RELIABILITY TESTING OF ISOTHERMALLY AGED DOPED LOW CREEP LEAD-FREE SOLDER PASTE ALLOYS UNDER VIBRATION AND SHOCK CONDITIONS

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ABSTRACT
In this study, the vibration and drop impact reliability of various doped lead-free solder paste alloys was investigated. The primary goal of this study was to find a manufacturable solder paste material that would reduce the effects of aging on the solder joints. The assemblies were tested at both no-aged and isothermally aged conditions. Reliability of 11 different solder paste alloys was studied in comparison with the baseline. CABGA208 package was used to conduct the study, Sn96.5 Ag3.0 Cu0.5 (SAC305) solder bumps and solder paste data was used as the baseline to compare with the doped solder paste alloys. The test vehicle consisted of 16 ball grid array packages (BGA) which were 15mm chip array ball grid array's (CABGA208) with perimeter solder balls on 0.8mm pitch. Two sets of test boards were manufactured, the first being no aged and the second set of boards were isothermally aged at 125^{0}C for 6 months and then tested. The boards were further categorized into 3 different reflow temperatures and 2 different stencil thicknesses, 4 mil and 6 mil respectively for the testing. JEDEC JESD22 B103B and JEDEC BS111 test standards were followed to conduct the vibration and drop impact tests. Both the no-aged and the aged test boards were subjected to accelerated life testing where the test end state was 20 hours for vibration testing and 300 drops for drop testing respectively. The results discuss the effects of aging, paste material, stencil size and reflow profile on the reliability of the test assemblies.

Key words**:** BGA, Lead-free, Reliability, Isothermal Aging, Flip Chip, Doping, Weibull Analysis

NOMENCLATURE

ASTM	American Society for Testing & Materials
BGA	Ball Grid Array
CABGA	Chip Array Ball Grid Array
IPC	Association Connecting Electronics Industries
IMC	Intermetallic Compound
JEDEC	Joint Electron Device Engineering Council
PCB	Printed Circuit Board
QFN	Quad Flat No-Lead package
RoHS	Restriction of Hazardous Substances
SAE	Society of Automotive Engineers
SEM	Scanning Electron Microscopy
WEEE	Waste from Electrical and Electronic Equipment

Symbols

Ag	Silver
Cu	Copper
Pb	Lead
Sn	Tin

Greek Symbols

β	Slope
η	Characteristic Life
ρ	Probability plot
Ω	Resistance

INTRODUCTION
Quality and reliability of IC packages are amongst the top attributes, electronics manufacturing industry are chasing after since last decade. Mechanical robustness under drop impact and vibration conditions are the hot topics of research in this field. A failure in a BGA package can most often be traced back to its solder joint. This is often caused by the induced stress in the joint which results in a fracture. Most common modes of solder joint failure observed in BGA-type solder joints are failure along the solder near the IMC boundary region due to excessive brittle intermetallics and failures through the bulk solder material. Aging of these solder joints has detrimental effects on their reliability. So in this paper, we will be discussing the various factors that influence this solder joint reliability and our attempts to address this issue.

The tin-lead solders which were known for their superior mechanical properties were banned in 2006 from the two European directives, WEEE and RoHS respectively. This led the electronics industry to steer towards using the ternary or near-ternary eutectic alloys of tin, silver and copper. An infinite number of solder alloy combinations were developed to match the Sn-Pb solder alloy properties. But SAC alloys emerged as environment friendly replacements and were recommended by International Tin Research Institute [1-7] and the National Electronics Manufacturing Initiative [8] for all the reflow applications.

The mechanical properties and corresponding failure behavior of various SAC alloys change for different electronic assemblies. Though SAC105 and SAC305 became the popular replacements, much of their characteristic behavior involving variations in manufacturing methods, doping composition and aging were relatively unknown especially regarding their reliability performance under drop impact and vibration testing environments. Long-term isothermal aging in elevated temperatures has a severe impact on the reliability of SAC solder joints. Two-parameter Weibull plot shows that the reliability of BGA packages degrades up to 70% after two years of aging at elevated temperature (125^{o} C) [11].

The degradation of materials is predicted to be more prominent under mechanical loading compared to higher temperatures [9, 10]. Also, the existing finite element models which are used to understand solder joint reliability during accelerated vibration testing and drop testing are not able to account for the effects of material properties on doped alloys. This paper reports the study of drop impact and vibration testing of isothermally aged doped low creep lead-free solder paste alloys. The test focuses on the study of the reliability of BGA's, QFN's and resistors on laminate assemblies which were built with various temperature profiles, stencil sizes and paste combinations.

BOARD DESIGN & BUILD MATRIX

The test boards used for vibration and drop testing were standard 4-layer PCB's composed of copper vias, glass epoxy covered by a thin solder mask on both sides and an overlaid silkscreen for labeling. All the components mounted on the boards were chosen carefully to study their reliability with various doped solder pastes in both non-aged and aged conditions. The test boards had 16, 15mm CABGA208 packages, they consisted of 208 I/O's with a 0.8mm lead pitch with standard daisy-chain wiring. The solder balls were 0.46mm in the diameter and were arranged in 17X17 matrix. 20, 2512 Resistors and 6, A-MLF20-5mm-0.65mm QFN's respectively, Figure 1 shows test board design and a finished board. Two sets of boards were manufactured, the first set was tested as soon as they were built and the second set of boards were placed in an isothermal chamber, and a steady temperature of 125^{0}C was maintained for 6 months to simulate aging before they were tested.

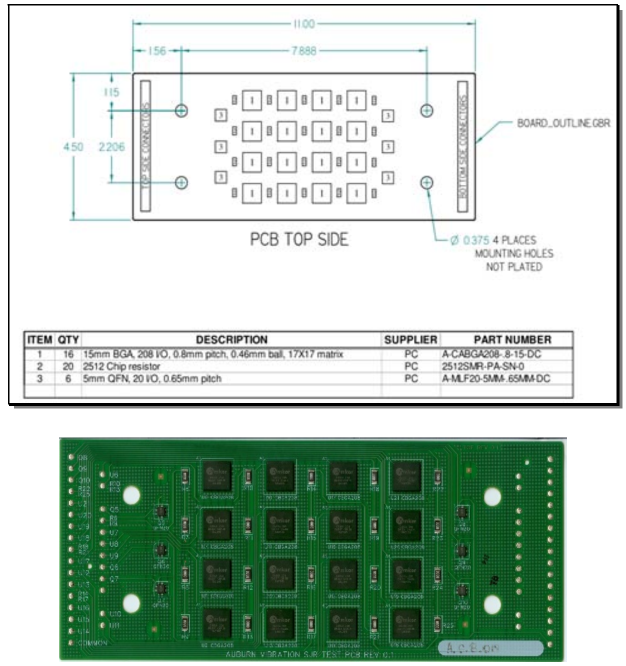

Figure 1: Test board design and manufactured board assembly

Table 3 shows the build matrix where all the test boards were built with different solder materials that were doped. SAC105/305 components and SAC305 paste data was considered as the baseline for this study. The Table 1&2 shows that the boards were built with 3 different temperature profiles namely low/high/best and 2 different stencil sizes 4mil and 6mil respectively. The reflow profile zone temperatures and the process windows of the same can be seen in Table 1 & 2 respectively. We also built limited sets of boards as per availability which had both solder balls and the pastes of the same material, these were called the matched boards. Each combination had 10 boards built, out of which 5 were tested in no-aged condition and the remaining after aging. All the samples were tested electrically after the build, and the yield was 100%.

Table 1: Reflow profile process window

Statistic Name	Low Limit	High Limit
Max Rising Slope (°C/seconds)	0	3
Preheat Time (seconds)	60	100
Soak Time (seconds)	60	90
Peak Temperature (°C)	235	245
Total Time above Liquidus Temperature (seconds)	45	90

Table 2: Reflow profile zone set point temperatures

Profile	Conveyor Speed (inch/min)	Zone Set point Temperatures (°C)							
		1	2	3	4	5	6	7	8
Best	27.5	145	155	170	175	180	225	245	250
Low	29.5	145	155	170	175	180	225	245	250
High	25.5	145	160	170	175	183	230	250	250

Table 3: Board build matrix

Solder Paste Manufacturer	Solder Paste	Stencil	Component mix	Profile
1	A (Baseline)	6mil	SAC305/105	Best
	B	4&6mil	SAC305/105	Low
				High
				Best
			Matched B	Best
	C	4&6mil	SAC305/105	Low
				High
				Best
			Matched C	Best
2	A	6mil	Alloy 1	Best
			Alloy 2	Best
3	D	4&6mil	SAC305/105	Low
				High
				Best
	E	4&6mil	SAC305/105	Low
				High
				Best
			Matched E	Best
4	F	4&6mil	SAC305/105	Low
				High
				Best
			Alloy 3	Best
			Alloy 4	Best
5	G	4&6mil	SAC305/105	Low
				High
				Best
	H	4&6mil	SAC305/105	Low
				High
				Best
6	I	4&6mil	SAC305/105	Low
				High
				Best
	J	4&6mil	SAC305/105	Low
				High
				Best
7	K	6mil	SAC305/105	Best
8	L	6mil	SAC305/105	Best

The SEM image of the BGA solder ball after assembly is shown in Figure 2. The board side consists of OSP coating and Non-Solder Mask Defined (NSMD) pad. The package side comprises of Solder Mask Defined (SMD) pad and ENIG coating.

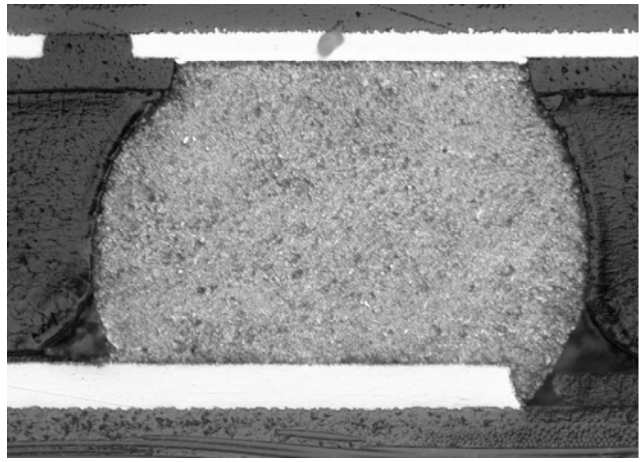

Figure 2: Cros section of the solder joint after assembly

EXPERIMENTAL DESIGN

Vibration test boards were mounted on an LDS LV217 electro-dynamic shaker table and were subjected to a 4.6 Grms stress vibration profile. The transfer functions were measured with input on the shaker and output on PC boards. According to the results, one major natural frequency appears at between 350 to 400 HZ as shown in Figure 4. The magnitudes are very consistent with close peak.

Lansmont M23 shock test system was used to conduct the drop testing. SAE F5/ASTM 26R1 standard felt was used to absorb the generated shock in this experiment. JEDEC BS111 test standard was followed, the maximum peak acceleration of 1500G and half-sine impact pulse duration of 0.5 milliseconds was maintained throughout the experiment and same can be seen in Figure 3.

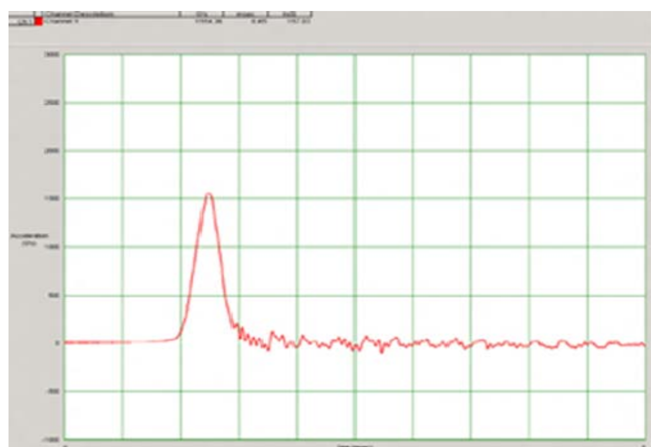

Figure 3: Drop test profile

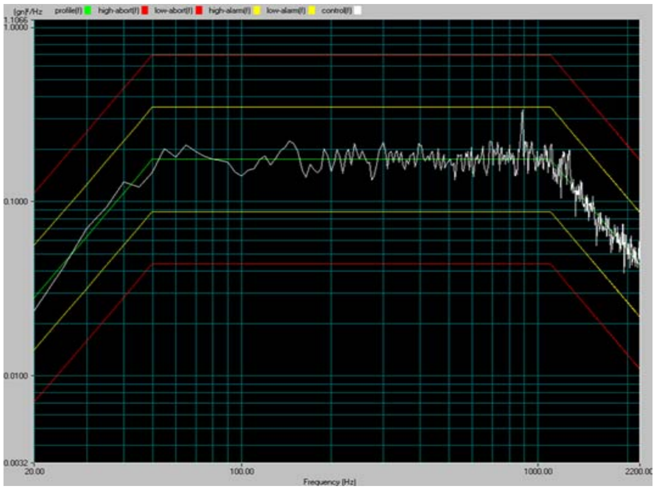

Figure 4: Vibration test profile

TEST METHOD

Measurements for failure detection were hand probed every sixty minutes during vibration testing and was based on resistance continuity measurements. Testing was stopped when the definition of failure which was taken as an intermittent event of value >300Ω, was met. The 4.6 Grms vibration profile was chosen in order to complete the test after 20 hours. It was observed that once a package suffered its initial open event, the remaining component failures occurred within a few hours of testing, and continued to complete failure of the package.

Drop test boards were dropped to a maximum of 300 times and were probed every 20 drops to check for component failures. The resistance for each package was monitored individually during the drop test. Failures were defined by the IPC-SM785 standard, i.e., the solder joint failure can be defined as an interruption of electrical continuity greater than 1000Ω.

TEST DESCRIPTION

The boards were mounted on vertical aluminum fixtures and are fastened onto the shaker table for vibration test. The vibration axis was chosen to be Z axis. First, it was necessary to determine the natural frequencies of the boards to calibrate the test parameters of the equipment. To determine the natural frequency of the boards, a laser source and oscilloscope was used on the boards to measure the natural frequencies of the test assembly. In this setup, the laser source recorded the frequencies induced with the highest distortions. Only the first natural frequencies which induced more damage to the components were measured in this test.

RESULTS & DISCUSSION

During the vibration and drop testing, none of the QFN's and Resistors failed at both no-aged and aged condition. 2-parameter Weibull (β, η) was used for analyzing the reliability data of the BGA packages. The least squares method estimates the characteristic life and slope of the Weibull distribution. The slope (β) categorizes different modes of failure, and the characteristic life (η) is the number of drops at which 63.2% of the population is expected to fail. (ρ) Represents the probability plot which indicates how well the data fits the regression line. 12 different solder pastes supplied from 8 different manufacturers were tested during the study. Only 3 of them will be discussed in this report as their performance was close to that of the baseline. The material A consisted of 80 BGA's built with SAC105 and other 80 built with SAC305. All the other materials had 60 BGA's with SAC305 and 20 with SAC105 alloys, and the matched set had a total of 80 BGA's which can be seen in the build matrix Table 3. But for this study, we have considered CABGA208 packages built with SAC305 solder bumps and solder paste A at the best temperature profile as the baseline.

Figure 5&6 shows the Weibull plot for the baseline paste A which were subjected to vibration and drop testing at no aged and aged condition. The reduction in the characteristic life values under no-aged and aged conditions seen in vibration testing was negligible compared to that of drop testing. The characteristic life of paste A was around 22 hours in both conditions during vibration testing whereas there was a big reduction from 154 to 95 drops during drop testing and the same can be seen from the eta values in the Figures 5&6.

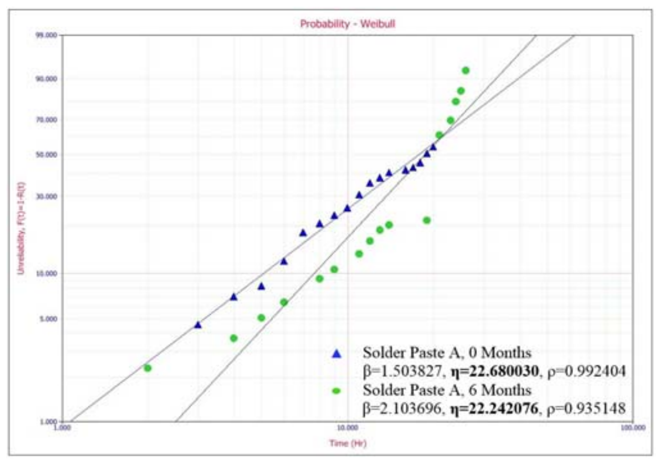

Figure 5: Vibration reliability comparison of the baseline material solder paste A at no aged and aged conditions

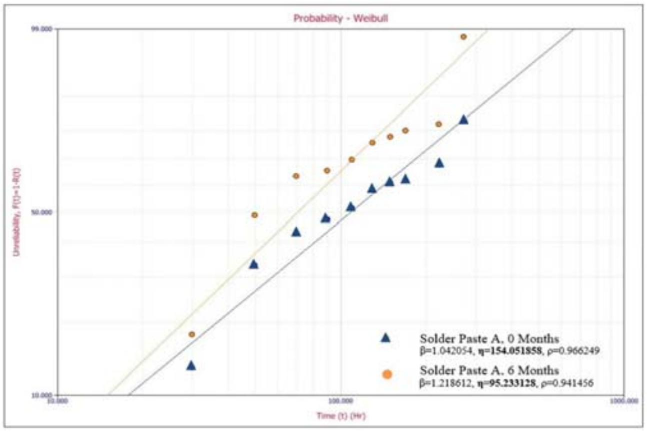

Figure 6: Drop impact reliability of the baseline material solder paste A at no aged and aged conditions [7]

Figure 7&8 shows the Weibull plot for the solder paste C which was subjected to vibration and drop testing at the no-aged and aged condition in comparison with the baseline. In both the tests, at the no-aged condition, the solder paste C outperformed the baseline, and its characteristic value was 28 hours compared to 22 hours of the baseline. The same trend was seen in drop test too where paste C had 183 drops compared to 154 drops of the baseline. But with aging, the reliability of the solder paste dropped below the baseline, and the eta values from Figure 7&8 confirm the same.

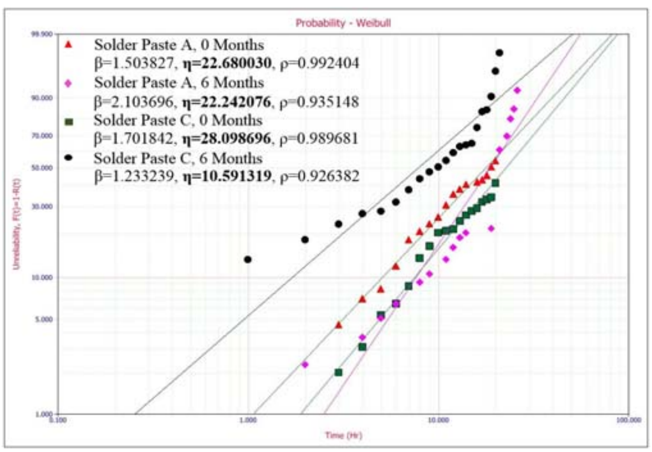

Figure 7: Vibration reliability comparison of solder paste C with the baseline

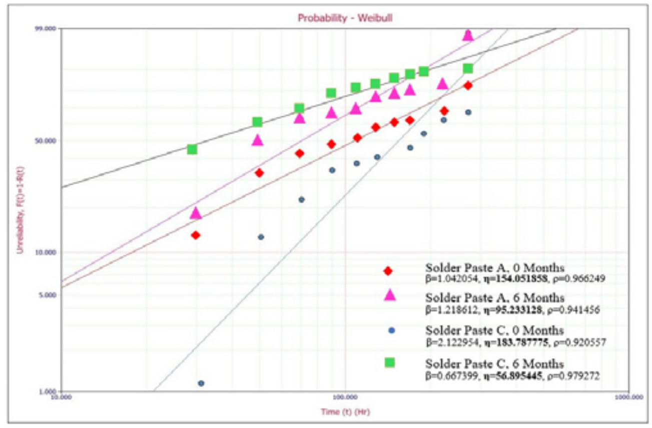

Figure 8: Drop impact reliability comparison of solder paste C with the baseline [7]

Figure 9&10 shows the Weibull plot for the solder paste K&J which was subjected to vibration and drop testing at the no-aged and aged condition in comparison with the baseline respectively. In both the tests at the no-aged condition the pastes K&J performed close to the baseline and the same can be seen from the eta values. But after aging their characteristic life reduced drastically.

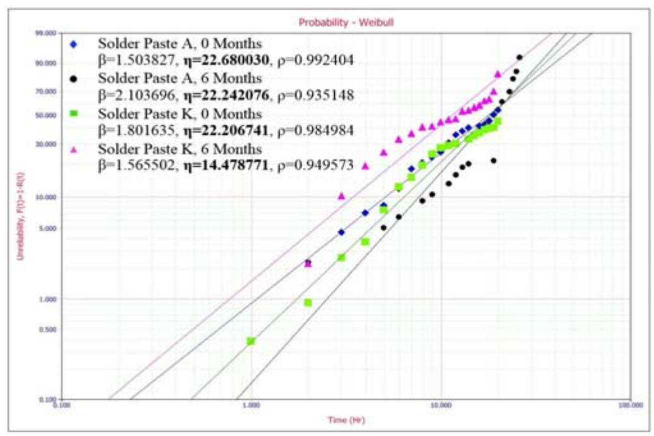

Figure 9: Vibration reliability comparison of solder paste K with the baseline

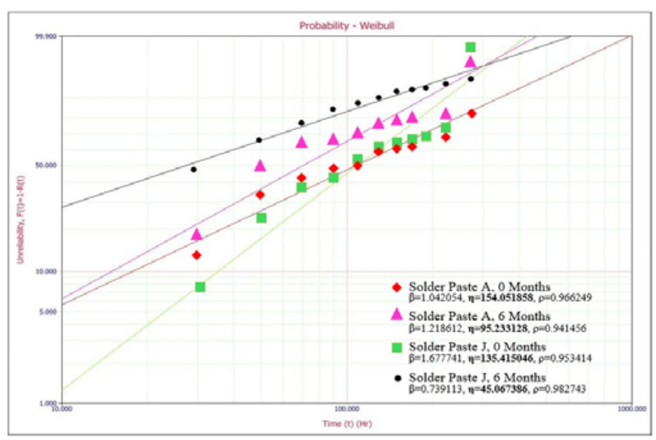

Figure 10: Drop impact reliability comparison of solder paste J with the baseline [7]

SUMMARY & CONCLUSION

The performance of 12 different solder pastes, supplied from 8 different manufacturers was evaluated at no-aged and aged conditions. The test boards, subjected to vibration and drop testing consisted of CABGA208 packages, QFN's and resistors. These boards were built with different temperature profiles and stencil thicknesses to help us choose the best combination for solving the current problem. During the testing, none of the QFN's and resistors failed. Hence we studied the reliability of the CABGA208 packages and compared their characteristic lifetime with the baseline.

Results from the baseline plots show that the decrease in the reliability after aging is higher in drop test when compared to vibration. Solder paste C exhibits better performance than the baseline at the no-aged condition, but the reliability reduces after aging in both the tests. Solder paste K&J performed close to the baseline at no-aged and their reliability drastically decreased after aging. We conclude by saying that the aging effects are alarming in harsh environment electronics applications and are in need of immediate attention.

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