Investigation on the Impact of Pb-free Solder Alloy Mixing on Solder Joint Integrity Using Ball Grid Arrays (BGAs)

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ABSTRACT

An investigation was conducted to assess the solder joint integrity (acceptable/nonacceptable) for three different solder alloys on ball grid arrays (BGAs) in a mixed metallurgy configuration as compared to a baseline SAC305 system. Thermal cycle testing using a -55 to +125 ºC range in accordance with the IPC-9701 specification was used. Weibull statistical assessment and metallurgical cross-sectioning analysis was completed after 800 total thermal cycles. This paper documents the investigation results.

BACKGROUND

Collins Aerospace was asked to participate in the International Electronics Manufacturing Initiative (iNEMI) consortium Pb-free Generation 3 Solder project in 2015. The objective of the Generation 3 project was to characterize and assess Pb-free solder alloys that could potentially replace the SAC305 solder alloy in harsh environments. A total of 14 solder alloys (see Table 1: Generation 3 Solder Project Solder Alloy List) were selected for thermal cycle testing. Collins played a critical role in the project by producing the different alloy test vehicles, conducting the -55 to +125ºC thermal cycle testing and completing a significant amount of failure analysis.

Table 1: Generation 3 Solder Project Solder Alloy List

Alloy	Nominal Composition (wt. %)							Melting
	Sn	Ag	Cu	Bi	Sb	In	other	Range, °C
SAC305	96.5	3.0	0.5					217-221
Innolot	91.3	3.5	0.7	3.0	1.5		0.12 Ni	206-218
HT	95.0	2.5	0.5			2.0	Nd	206-218
MaxRel Plus	91.9	4.0	0.6	3.5				212-220
M794	89.7	3.4	0.7	3.2	3.0		Ni	210-221
M758	93.2	3.0	0.8	3.0			Ni	205-215
SB6NX	89.2	3.5	0.8	0.5		6.0		202-206
Violet	91.25	2.25	0.5	6.0				205-215
Indalloy 272	90.0	3.8	1.2	1.5	3.5			216-226
Indalloy 277	89.0	3.8	0.7	0.5	3.5	2.5		214-223
Indalloy 279	89.3	3.8	0.9		5.5	0.5		221-228
LF-C2	92.5	3.5	1.0	3.0				208-213
SN100CV	97.8		0.7	1.5			0.05Ni	221-225
405Y	95.5	4.0	0.5				0.05 Ni; Zn	217-221

A key finding from the Pb-free Generation 3 Solder project results was the improved solder alloy thermal cycle reliability in comparison to the SAC305 solder alloy [1]. Figure 1 illustrates how the tested solder alloys performed in three different thermal cycle test ranges in comparison to the SAC305 solder alloy for one of the components.

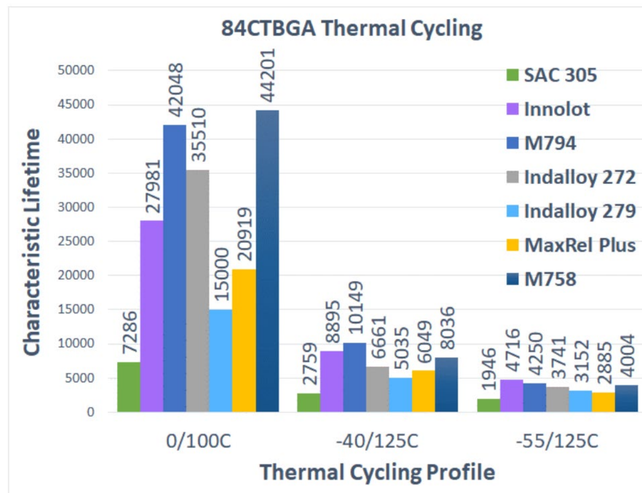

Figure 1: Pb-free Generation 3 Solder Project Thermal Cycle Test Results Comparison Data

The reason for the improved performance of the Generation 3 solder alloys is the addition of constituent elements that improve the solder joint microstructure strengthening mechanisms. The SAC305 solder alloy utilizes the formation of the Ag_3Sn intermetallic compound (IMC) at the tin matrix grain boundaries for fatigue resistance. However, these Ag_3Sn IMC precipitates coarsen over time, due to the combination of temperature and strain. Figure 2 illustrates the coarsening behavior of the SAC305 solder alloy. The Generation 3 solder alloys utilized bismuth (Bi), indium (In) and antimony (Sb) as the solder joint microstructure strengthening mechanism. These elements have better temperature stability and improved IMC interactions with the tin matrix grain boundaries, resulting in better fatigue resistance (Figure 3).

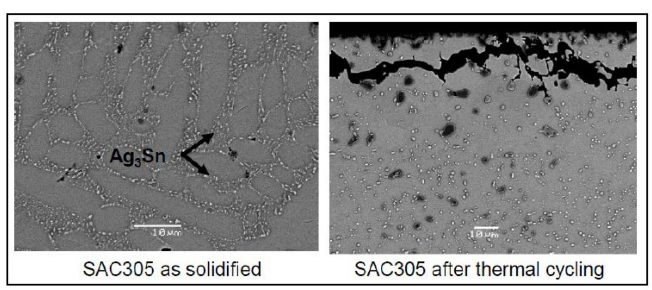

Figure 2: Solder Joint Microstructure Coarsening Behavior of SAC305 Solder

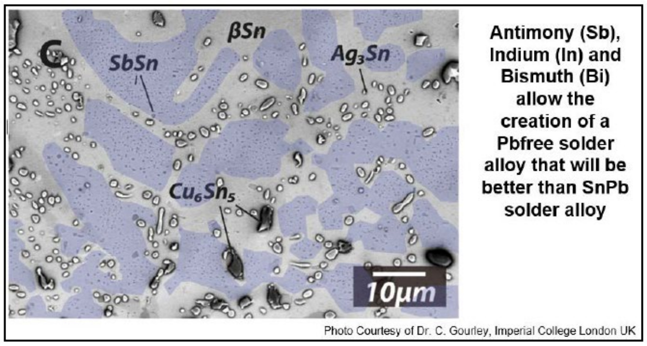

Figure 3: Interaction of IMCs and Solder Joint Microstructure [2]

The Pb-free Generation 3 Solder project was conducted as a "pure" metallurgy configuration, i.e., the solder paste and the BGA solderballs were the same. Currently, industry BGA component fabricators supply their components with solderball alloys that are in the SAC alloy family, which is recognized as SAC105, SAC305, and SAC405. Soldering these BGA alloys with a SAC305 solder paste creates a solder joint that is suitable for a wide range of product use environments despite not being "perfectly" a SAC305 solder alloy. It is expected that BGA component fabricators will continue to supply BGAs using the SAC alloy family, even if one of the Generation 3 solder alloys were to be implemented as the solder paste alloy. This will result in a "mixed metallurgy" condition for the foreseeable future that must be characterized. The two promising Generation 3 solder alloys selected were the Indalloy 292 and Senju M794 products. The Senju M794 alloy has been extensively used by the cell phone industry for at least 5 years and to a limited extent in the automotive industry. The Indalloy 292 alloy appears to have metallurgically optimal Bi and Sb additions based on previous work done [1]. The investigation also included SnPb and SAC305 solder pastes for the purposes of creating baseline data comparisons.

Objective

The objective of the investigation was to assess the solder joint integrity of two new high reliability solder pastes in a mixed metallurgy configuration with SAC305 BGAs. Senju M794 and Indalloy292 solder pastes were selected for the investigation. These results were compared to two different baseline data sets: for BGAs with SAC305 solder spheres that were assembled with SAC305 pastes and a traditional mixed metallurgy condition of SAC305 BGAs assembled with SnPb paste.

Procedures

Test Components

The component selected for the investigation was a BGA from Practical Components Inc. The BGA component had 256 connections using a SAC305 solderball alloy. A total of 240 individual component of each type were procured (60 components for each solder alloy in the test matrix). The BGA component was daisy chained to allow for electrical continuity monitoring during thermal cycle testing. Figure 4 illustrates the mechanical configuration of the components.

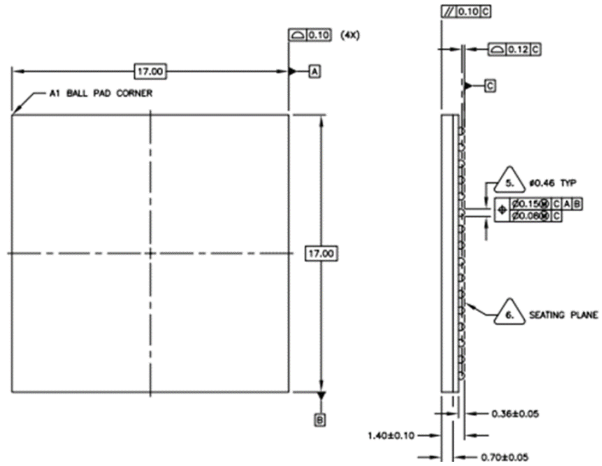

Figure 4: BGA Component Mechanical Configuration

Test Vehicle

The test board was 0.081 ± 0.008 inches thick with 8 dummy inner layers. The board was constructed using FR-4 material in accordance with IPC-4101/126 with an immersion silver surface finish. Through-holes are arranged along one side of the test vehicle for ease of organizing cabling. Instead of using a connector, ribbon cable leads were manually soldered to the through holes corresponding to each component I/O pair. The test vehicle included a population of 60 samples. Figure 5 illustrates the board construction.

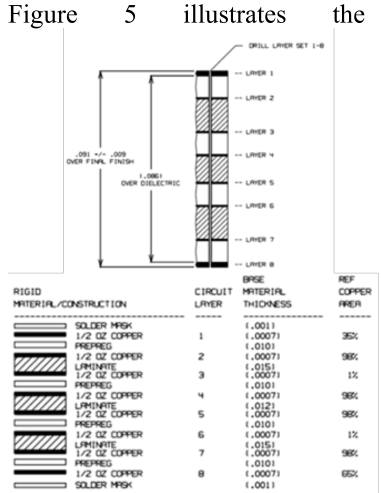

Figure 5: Test Vehicle Construction

Test Vehicle Assembly

The test vehicles were assembled at the Collins Aerospace Coralville, IA production facility. Each solder alloy was processed for the BGA component as an individual build lot run. The component was placed using a Universal Advantis automated placement machine. The assemblies were reflowed in a Heller 1912EXL reflow oven using the standard SAC305 solder alloy profile (except for the SnPb test vehicles). Assemblies were cleaned in the Aquastorm 200 inline cleaner using the Kyzen Aquanox 4625 saponifier. Figure 6 illustrates an assembled test vehicle.

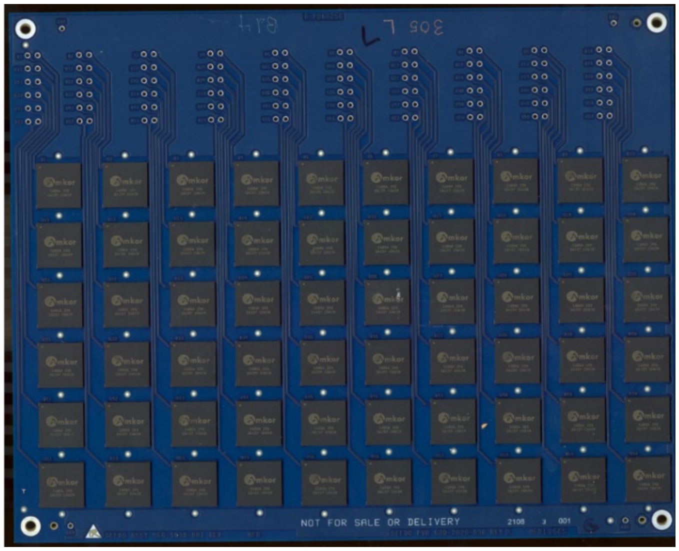

Figure 6: Assembled Test Vehicle

Thermal Cycle Testing

The test vehicles were placed into a thermal chamber set for a temperature range of -55°C to 125°C. The ramp rate was set for a maximum temperature ramp of 10°C per minute with 10 minute dwells at each temperature extreme. The continuity of the components was continuously monitored throughout thermal cycle testing by an event detector in accordance with the IPC-9701 specification. Each component was treated as a single resistance channel. An "event" was recorded if the resistance of a channel exceeded 300 Ω for longer than 0.2 µsec within a 30-second period.

A failure was defined as a component either:

- Exceeding the maximum resistance for 15 consecutive events; or
- Having five consecutive detection events and proceeded to record at least 15 events; or
- Becoming electrically open

A total of 800 thermal cycles were completed and Figure 7 illustrates the thermal cycle profile used in the investigation.

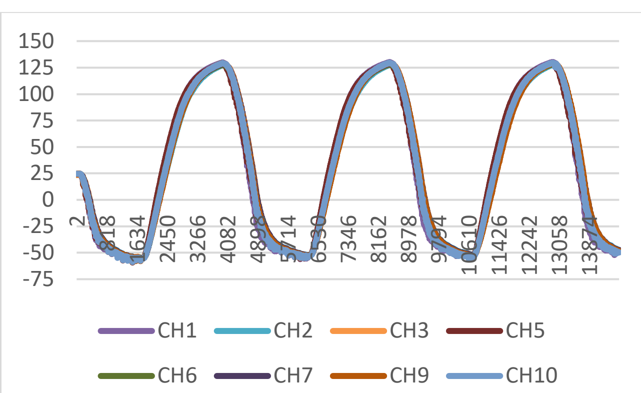

Figure 7: Thermal Profile [Y axis = Temperature (C), X axis = Time (sec)]

After reaching 800 thermal cycles, the components were removed from the thermal cycle chamber for metallographic cross-sectional analysis.

Test Results

Statistical Analysis

The solder joint thermal cycle integrity was statistically analyzed using regression analysis to determine the Weibull shape factor (β) and characteristic lives (θ) for the failure data. The Weibull function relates the cumulative failure distribution, F(n), to the number of thermal cycles at which a failure occurred, n, as:

$$F(n) = 1 - \exp\left(-\frac{n}{\theta}\right)^{\beta}$$

The characteristic life in a Weibull distribution, θ, corresponds to the number of cycles at which 63.2% of the population is expected to have failed. This parameter is often referred to as "N63" and may be thought of as an indication of the approximate average life of the population. The shape factor (β) is often referred to as the Weibull slope and is a measure of how tightly grouped the failures are. The lower the shape factor, the wider the range of failure data (i.e., a wider range of thermal cycles where failures are seen). The higher the shape factor, the more uniform the reliability across the population is; if all components fail at exactly the same point, the shape factor would be infinity. A shape factor of less than 1.0 is generally considered to be indicative of infant mortality. Electronic components in thermal cycling that are undergoing 'post infant mortality' failures have typically exhibited shape factors in the range of 4-8, depending on the particular packaging style.

The test results produced well-behaved Weibull statistics (Table 2).

Table 2: Investigation Weibull Statistics

Alloy	Sample Size	Overall Failure Rate	Cycles to 1st Failure	Weibull Fit		
				β	θ	R^2
SnPb	58	97%	119	3.44	283	89%
SAC305	59	100%	117	3.98	273	95%
Senju 794	60	93%	148	2.99	474	96%
Indalloy 292	59	86%	221	3.86	564	97%

Figure 8 shows the failure distributions for the four solder alloys (in symbols) along with the corresponding Weibull fits (in lines) for the data listed in Table 2**.**

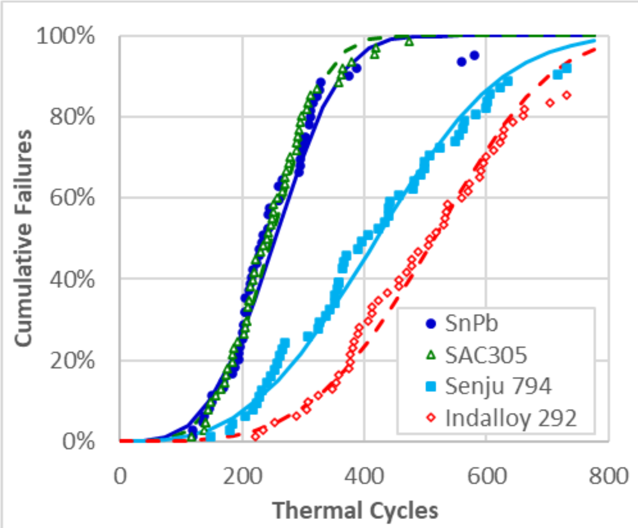

Figure 8: Weibull Graphs for BGA Components using different solder pastes

The Weibull statistics and graphs illustrate the improved reliability of the newest generation of Pb-free solder alloys. For the BGA components, the SnPb and SAC305 solder alloys have similar results. BGAs with the Senju 794 and the Indalloy 292 solder paste performed significantly better than either of the baseline alloys.

Cross-sectional Photodocumentation

The following sections show metallographic cross-sectioning results of the components to illustrate the primary failure modes in the mixed metallurgy condition for each alloy.

BGA Component Cross-sections

SAC305 Solder Alloy

Cross-sectioning of the SAC305 samples revealed solder joint cracking in the solder joint microstructure and at the solder joint/printed circuit pad interface. Figure 9 illustrates the observed solder joint cracks.

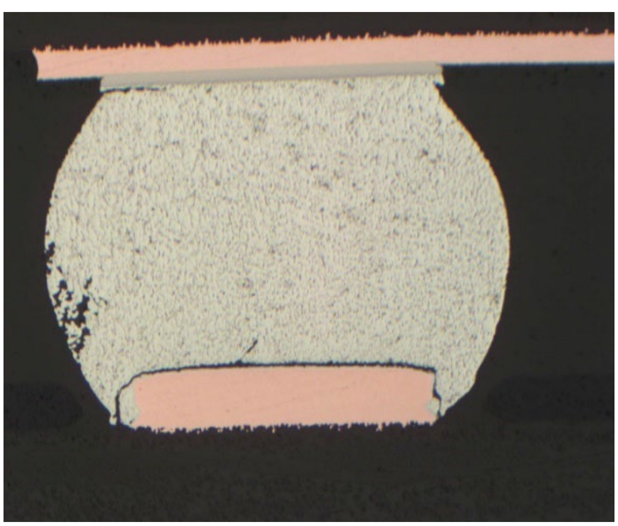

Figure 9: SAC305 BGA (failed at 193 cycles)

Indalloy 292 Solder Alloy

Cross-sectioning of the Indalloy 292 samples revealed several instances of cracking throughout, with more significant cracking seen in solder joints located at component edges. The presence of the voids did not impact the solder joint cracking for the BGA components. Figure 10 illustrates the observed solder joint cracks.

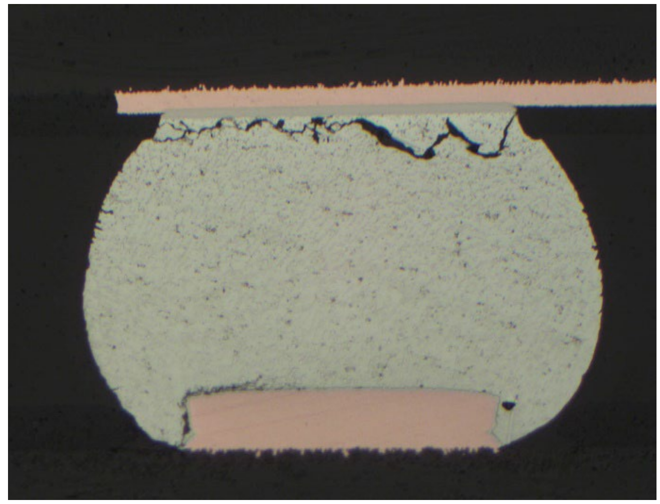

Figure 10: Indalloy 292 BGA (failed at 235 cycles)

Senju M794 Solder Alloy

Cross-sectioning of the Senju M794 samples revealed several instances of cracking throughout, with more significant cracking seen in solder joints located at component edges. Interfacial cracking was more prominent among the BGA samples. Figure 12 illustrates the observed solder joint cracks.

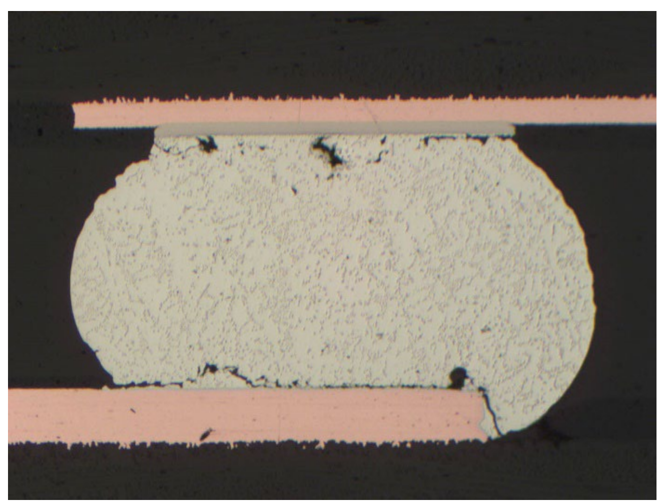

Figure 11: Senju 794 Solder Alloy BGA (failed at 700 cycles)

SnPb Solder Alloy

Cross-sectioning of the SnPb solder alloy revealed a number of microstructure issues. A Pb-free/SnPb mixed metallurgy solder joint microstructure was created for the BGA components as the BGA solderball alloy was SAC305 alloy and the solder paste SnPb alloy. Studies [3,7] have demonstrated that this mixed Pb-free/SnPb metallurgy microstructure will significantly degrade solder joint integrity. Figure 13 illustrates the observed solder joint cracks.

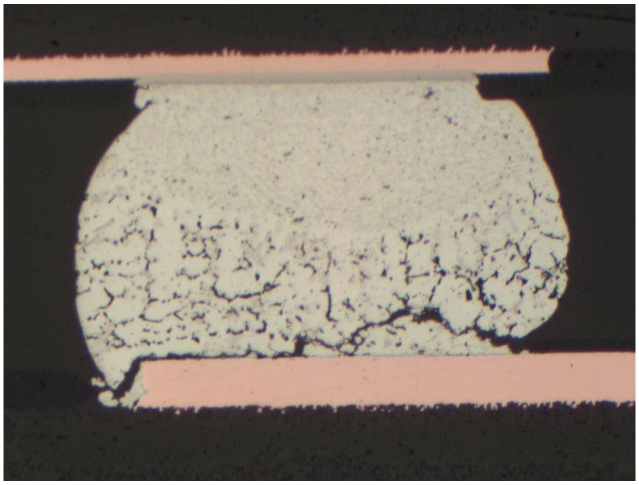

Figure 12: SnPb Solder Alloy BGA (failed at 316 cycles)

Discussion

The investigation results demonstrate that, in a SAC305 BGA component package, the use of Senju M794 and the Indalloy 292 Pb-free solder pastes lead to better thermal cycle reliability as compared to components assembled with SnPb or SAC305 solder paste. These results are encouraging as Collins products have achieved acceptable solder joint integrity using the SnPb and SAC305 solder alloys. The concern of a BGA "mixed Pb-free metallurgy" reliability degradation with BGA solderballs being a SAC family alloy and the solder paste being a different solder joint alloy was not realized. The Senju M794 and Indalloy 292 solder alloys performed very well in comparison to the matched SAC305 BGA components. This is encouraging because there will be a time period where such a combination will exist. The occurrence of interfacial cracking in the BGA components was unexpected. Interfacial cracking is a function of many possible factors and is randomly observed in Pb-free BGA solder joints (Figure 13). The regular occurrence of interfacial cracking of the BGA solder joints in this study suggests that additional stress states were imposed during thermal cycle conditioning. As shown in Figure 13, the component pad appears to have significant Z axis warp (i.e., flexing) that would cause a peeling motion at the solder joint/board pad interface. The Z axis warpage observed is a component-specific issue and is not reflective of the solder alloy characteristics.

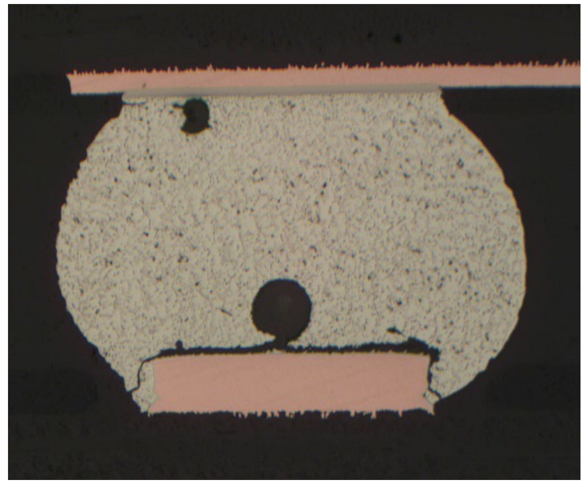

Figure 13: Examples of BGA Solder Joint Interface Failure Mode for SAC305 (bottom)

Conclusions

The investigation produced the following conclusions:

- The concern of a "mixed Pb-free metallurgy" BGA configuration for Pb-free soldered products degrading solder joint integrity was not observed with the Pb-free solder alloys tested. BGAs assembled with Senju M794 and the Indalloy 292 solder paste both performed better in thermal cycle testing than the SAC305 solder alloy.
- Reflow oven profile development should be reviewed as part of any implementation action for either the Senju 794 or the Indalloy 292 solder alloys in an effort to reduce/eliminate the incidence of solder joint interfacial cracking failure modes.
- Further work needs to be done with SEM analysis to determine the if the methods of solder strengthening is consistent with previous work done in pure alloy configurations.

REFERENCES

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[6] D. Hillman, etal, "IPC/PERM DoD Phase 3 Pb-free Solder Alloy Thermal Cycle Test Report: Part 1", Working Paper WP22-3001, 2022

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Table 3: Investigation Weibull Statistics Including All Data Points

Alloy	Part	Sample Size	Overall Failure Rate	Cycles to 1st Failure	Weibull Fit		
					Beta	N63	R^2
SnPb	BGA	58	97%	119	3.44	283	89%
SAC305		59	100%	117	3.98	273	95%
Senju 794		60	93%	148	2.99	474	96%
Indalloy 292		59	86%	221	3.86	564	97%
SnPb	LGA	59	100%	80	4.60	337	89%
SAC305		59	100%	108	4.68	265	99%
Senju 794		59	71%	229	4.78	638	96%
Indalloy 292		60	62%	81	2.02	964	83%

Table 4: Investigation Weibull Statistics with Removal of Assignable Cause Failures (Filter indicates cycle below which data were removed for assignable cause)

Alloy	Part	Sample Size	Overall Failure Rate	Cycles		Weibull Fit		
				1st Failure	Filter	β	N63	R^2
SnPb	BGA	58	97%	119	n/a	3.44	283	89%
SAC305		59	100%	117	n/a	3.98	273	95%
Senju 794		59	93%	179	150	3.11	478	94%
Indalloy 292		59	86%	221	n/a	3.86	564	97%
SnPb	LGA	58	100%	191	100	6.63	332	98%
SAC305		59	100%	108	n/a	4.68	265	98%
Senju 794		58	71%	346	250	5.67	629	92%
Indalloy 292		58	60%	360	125	4.93	741	96%