LONG TERM ISOTHERMAL AGING OF BGA PACKAGES USING DOPED LEAD FREE SOLDER ALLOYS

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ABSTRACT

This work considers the deterioration in characteristic lifetime and mean time to failure (MTTF) under isothermal aging at 75°C for 6, 12, and 24 months for 15mm and 17mm BGA assemblies on 0.200” power computing printed circuit boards. The solders were doped, low creep, lead free alloys designed for high-temperature reliability: SAC doped Sb, Sn-4Ag-0.5Cu-0.05Ni, Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni and Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni. The board substrate was Megtron6. The assemblies were subjected to thermal cycles of -40°C to +125°C with a 120-minute thermal profile with a 15-minute dwell time and 45-minute transition time. We find that the solder pastes have lower degradation as measured by characteristic lifetime after 24-months of aging at 75°C compared with Sn-3Ag-0.5Cu (SAC305) and tin-lead (SnPb) solder pastes [1]. Sn-4Ag-0.5Cu-0.05Ni has shown the least degradation compared with the other solder pastes. The design of experiments (DOE) method was performed to analyze the factors key to the degradation, such as the solder paste, BGA package, and aging time. We find that all of the factors have significant effect on MTTF with a 90% level of confidence. Failure analysis indicated that crack propagation occurred at the top and bottom of the solder joint.

Key words: BGA, High Reliability Solder, Doping, PCB, Reliability, Solder, lead free

NOMENCLATURE

ANOVA	Analysis of Variance
BGA	Ball Grid Array
CTE	Coefficient of Thermal Expansion
DMM	Digital Multimeter
DOE	Design of Experiments
FR	Flame Retardant
JEDEC	Joint Electron Device Engineering Council
MTTF	Mean Time to Failure
OSP	Organic Solderability Preservative
PCB	Printed Circuit Board
TC	Thermal Cycling

Symbols

Ag	Silver
Bi	Bismuth
Cu	Copper
Ni	Nickel
Pb	Lead
Sb	Antimony
Sn	Tin
SAC305	96.5%Sn-3.0%Ag-0.5%Cu solder

Greek Symbols

β	Slope
η	Characteristic Life
ρ	Probability plot

Subscripts

T_g	Glass Transition Temperature

INTRODUCTION

Electronic packages are frequently exposed to harsh environments and power cycling causing thermally induced stress and lower reliability. The primary failure modes of solder joints subjected to extreme temperature gradients are solder joint fatigue and creep deformation [1]–[4]. This is complicated by modern electronics manufacturing techniques which strive to reduce the size of components and solder bumps and increase the packaging density. Common factors that affect the solder joint reliability are the chip dimensions, chip structure, and the material properties of the solder joints [5]–[9].

Bulk solder properties are affected by the composition and microstructure of the solder alloy. The starting microstructure of the solder will evolve over time and temperature during the lifetime of the solder joints. The combination of coefficient of thermal expansion (CTE) and temperature excursion during cycling can weaken the solder joints and result in package failure [10]–[13].

Numerous studies have indicated that BGA packages with 96.5Sn-3Ag-0.5Cu (SAC305) solder alloy when aged at elevated temperatures result in ~ 70% reduction in lifetime characteristics. This was observed in thermal cycling, vibration, and drop tests [14]–[23]. Sanders [1], [24], [25] conducted thermal cycling tests of BGA packages with SnPb and SAC305 solder joints, isothermally aged at 25°C, 50°C, and 75°C, and with aging times of 0, 6, 12 and 24 months. The substrates were FR-4 and Megtron6. The characteristic lifetime of the above mentioned solder pastes showed ~ 60% deterioration after 24-months of aging at 75°C on the Megtron6 substrate compared with the FR-4 substrate. This paper evaluates the long term aging effect of various doped lead free solders built using Megtron6 substrate under other, different aging conditions.

BOARD ASSEMBLY

Test Vehicle

JEDEC specifications were followed for the test vehicle (TC1-SJR). The dimensions of the board was 173 mm x 254 mm and thickness 5mm (200 mil). The surface finish was Organic Solderability Preservative (OSP). The top side of the test board had 19 channel readouts while the bottom side had 39 channel readouts, shown Figure 1. The substrate material used for the board was Megtron6 with a glass transition temperature (Tg) of 185°C.

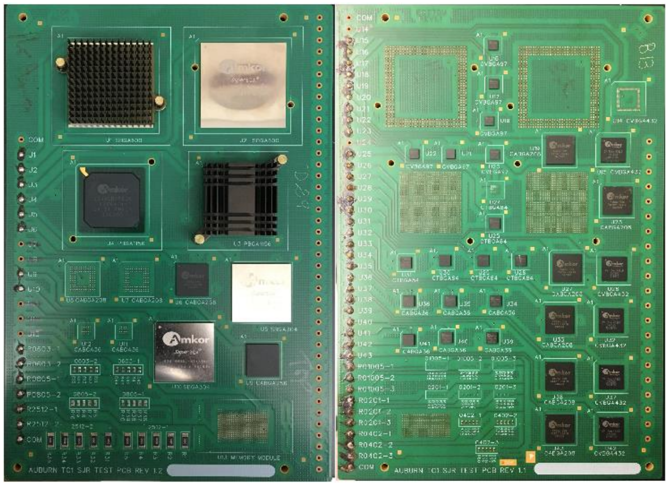


Figure 1. Board Design: Top side (Left), Bottom side (Right)

A simple daisy chain structure was used to monitor the joint resistance of the ball grid array (BGA) wiring scheme. The test components were assembled at STI Electronics Inc. in Madison, Alabama.

A total of 260 boards were assembled in two groups. 180 boards were built as 'topside' boards, with only the top-side components assembled. 80 boards were built as 'bottom-side' boards, with only the bottom-side components assembled. The baseline reflow profile for top and bottom side boards is shown in Table 1 below. The temperatures used were based on solder paste manufacturer specifications.

Table 1. Reflow profile settings

Reflow Profile	Conveyor Speed (inch/min)	Zones (°C)													
		Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8	Z9	Z10	Z11	Z12	Z13	Z14
Top	40	135	140	160	185	195	205	215	220	245	270	270	240	220	130
Bottom	37	180	195	215	225	240	245	250	260	275	300	300	270	220	145

Our experiment was designed to evaluate the effect of long term isothermal aging on the reliability of several lead-free solder alloys. The build matrix is shown in Table 2. There are four (4) aging times (0, 6, 12, and 24 months) and one aging temperature 75°C.

Table 2. Build Matrix

Material Code	Solder Paste	Solder ball alloy
A	Sn-4Ag-0.5Cu-0.05Ni	SAC305
B	SAC Doped Sb	SAC305
C	Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni	SAC305
D	Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni	SAC305

The test components for this paper were ball grid array (BGA) packages of 15mm and 17mm with solder ball pitches varying from 0.8 mm to 1.0 mm. Four different solder paste compositions were used, in combination with a SAC305 solder ball alloy.

Test Setup

The packages were daisy chained for electrical continuity testing and in-situ, continuous, monitoring throughout the thermal cycling (TC). The boards were subjected to thermal cycles of -40°C to +125°C with a 120-minute thermal profile in a single-zone environmental chamber to assess the solder joint performance. The TC was based on the JEDEC JESD22-A104-B standard high and low temperature test. The transition time was 45 minutes. The temperature profile is shown in Figure 2.

The boards were placed vertically in the chamber as seen in Figure 3 and the wiring passed through access ports to a LabVIEW-based monitoring system.

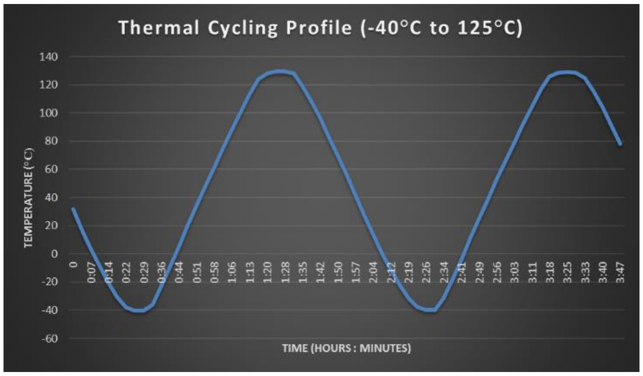


Figure 2. Thermal Cycling Profile with dwell time of 15 minutes and 45 minutes transition time

A Keithley 7002 switching system and Keithley 2000 digital multimeters (DMMs) are the monitoring systems used as shown in Figure 3. The resistance of the BGA joints are monitored with a failure defined by a resistance > 100 ohms for five consecutive measurements. The test for each aging group was terminated at 3000 cycles.

Figure 3 Test boards stacked inside the chamber (left); Multimeter and multiplexer monitoring system.

RESULTS AND DISCUSSIONS

Thermal Cycling Results

The characteristic lifetime (η) and the slope (β) of the solder joints were determined using a 2-parameter Weibull analysis. The test results below show the reliability data for the 15mm and 17mm BGA package under no aged, 12-, and 24-month aging conditions. The reliability data for 6-month aged can be found in previous publications [3], [4]. The 15mm BGA (CABGA 208) component is found only on the bottom side of the boards and 17mm BGA (CABGA256) is found only on top side of the boards.

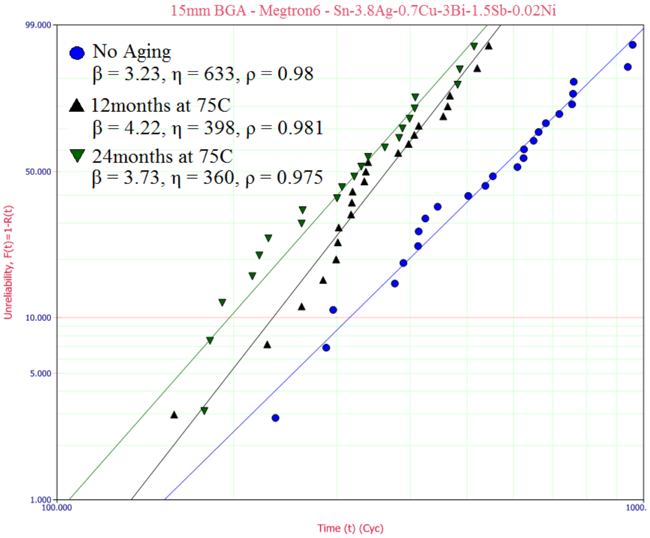


Figure 4. Thermal Cycling Reliability of 15mm BGA package with Megtron6 substrate for Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni solder paste with SAC305 alloy

The long term isothermal aging of four different solder pastes are shown. The thermal cycling reliability of 15mm BGA and 17mm BGA for Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni solder paste with SAC305 solder ball alloy are shown in Figure 4 and 5. For the 15mm package, the characteristic lifetime degradation after 24-months of aging at 75°C was 43% and 31% for 17mm BGA package.

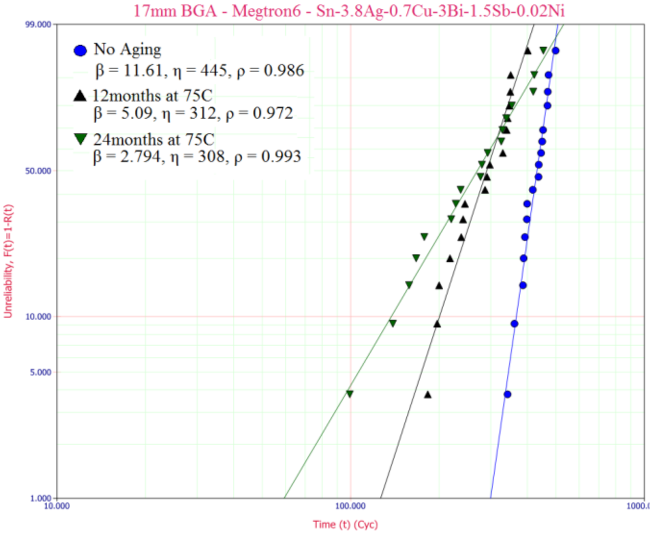


Figure 5. Thermal Cycling Reliability of 17mm BGA package with Megtron6 substrate for Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni solder paste with SAC305 alloy

The thermal cycling reliability of Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni solder paste with SAC305 solder ball alloy for 15mm and 17mm BGA are shown in Figure 6 and 7.

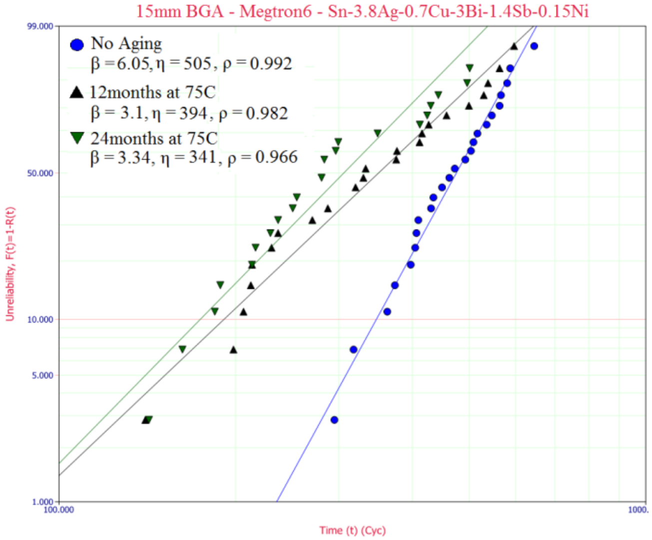


Figure 6. Thermal Cycling Reliability of 15mm BGA package with Megtron6 substrate for Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni solder paste with SAC305 alloy

After 24-months of aging at 75°C, the degradation of characteristics lifetime was measured to be 32% for 15mm BGA and 26% for 17mm BGA package.

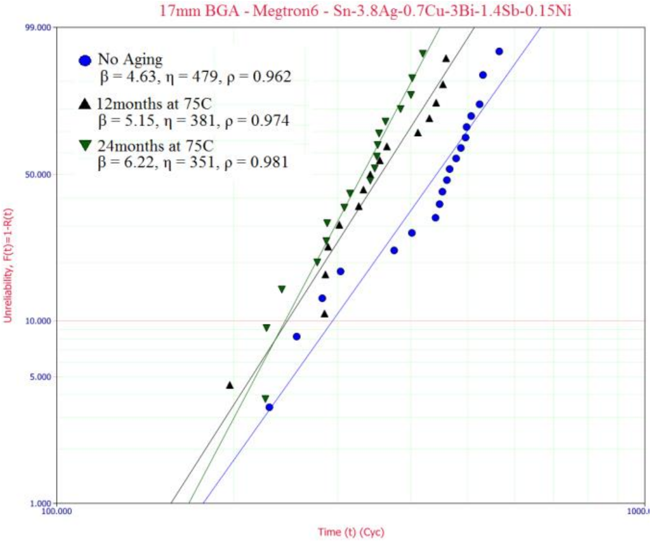


Figure 7. Thermal Cycling Reliability of 17mm BGA package with Megtron6 substrate for Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni solder paste with SAC305 alloy

Figure 8 and 9 shows the thermal cycling reliability of 15mm and 17mm BGA comparing different aging groups for SAC doped Sb with SAC305 solder ball alloy.

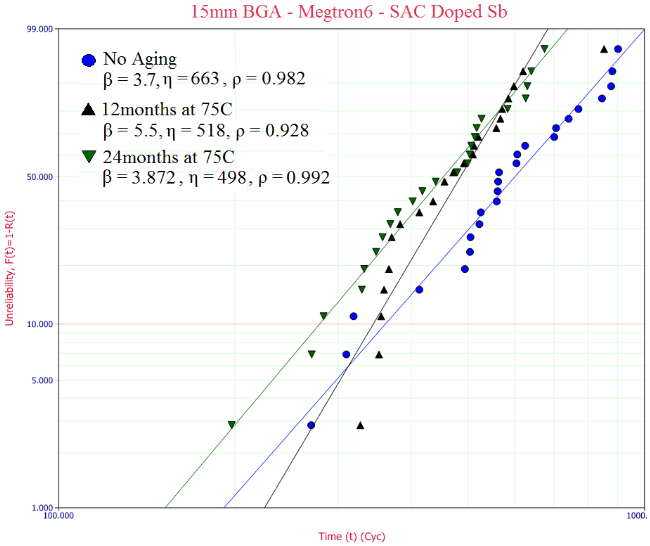


Figure 8. Thermal Cycling Reliability of 15mm BGA package with Megtron6 substrate for SAC doped Sb solder paste with SAC305 alloy

For SAC Doped Sb, the characteristics lifetime degradation after 24-months of aging at 75°C was 25% for 15mm BGA package and 16% for 17mm BGA package.

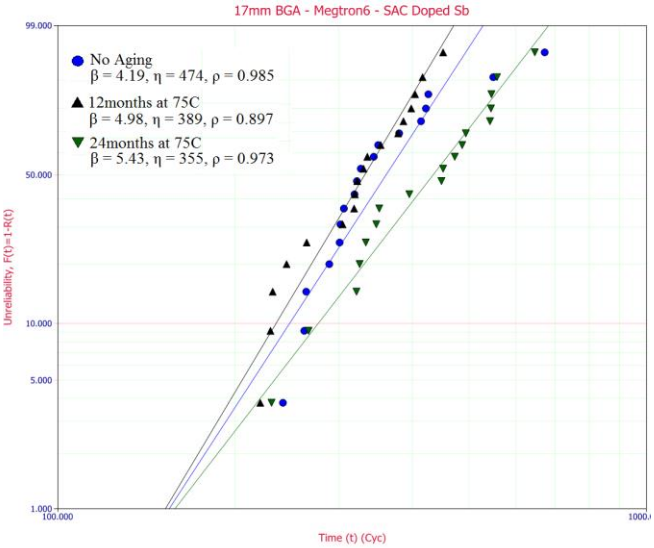


Figure 9. Thermal Cycling Reliability of 17mm BGA package with Megtron6 substrate for SAC Doped Sb solder paste with SAC305 alloy

The thermal cycling reliability of 15mm BGA and 17mm BGA for Sn-4Ag-0.5Cu-0.05Ni solder paste with SAC305 solder ball alloy are shown in Figure 10 and 11.

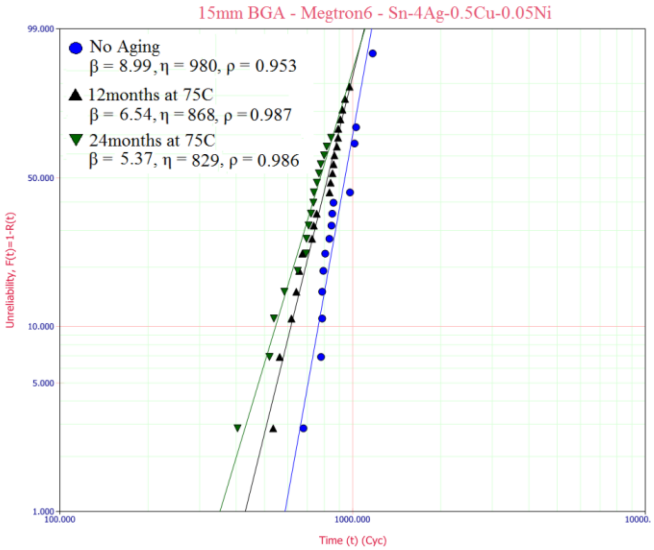


Figure 10. Thermal Cycling Reliability of 15mm BGA package with Megtron6 substrate for Sn-4Ag-0.5Cu-0.05Ni solder paste with SAC305 alloy

For the 15mm package, the characteristics lifetime degradation after 24-months of aging at 75°C was 15% and 17% for 17mm BGA package.

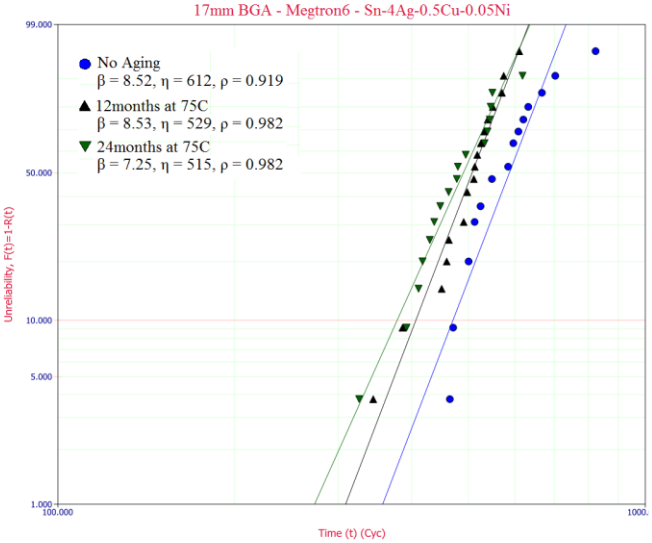


Figure 11. Thermal Cycling Reliability of 17mm BGA package with Megtron6 substrate for Sn-4Ag-0.5Cu-0.05Ni solder paste with SAC305 alloy

Based on the thermal cycling reliability data shown above, the mean time to failure (MTTF) of the solder pastes are calculated under the assumption that the data follows a 2-parameter Weibull distribution. The formula for calculating MTTF is shown below [26].

$$\boldsymbol{MTTF = \eta * \Gamma\left(1 + \frac{1}{\beta}\right)}$$

The MTTF for four different solder pastes with 15mm and 17mm BGA package are shown in Figure 12 and 13. Sn-4Ag-0.5Cu-0.05Ni shows the least deterioration after 24 months of aging at 75°C, followed by SAC doped Sb.

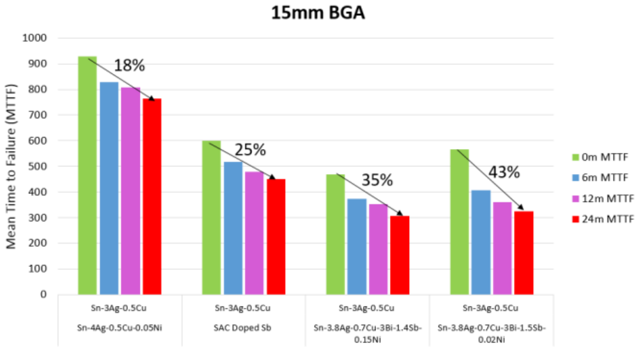


Figure 12. Mean time to failure comparison for 15mm BGA package.

Similar trends is shown for the 17mm BGA package in Figure 13. The aging deterioration for the 17mm BGA are relatively lower than the 15mm BGA package.

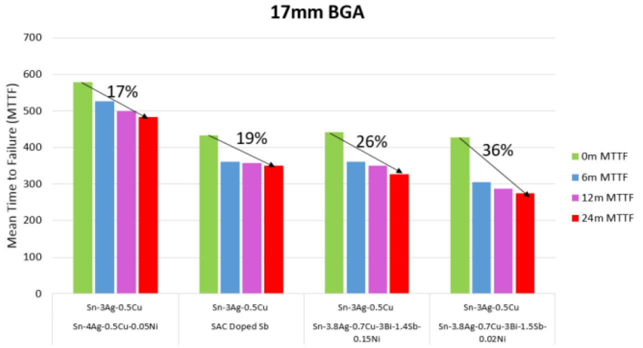


Figure 13. Mean time to failure comparison for 17mm BGA package.

Design of Experiments Analysis

A design of experiments (DOE) evaluation was performed to analyze the factors contributing to the MTTF. The response variable used in this experiment is the MTTF of the BGA's. The independent variables used were solder pastes, packages, and aging times as shown in Table 3.

Table 3. Design of experiments variables.

Factors	Levels	Description
Solder Paste	4	Material A, B, C and D
Package	2	15mm (CABGA208), 17mm (CABGA256)
Aging Times	4	No Aged, 6months at 75C, 12months at 75C and 24months at 75C

A factorial plot considering the main effects is shown in Figure 14. There is a significant difference in MTTF when comparing Sn-4Ag-0.5Cu-0.05Ni against other solder pastes.

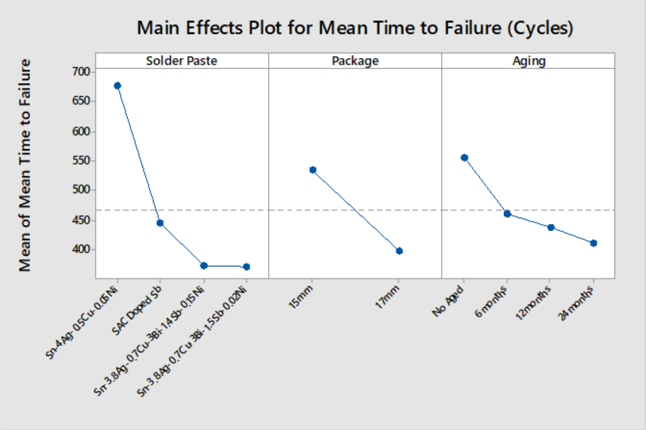


Figure 14. Main effects plot.

The MTTF for SAC doped Sb is significantly different from the other solder pastes. There is no difference in MTTF when comparing Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni and Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni solder pastes. The Sn-4Ag-0.5Cu-0.05Ni solder paste has the highest MTTF.

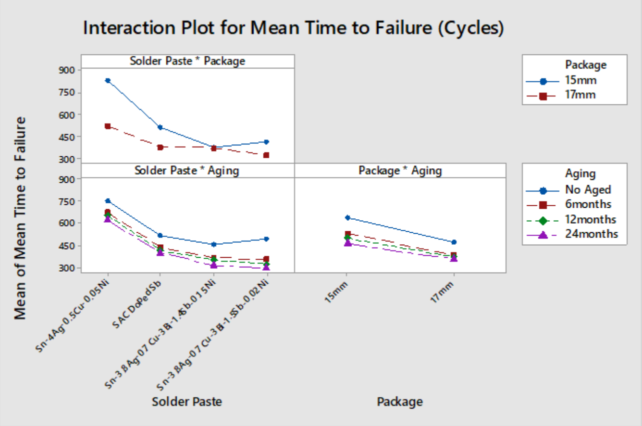
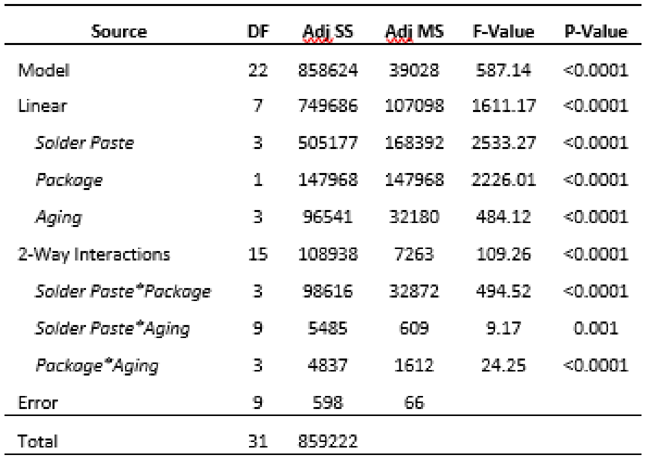


Figure 15. Interaction plot.

The 15mm BGA package is more reliable than the 17mm BGA and significant differences in MTTF are observed. A difference in MTTF is also seen between different aging groups.

The interaction plots for different factors are shown in Figure 15. There is a significant difference in MTTF of 15mm and 17mm for Sn-4Ag-0.5Cu-0.05Ni, SAC doped Sb and minor difference was seen for Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni solder paste. For Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni solder paste, the MTTF difference is insignificant. Other interaction factors show a significant difference in MTTF between the no-aged and other age groups for packages and pastes.

Table 4. Analysis of Variance (ANOVA) Table



Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	22	858624	39028	587.14	<0.0001
Linear	7	749686	107098	1611.17	<0.0001
Solder Paste	3	505177	168392	2533.27	<0.0001
Package	1	147968	147968	2226.01	<0.0001
Aging	3	96541	32180	484.12	<0.0001
2-Way Interactions	15	108938	7263	109.26	<0.0001
*Solder Paste*Package*	3	98616	32872	494.52	<0.0001
*Solder Paste*Aging*	9	5485	609	9.17	0.001
*Package*Aging*	3	4837	1612	24.25	<0.0001
Error	9	598	66		
Total	31	859222			

The Analysis of Variance (ANOVA) for MTTF is shown in Table 4. There are significant differences in MTTF for the solder pastes, packages, and aging times which appeared to be similar as shown in Figure 15. All the three interaction terms appear to be significantly different.

Failure Analysis

Optical crossed polarized images of the solder joints from 17mm BGA packages are shown in Figure 16 to 19.

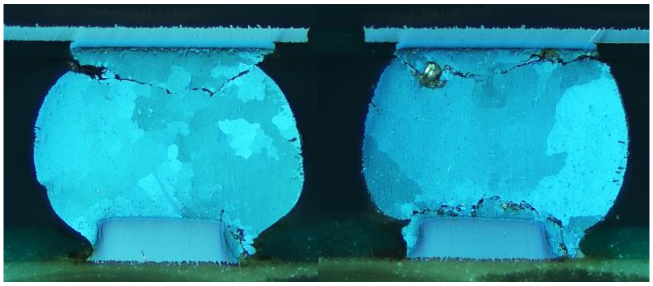


Figure 16. Cross polarized images for Sn-4Ag-0.5Cu-0.05Ni solder paste with SAC305 solder ball alloy.

Substantial recrystallization is observed in all the solder joints. For the Sn-4Ag-0.5Cu-0.05Ni solder paste with SAC305 solder ball alloy, crack propagation was observed at the top and bottom of the solder joint through the bulk solder as shown in Figure 16. The Cu_6Sn_5 intermetallic compound (IMC) appeared to be changing the path of crack propagation at the bottom of the joint.

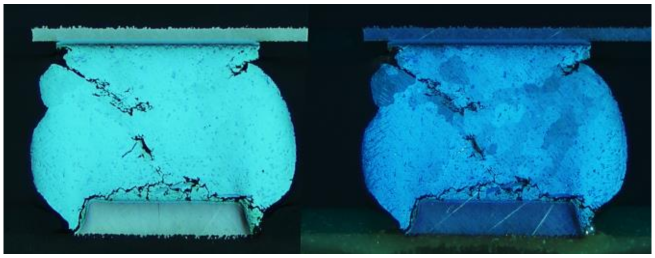


Figure 17. Failure analysis for Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni solder paste, optical microscope image (left); Cross polarized image (right).

The crack propagation was seen at the bottom of solder joint for Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni solder paste as shown in Figure 17. The crack initiation and propagation was observed at the top of the solder joint.

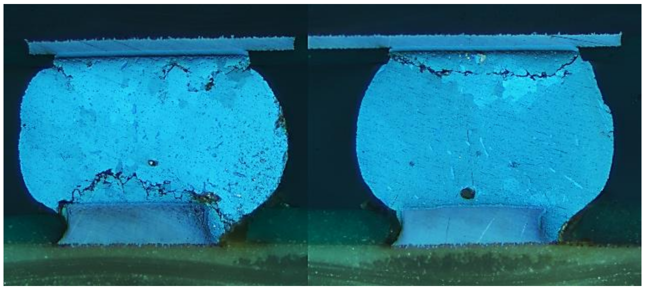


Figure 18. Cross polarized images for SAC Doped Sb solder paste with SAC305 solder ball alloy.

Figure 18 shows the cross section of SAC doped Sb with SAC305 solder ball. The crack propagation was observed at the top and bottom of the solder joint through bulk solder. Crack propagation through bulk solder was seen in Figure 19 for Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni solder paste with SAC305 solder ball alloy.

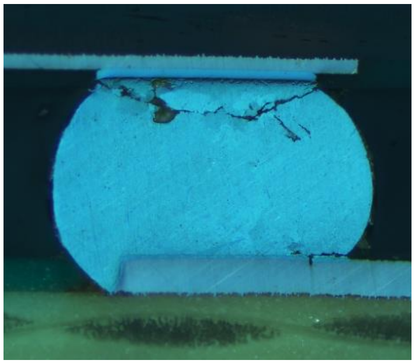


Figure 19. Cross polarized images for Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni solder paste with SAC305 solder ball alloy.

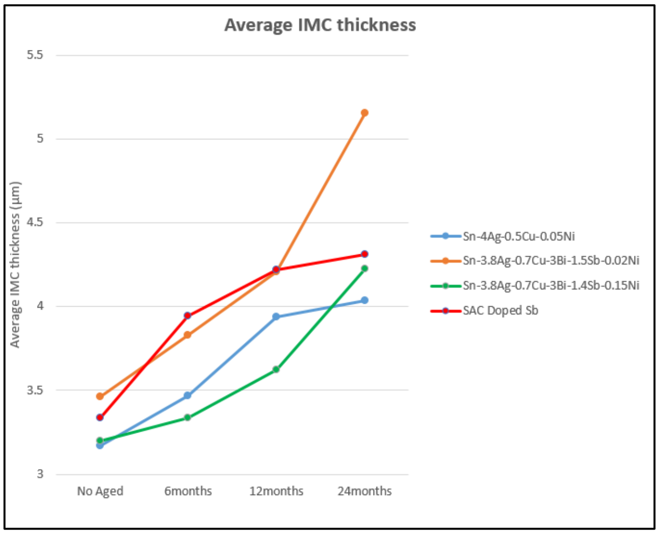


Figure 20. Average IMC measurement for each solder paste.

The average IMC thickness measurement of solder pastes under different aging groups was measured for the 17mm BGA package as shown in Figure 20. The IMC growth curve for Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni is higher than Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni solder paste. This is possibly due to the presence of additional nickel present in Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni solder paste that inhibited the growth of Cu_3Sn IMC layer. The IMC growth curve for SAC doped Sb is higher than that of Sn-4Ag-0.5Cu-0.05Ni solder paste. The presence of nickel in SAC alloy reduced the growth of IMC for both Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni and Sn-4Ag-0.5Cu-0.05Ni solder paste.

SUMMARY AND CONCLUSION

The thermal cycling reliability of 15mm and 17mm BGA packages with different lead-free solder pastes exposed to 6, 12, and 24 months of isothermal aging at 75°C has been studied. The performance of the lead-free solder pastes was compared with SAC305 and SnPb [1]. The pastes show reduced degradation in characteristic lifetime after 24-months of aging at 75°C compared with SAC305 and SnPb. Considering the doped lead-free solder pastes that were tested, Sn-4Ag-0.5Cu-0.05Ni has shown the highest characteristic lifetime followed by SAC doped Sb. A DOE analysis was performed to analyze the effects of solder paste type, package configuration, and aging time. It was found that, within a 90% level of confidence, all these factors, including their interactions, have significant effect on MTTF. Failure analysis showed crack propagation in failed interconnects at the top and bottom of the solder joint. Intermetallic thickness measurements showed that the growth curve was least for Sn-3.8Ag-0.7Cu-3Bi-1.4Sb-0.15Ni and Sn-4Ag-0.5Cu-0.05Ni solder paste compared with Sn-3.8Ag-0.7Cu-3Bi-1.5Sb-0.02Ni and SAC doped Sb. The Sn-4Ag-0.5Cu-0.05Ni solder paste was significantly better than other lead-free solder pastes, with the least deterioration after 24-months of aging at 75°C.

REFERENCES

[1] T. Sanders, “Extreme Environment Reliability of Components for Computing with SAC305 and Alternative High Reliability Solders,” Auburn University, 2016.

[2] F. Zhu, S. Song, W. Zhang, and S. Liu, “Creep behavior investigation of lead-free solder alloy Sn96.5Ag3Cu0.5,” in *11th International Conference on Electronic Packaging Technology & High Density Packaging (ICEPT-HDP)*, 2010, pp. 195–198.

[3] A. Raj *et al.*, “Comparative Study on Impact Of Various Low Creep Doped Lead Free Solder Alloys,” in *SMTA International*, 2017, pp. 820–826.

[4] S. Sridhar, A. Raj, J. Evans, M. Bozack, W. Johnson, and S. Hamasha, “Reliability Study of

Doped Lead Free Solder Paste Alloys by Thermal Cycling Testing," in *SMTA International*, 2017, pp. 562–567.

[5] S. Thirugnanasambandam *et al.*, "The study of vibrational performance on different doped low creep lead free solder paste and solder ball grid array packages," in *IEEE ITHERM Conference*, 2014, pp. 920–923.

[6] A. Raj *et al.*, "Thermal Shock Reliability Test on Multiple Doped Low Creep Lead Free Solder Paste and Solder Ball Grid Array Packages," in *SMTA International*, 2015, pp. 354–361.

[7] A. Raj *et al.*, "Proportional Hazard Model of doped low creep lead free solder paste under thermal shock," in *2016 15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 2016, pp. 1191–1201.

[8] S. Thirugnanasambandam *et al.*, "Proportional Hazard Model of doped low creep lead free solder paste under vibration," in *Proceedings of the 15th InterSociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, ITherm 2016*, 2016, pp. 1209–1217.

[9] T. Sanders, S. Thirugnanasambandam, J. Evans, M. J. Bozack, W. Johnson, and J. Suhling, "Component Level Reliability For High Temperature Power Computing With SAC305 And Alternative High Reliability Solders," in *SMTA International*, 2015, pp. 144–150.

[10] F. J. Akkara *et al.*, "Effect of Solder Sphere Alloys and Surface Finishes on the Reliability of Lead-Free Solder Joints in Accelerated Thermal Cycling," in *17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 2018, pp. 1374–1380.

[11] S. Hamasha *et al.*, "Effect of Surface Finish and High Bi Solder Alloy on Component Reliability in Thermal Cycling," in *Electronic Components and Technology Conference*, 2018, pp. 2032–2040.

[12] S. Su, N. Fu, F. John Akkara, and S. Hamasha, "Effect of Long-Term Room Temperature Aging on the Fatigue Properties of SnAgCu Solder Joint," *J. Electron. Packag.*, vol. 140, no. 3, pp. 31005–31009, May 2018.

[13] S. Hamasha, S. Su, F. J. Akkara, A. Dawahdeh, P. Borgesen, and A. Qasaimeh, "Solder joint reliability in isothermal varying load cycling," in *16th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 2017, pp. 1331–1336.

[14] N. Vijayakumar *et al.*, "The effect of iso-thermal aging on vibrational performance of SAC 105 and 305 alloys," in *IEEE International Symposium on Advanced Packaging Materials (APM)*, 2013, pp. 69–81.

[15] C. Zhao, C. Shen, Z. Hai, J. Zhang, M. Bozack, and J. L. Evans, "Long Term Aging Effects on The Reliability of Lead Free Solder Joints in Ball Grid Array Packages With Various Pitch Sizes and Ball Arrangement," *J. Surf. Mt. Technol.*, vol. 29, no. 2, pp. 37–46, 2016.

[16] J. Zhang *et al.*, "Thermal Aging Effects on the Thermal Cycling Reliability of Lead-Free Fine Pitch Packages," *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 3, no. 8, pp. 1348–1357, 2013.

[17] J. C. S. Mohammad Motalab, Muhannad Mustafa, J. Zhang, J. Evans, M. J. Bozack, and P. Lall, "Correlation of reliability models including aging effects with thermal cycling reliability data," in *Electronic Components and Technology Conference*, 2013, pp. 986–1004.

[18] J. Zhang, S. Thirugnanasambandam, J. Evans, M. J. Bozack, and R. Sesek, "Impact of Isothermal Aging on the Long-Term Reliability of Fine-Pitch Ball Grid Array Packages With Different Sn-Ag-Cu Solder Joints," *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 2, no. 8, pp. 1317–1328, 2012.

[19] Z. Hai *et al.*, "Reliability Comparison of Aged SAC Fine-Pitch Ball Grid Array Packages Versus Surface Finishes," *IEEE Trans. Components, Packag. Manuf. Technol.*, vol. 5, no. 6, pp. 828–837, 2015.

[20] C. Shen *et al.*, "Packaging Reliability Effect of ENIG and ENEPIG Surface Finishes in Board Level Thermal Test under Long-Term Aging and Cycling," *Materials (Basel).*, vol. 10, no. 5, 2017.

[21] F. J. Akkara *et al.*, "Effects of long term aging on SnAgCu solder joints reliability in mechanical cycling fatigue," in *SMTA International*, 2017, pp. 419–425.

[22] S. Sridhar, A. Raj, S. Gordon, S. Thirugnanasambandam, J. L. Evans, and W. Johnson, "Drop impact reliability testing of isothermally aged doped low creep lead-free solder paste alloys," in *IEEE ITHERM Conference*, 2016, pp. 501–506.

[23] S. Gordon *et al.*, "Reliability of Doped Ball Grid Array Components in Thermal Cycling after Long-Term Isothermal Aging," in *SMTA International*, 2017, pp. 438–442.

[24] S. Thirugnanasambandam, T. Sanders, J. Evans, M. Bozack, W. Johnson, and J. Suhling, "Component Level Reliability for High Temperature Power Computing With SAC305 and Alternative High Reliability Solders," in *SMTA International*, 2014, pp. 262–270.

[25] T. Sanders, S. Thirugnanasambandam, J. Evans, M.

Bozack, W. Johnson, and J. Suhling, “Component Level Reliability for High Temperature Power Computing With SAC305 and Alternative High Reliability Solders,” in *SMTA International*, 2015, pp. 144–150.

[26] C. E. Ebeling, *An Introduction to Reliability and Maintainability Engineering.*, 2nd ed. Waveland Press, 2010.