing Initiative (iNEMI) as the primary solder replacements after the adoption of lead-free legislation [1], [2]. The high silver near-eutectic SAC alloys included Sn-4.0Ag-0.5Cu (SAC405), Sn-3.8Ag-0.7Cu (SAC387), and so on. The first move from the near-eutectic SAC alloys towards a lower silver content alloy was partly motivated by the cost savings in reducing the amount of silver and to avoid intellectual property issues with Iowa State University [2], [3]. In addition, the formation of large Ag_3Sn platelets in the near-eutectic SAC alloys was believed to degrade their thermal fatigue resistance [2], [4]. The Japanese Electronics Industry Association (JEITA) and then the IPC recommended the hypoeutectic Sn-3.0Ag-0.5Cu (SAC305) alloy. The SAC305 alloy has excellent thermal cycling reliability due to the presence of silver and thereby became the de facto industry standard.

The high flow stress and elastic modulus in high silver SAC alloy made the solders susceptible to failures under drop/shock loading. To improve the drop/shock reliability, the silver content in SAC alloys was reduced from three percent, to as low as no silver. Another driving factor to lower Ag content was the high cost of Ag, which led to the use of SAC205 and SAC105 alloys. The copper content was later adjusted to improve metallurgical stability, resulting in SAC107 alloy [2] [3]. Although studies [5]-[7]showed that the thermal fatigue durability of SAC alloys improved with the increase in silver content, data from a comprehensive set of temperature cycling conditions is unavailable and a quantitative relationship has not been established.

Solder dopants, also known as microalloy additions, are elements (typically 0.1% or lower) other than the main constituents of the alloy that have been shown to improve solder performance [2]. Nickel (Ni) was added to SnAg and Sn-Ag-Cu alloys to improve performance under high strain-rate loading [2] and to address issues during wave soldering [3]. Other commonly used microalloy additions are bismuth (Bi), manganese (Mn), and antimony (Sb). The exploration of the possible benefits of microalloy additions is ongoing, with several already being used commercially.

Studies in the literature have shown that the thermal cycling durability of solders decreased with aging [8], [10]. Since conflicting results have been published by some studies [11], the impact of aging cannot be generalized among all solders. The impact of aging on fatigue life needs to be determined for SAC solder alloys at different temperature cycling profiles.

The reliability of alternative alloys needs to be benchmarked against eutectic SnPb and SAC305 to understand the impact of lower silver content and microalloy additions. Although the impact of lower silver and microalloy additions has been studied, a comprehensive data on the reliability of alternative solders benchmarked against SnPb and SAC305 is unavailable. To fill the gap in the thermal fatigue knowledge and data of these new solder alloys, iNEMI initiated the Characterization of Pb-Free Alloy Alternatives project in 2008 [2] [12]. In this paper, the initial findings from one of the iNEMI test profiles, -15ºC to 125ºC, with dwell times of 60 minutes at both extremes, are reported.

II. iNEMI Tests

The test vehicles and accelerated temperature cycling tests conditions were designed by the iNEMI Pb-free Alloy Alternative team. The primary objectives of this paper are to determine the effect of: 1) lower silver content, 2) microalloy additions, and 3) aging on thermal cycling fatigue life. The alternative solders to be tested were selected such that the objectives are addressed. Two different package sizes were included in the test matrix to understand the effect of package geometry on thermal cycling durability.

A. Test Matrix and Vehicle

The test board, as shown in Figure 1, was constructed with LG451HR, a laminate qualified for Pb-free assembly temperatures, and was 0.093" (2.36mm) thick. The board had 6 layers with 2 common ground planes. The glass transition temperature (T_g) of the board was approximately 150ºC and CTE_x and CTE_y were 13.8 and 12.2 ppm/ºC respectively. Package side and board side pad finishes were electrolytic Ni/Au and high temperature OSP, respectively. Fifteen tin-based lead-free solders were selected for the test to be benchmarked against eutectic SnPb solder, as shown in Table. I. For these tests, the listed solder is for the BGA solder sphere. The solder sphere compositions included SAC alloys with varying Ag content, SN100C solder with two types of solder pastes, SAC alloys with microalloy additions, and SAC alloys aged at 125ºC for 10 days. SAC105+Ni and SAC205+Ni solders have 0.05 wt. % Ni added to SAC105 and SAC205 respectively. SACX is Sn-0.3Ag-0.7Cu +Bi+X and SACi is Sn-1.7Ag-0.64Cu+Sb. BGAs with eutectic SnPb solder balls were soldered using SnPb solder paste and one set of BGAs with SN100C solder balls were soldered with SN100C solder paste. SAC305 solder paste was used for all other BGA solder compositions, as shown in Table. I.

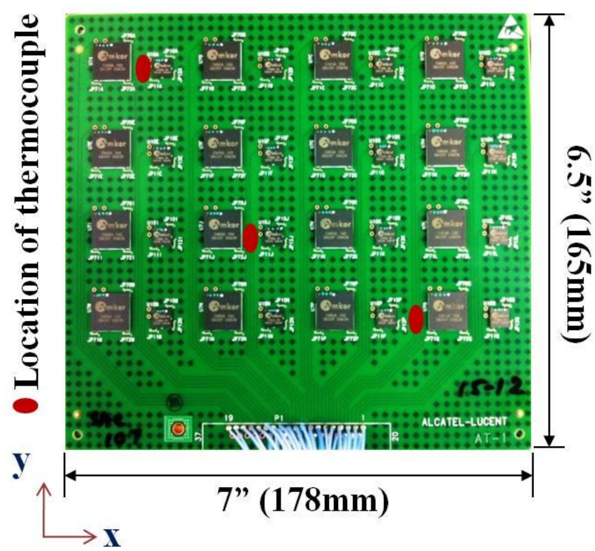

Figure 1. iNEMI test vehicle

Table. I Solder ball and solder finish

No	Solder ball	Solder paste	No	Solder ball	Solder paste
1	SnPb	SnPb	**9**	SAC105 + Ni	SAC305
2	SN100C	SN100C	**10**	SAC205 + Ni	SAC305
3	SN100C	SAC305	**11**	SAC-Mn	SAC305

4	SAC0307	SAC305	**12**	SACX	SAC305
5	SAC105	SAC305	**13**	SAC105-Aged	SAC305
6	SAC205	SAC305	**14**	SAC305-Aged	SAC305
7	SAC305	SAC305	**15**	SAC107	SAC305
8	SAC405	SAC305	**16**	SACi	SAC305

Two types of BGA packages were tested: 192 I/O CABGA (ChipArray® BGA) and 84 I/O CTBGA (Thin ChipArray ® BGA). Properties and dimensions of the BGA packages are listed in Table. II. Each board had sixteen 192 I/O CABGAs and sixteen 84 I/O CTBGAs. Each assembled package formed a single low resistance path that included each of its solder interconnects.

Table. II Package dimensions and properties

Package Type		**192 I/O CABGA**	**84 I/O CTBGA**
Pitch		0.8 mm	0.5 mm
Dimension		14 mm X 14 mm	7 mm X 7 mm
Die dimension		12.07 mm X 12.07 mm	5.08 mm X 5.08 mm
Die thickness		0.26 mm	0.22 mm
Solder ball size		0.46 mm	0.3 mm
Package CTE	**X axis**	7.0 ppm/°C	8.5 ppm/°C
	Y axis	7.6 ppm/°C	9.6 ppm/°C

B. Temperature Cycling Profile

The ten temperature cycle test conditions under investigation through the iNEMI Pb-Free Alternative Alloy program are presented in Table. III. This paper will present results from profile 9, -15ºC to 125ºC with dwell times of 60 minutes.

Table. III iNEMI test profiles

Profile	**T_{min}(°C)**	**T_{max}(°C)**	**t_{dwell}(min)**
1	0	100	10
2	0	100	60
3	-40	100	10
4	-40	100	60
5	-40	100	120
6	25	125	10
7	25	125	60
8	-15	125	10
9	***-15***	***125***	***60***
10	-40	125	10

The ramp rates during heating and cooling were 7ºC/min. Failure criterion was defined as the occurrence of resistance value greater than 1000Ω confirmed by 9 additional interruptions within an additional 10% of the cyclic life

C. Temperature Cycling Test Results

Measurements prior to temperature cycling test revealed that package resistances for 192 I/O CABGA and 84 I/O CTBGA were 1 Ω and 0.5-0.6 Ω respectively and two components were "dead on arrival" (open circuits). Optical and X-ray inspections of the failed components did not reveal any manufacturing defects, such as missing solder balls or solder bridging.

The time to failure results were statistically examined using the Weibull++ software package and two parameter Weibull statistics were determined for each solder type, presented in Table IV. Eutectic SnPb solder was the first to fail among all the tested solders in both BGA package types, This result is consistent with the results from other temperature cycling profiles reported by iNEMI [3]. Weibull plot of 192 I/O and 84 I/O BGA packages is shown in Figure 2. SAC305 solder was the last to fail in 192 I/O and SAC205+Ni in 84 I/O package types.

Table. IV Weibull characteristics of all solder types in -15ºC to 125ºC, 60 minute dwell test

No	**Solder**	**192 I/O**		**84 I/O**	
		β	**η**	**β**	**η**
1	SnPb	8.2	946	6.4	1333
2	SN100C+SN100C	11.7	1077	9.5	2366
3	SN100C+SAC305	10.9	1048	6.8	2356
4	SAC0307	6.7	1327	14.0	2286
5	SAC105	7.3	1473	6.8	2448
6	SAC205	6.4	1736	7.8	3100
7	SAC305	9.3	2107	8.1	3496
8	SAC405	9.6	1713	7.3	3310
9	SAC105 + Ni	9.1	1705	8.2	3302
10	SAC205 + Ni	6.9	1663	7.9	3526
11	SAC-Mn	3.3	1394	6.8	2398
12	SACX	4.7	1603	8.8	2638
13	SAC105-Aged	3.6	1492	4.4	2421
14	SAC305-Aged	4.0	1940	9.0	2917
15	SAC107	6.4	1340	7.4	2652
16	SACi	9.1	1689	5.8	2579

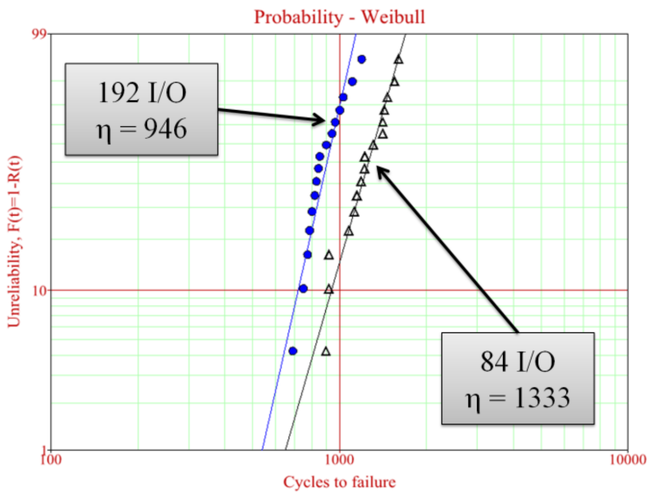

Figure 2. Weibull analysis of eutectic SnPb solder.

III. Discussions

From examination of the time to failure data, some interesting observations can be made.

A. Effect of Package Size

For test condition 9, the 192 I/O packages failed earlier than 84 I/O packages for all solder types because the strain levels at interconnects are higher in a larger package due to greater distance from neutral plane than a smaller package. In addition, the outer row of solder balls in 84 I/O BGA lies outside the die shadow, whereas the die shadow in 192 I/O BGA extends beyond the outer row causing additional strain. The smaller Sn dendrite size and fine Ag_3Sn precipitate features, increased Ag content derived from adding SAC305 paste to a smaller solder ball, and a lower stand-off height may have benefitted the 84 I/O BGA.

B. Effect of Silver Content

The increase in silver content resulted in improvement in the characteristic lives of SAC soldered 192 I/O packages, except SAC405. SN100C solders which do not have any Ag showed lower durability than all SAC solders, as shown in Figure 3. The characteristic life of SAC305 (3 wt. % Ag) solder was approximately twice that for SN100C (no Ag) solder. A similar trend was observed in 84 I/O packages, except that difference in life was statistically insignificant when the silver content dropped below 2% (Figure 4).

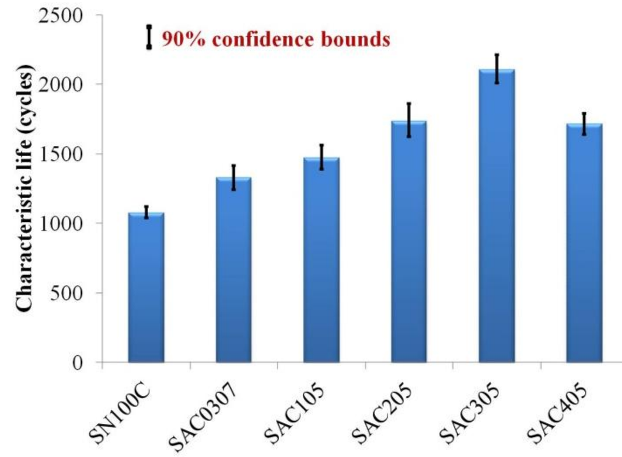

Figure 3. Characteristic life with 90% confidence bounds of solders in 192 I/O BGAs with varying silver content.

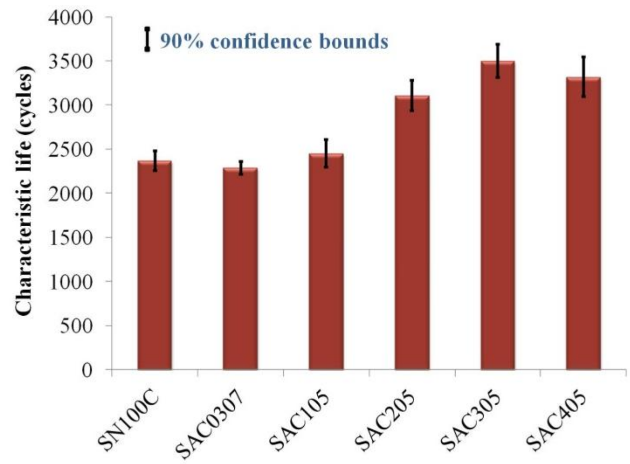

Figure 4. Characteristic life with 90% confidence bounds of solders in 84 I/O BGAs with varying silver content.

In 192 I/O packages, SAC405 had lower characteristic life than SAC305, and statistically the same as that of SAC205 solders, as shown in Figure 5. The behavior of SAC405 solder is contrary to the results obtained from iNEMI profiles 1 and 10, as reported in [13]. The lower reliability of SAC405 may be due to the presence of large Ag_3Sn intermetallic platelets in the solder microstructure providing a path to accelerate crack propagation [4]. This hypothesis will be investigated during failure analysis. The mean cyclic temperature, cyclic temperature range, dwell time and ramp time may have played a role in the relatively poor reliability of SAC405. Results from all iNEMI test profiles will be analyzed later to provide a more general conclusion.

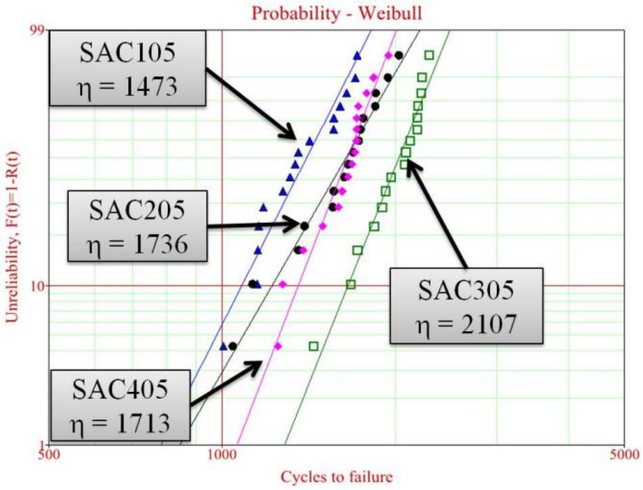

Figure 5. Weibull analysis of Sn-Ag-Cu solders with varying Ag content in 192 I/O BGAs.

Failure data of SAC solders with low Ag and low Cu showed that slight changes in the Ag and Cu content did not result in any statistical difference in characteristic life, as shown in Figure 6.

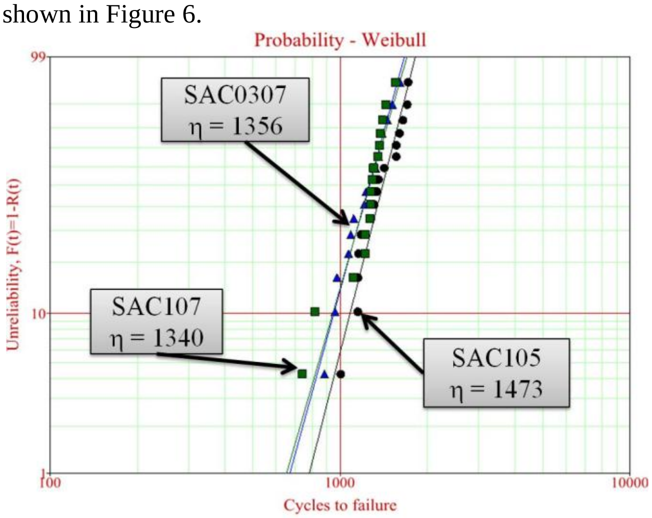

Figure 6. Weibull analysis of Sn-Ag-Cu solders with low Ag and Cu content in 192 I/O BGAs.

C. Effect of Element Doping

The effect of microalloying SAC solder with select elements varied with BGA size. For instance, the addition of Ni resulted in increased cycles to failure for SAC105 solders, as shown in Figure 7. The percentage increase in cycles to failure was greater in the smaller 84 I/O BGAs (35%) than the 192 I/O BGAs (15%). In SAC205 solders, the addition of Ni resulted in slight improvement in characteristic life in the 84 I/O BGAs (14%) whereas no improvement was observed in the 192 I/O BGAs (Figure 8). The common trend in both SAC105 and SAC205 solders is that the effect of Ni addition is more prominent in smaller package size. This suggests that the effect of Ni addition is dependent on the strain in the solder interconnects. Improvement in cycles to failure of solder interconnects is present at lower strain and becomes masked at higher strains. Small additions of Ni are known to alter the solder solidification and microstructure [3], which also could result in improved performance. The detailed microstructural analysis needed to confirm that interaction is beyond the scope of the current work.

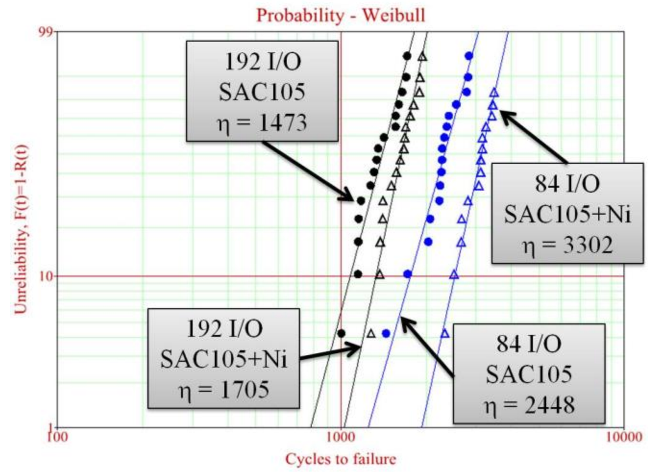

Figure 7. Weibull analysis of Ni addition in SAC105 solder

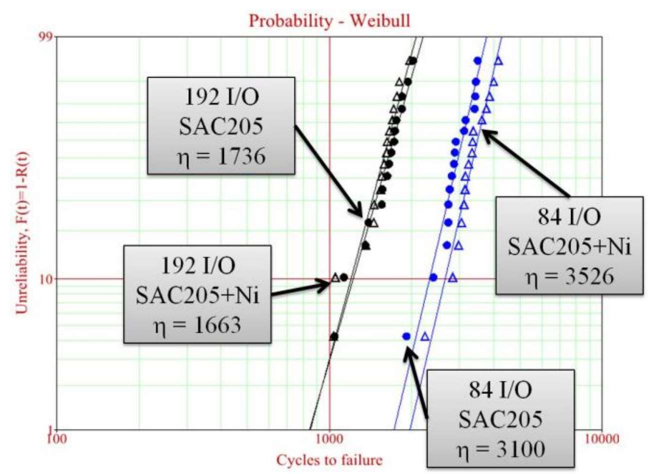

Figure 8. Weibull analysis of Ni addition in SAC205 solder

Comparison of the characteristic life of SAC105 and SAC105+Mn showed no statistical difference with Mn addition for both BGA types, as shown in Figure 9. However, in 192 I/O BGAs with Mn doped SAC105 experienced earlier failures resulting in a lower slope, i.e., wider distribution of failures.

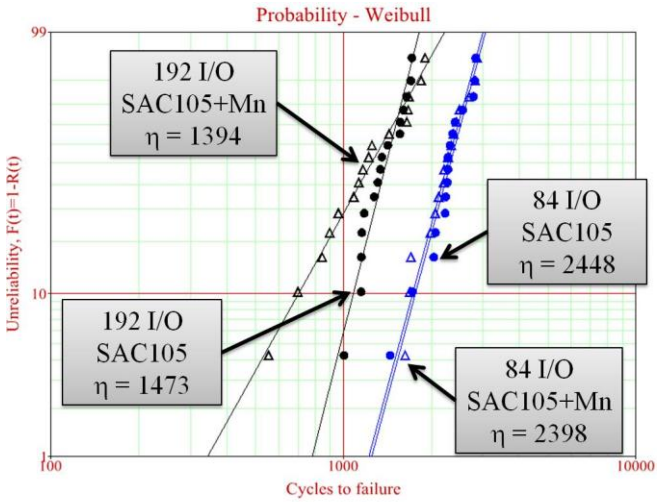

Figure 9. Weibull analysis of Mn addition in SAC105 solder.

Figure 10 depicts probability of failure curves for three low silver alloys with different doping elements. Although comparison of characteristic life does not show a significant difference, $B_{10\%}$ life varies considerably between the three solder types. SACi had the highest $B_{10\%}$ life with 1318 cycles, followed by SACX with 997 cycles, and SAC105+Mn had the lowest with 702 cycles. In this case, the higher silver content found in SACi may play role. However, the SAC105+Mn solder has higher silver than the SACX solder, so here the addition of Bi may be a factor. Further, failure data shows that the selection of a specific alloy should not be solely based on the characteristic life of the failed dataset. For critical applications, such as aerospace, in which even a single failure cannot be tolerated, parameters like $B_{1\%}$ or $B_{10\%}$ life should be considered.

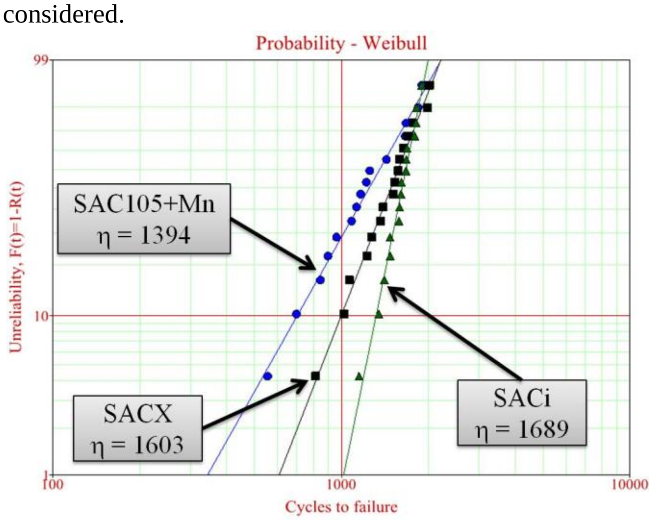

Figure 10. Special solder alloys with microalloy additions in 192 I/O BGAs.

D. Effect of Aging

Aging of SAC solders at 125ºC for 10 days was found to have a stronger influence on the SAC305 solder as compared with the SAC105 solder. Comparison of characteristic life showed that aging did not affect the reliability of SAC105 solders for both BGA package types, as shown in Figure 11. This result is consistent with the results from other iNEMI profiles reported in [14]. However, aging resulted in earlier failures thereby reducing the slope of the Weibull plot. The earlier failures may be due to the formation of Ag_3Sn intermetallic compounds in the solder, thereby decreasing the fatigue resistance of the solder.

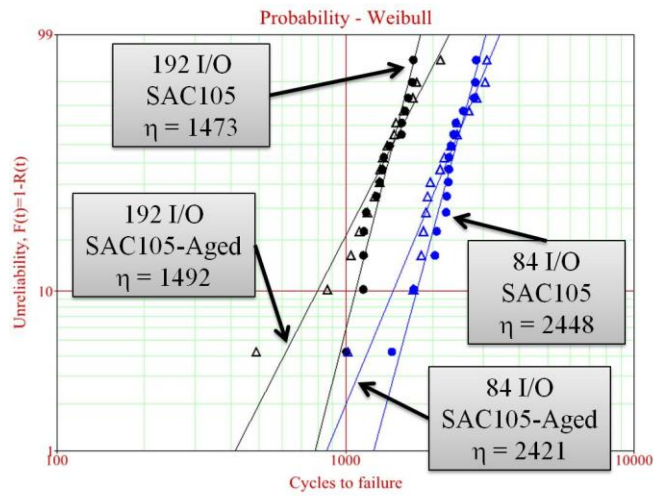

Figure 11. Weibull analysis of aged SAC105 solders.

The effect of aging in SAC305 solders was different from that observed in SAC105 solders, as shown in Figure 12. Aging resulted in a slight reduction (8%) in characteristic life in 192 I/O BGAs and a considerable reduction (17%) in the 84 I/O BGAs.

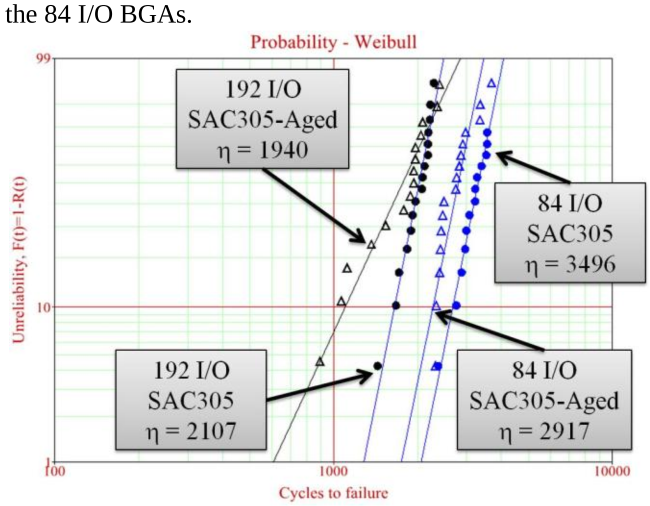

Figure 12. Weibull analysis of aged SAC305 solders.

E. Effect of Solder Pastes

To study the effect of solder paste on the thermal cycling durability, SN100C solder paste was used to reflow one set of SN100C solder balled BGAs whereas SAC305 solder paste was used for another set of SN100C soldered BGAs. Weibull analysis showed that, the used of solder paste did not result in any statistically significant difference in the characteristic life, as shown in Figure 13. The results suggest addition of a slight amount of silver (from the SAC305 solder paste) did not improve the thermal cycling durability of no-silver solder.

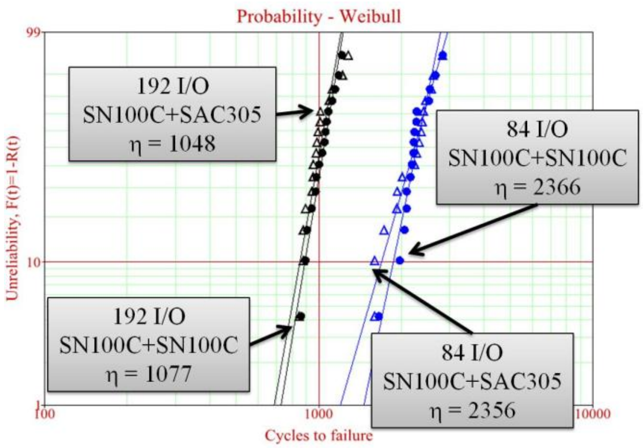

Figure 13. Weibull analysis of SN100C solder balls with SN100C and SAC305 solder pastes.

IV. Failure Analysis

A baseline characterization of the microstructure was carried out on control samples of all solder types to enable comparisons to failed temperature cycled samples. Characterization was carried out using optical metallography (destructive cross-sectional analysis), scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS). Analysis of the microstructures of control samples of all solder types did not show any defects. Characterization of the SAC405 control sample, along with the bulk solder microstructure is shown in Figure 14. Microstructure and the intermetallic compounds formed at the package-solder and solder-board interfaces of an SAC405 control sample are shown in Figure 15.

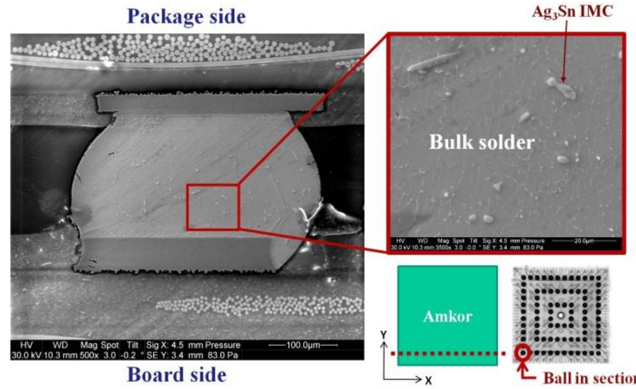

Figure 14. Characterization of SAC405 control sample

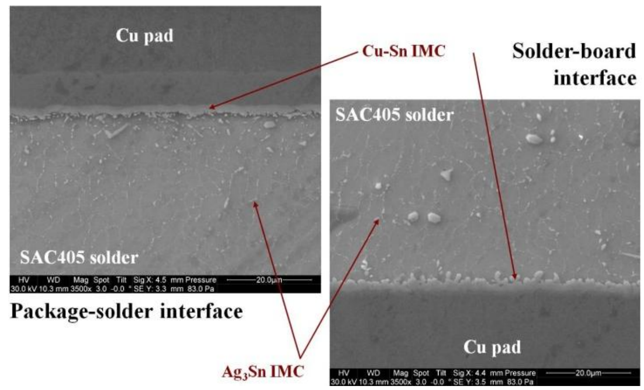

Figure 15. Package-solder and solder-board interfaces of SAC405 control sample

Physical analysis on the failed samples is carried out to identify the failure sites/mechanisms in the solder interconnects subjected to temperature cycling loading condition. Physical analysis of the failed samples is in progress and will be reported in a subsequent publication. Since the loading is due to thermal stress, the failure mode is expected to be cracks in the bulk solder at the package side and the failure mechanism to be thermo-mechanical fatigue.

V. Summary and Conclusions

The initial trends from one of the iNEMI test profiles, -15ºC to 125ºC, with dwell times of 60 minutes at both extremes, were reported. However, the observations made in this paper should be considered preliminary until they have been compared with results of the full data set that is being generated under the iNEMI Pb-free Alternative Alloy program. One important finding, consistent with other reported data, is the longer fatigue life of the Pb-free alternative alloys compared with eutectic SnPb. This finding recommends any of the tested alloys for temperature cycle reliability over SnPb. For highest temperature cycling fatigue durability, increased silver content is preferred. However, content above 3% may not further improve thermal fatigue reliability.

Acknowledgment

The authors would like to acknowledge the continued guidance of iNEMI, particularly that of David Godlewski. The authors would also like to thank all the members and companies involved in the “iNEMI Pb-Free Alloy Characterization Project” for their valuable feedback and assistance.

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