EFFECTS OF MIXING SOLDER SPHERE ALLOYS WITH BISMUTH-BASED PASTES ON THE COMPONENT RELIABILITY IN HARSH THERMAL CYCLING

Francy John Akkara, Cong Zhao, Mohammed Abueed, Sinan Su, Sa'd Hamasha, Jeffrey Suhling, Pradeep Lall, Ph.D.
Department of Industrial and Systems Engineering
Auburn University
AL, USA
francy@auburn.edu

ABSTRACT

Reliability of the new solder alloys has been a serious concern, especially in the harsh environment. Aging at elevated temperature alters the structural and mechanical properties of the solder joint and leads to the coarsening of the precipitates in the bulk solder and growth of the intermetallic compound layer, which in turn deteriorates the solder joint. Various new elements such as bismuth, antimony, and nickel are micro-alloyed into the SnAgCu based alloys to slow down this deterioration process and improve the reliability. There haven't been many studies about the effect of solder sphere alloys with bismuth pastes on the harsh thermal reliability. In this paper, the effect of mixing solder sphere alloys (SAC105, SAC305, matched solder sphere - paste) with Bi-based solder pastes on the component reliability in accelerated thermal cycling is studied. Two surface finishes, namely OSP (Organic Solderability Preserve) and ImAg (Immersion Silver) are considered. The test vehicle consists of 15mm and 6mm Ball Grid Array (BGA) components. The assembled test boards were isothermally aged at 125^{o}C for 12 months, which are then thermally cycled between -40^{o}C to +125^{o}C for 5800 cycles. Two-parameter Weibull analysis is done for all combinations. ANOVA is done to observe the main effects and interaction effects. Representative cross sections are also presented with IMC (intermetallic compound) layer thickness measurement.

Key words: Lead-free solder, Thermal Cycling, Aging, BGA, Weibull Analysis, Bismuth, ANOVA analysis, SAC105, SAC305

I. INTRODUCTION

For the past decade, SnAgCu based alloys were used as a replacement of Sn-Pb (Tin-Lead) solders in electronics packaging. Later on, several elements such as bismuth (Bi), nickel (Ni), antimony (Sb) has been microalloyed to improve their structural and mechanical properties. Since then, reliability of these new alloys has been a concern, especially in harsh environments. The solder joints, exposed to thermal cycling, alters its structural and mechanical properties adversely and thus reduces its useful life. Beyer, et al. [1] investigated the reliability of lead-free (SAC387, 95Sn5Sb, and 62Sn36Pb2Ag) large area solder joints in IGBT modules. Sn5Sb, and 62Sn36Pb2Ag showed the best reliability under passive thermal cycling, whereas SAC387 was the best under active test. Qi, et al. [2] studied the effect of thermal fatigue on SnPb and SAC based surface mount resistors under different accelerated conditions. Under certain conditions, SAC solders have a longer life than SnPb, but this case is reversed for higher temperature range. Aging was found to significantly affect SAC solder reliability even at room temperature (RT). Solder microstructure keeps evolving during aging which will cause the degradation in the mechanical properties.

Aging has been found to reduce the solder reliability drastically when compared to Pb-based alloys. Zhang et al., [3] examined the mechanical behavior of different SAC alloys aged for various durations (0-6 months) and temperatures ranges. Also, Sn-Pb alloys were tested for comparison purposes. The percentage of silver within alloys play a key role in the creep deformation rate. Alloys with lower Ag contents appear to have higher creep rates than the ones with higher Ag content. Furthermore, microstructure study was performed for alloys before and after aging. Zhang et al., [4] investigated the effect of aging (1 year) on the thermal cycling reliability. Fine secondary phases are responsible for blocking the dislocation movements. Aging leads to the coarsening of these phases, which then becomes less effective in blocking the dislocation movements, thus leading to reduced mechanical strength. Several packages with Lead (Sn-37Pb) & SAC (105&305) based materials were used as solder joints. More than 50% of degradation was noticed for SAC alloys where as stable behavior was recorded for Sn-37Pb alloy. Couple other studies on the effects of thermal and mechanical cycling on solder joint reliability were done by Thirugnanasambandam et al. [5-10]. Furthermore, new finite element reliability models were validated with thermal cycling by Motalab et al., [11] Several packages with different aging times and temperatures were checked for this test. Lead and lead free materials were used as solder spheres. Significant degradation was recorded by comparing prediction models of aged & non-aged samples. Effects of different types of mechanical cycling were studied by Sinan et al., [12,13] considering the effect of long term aging on the fatigue properties of SAC solder joints.

Board surface finish is found to affect the reliability of lead & lead-free based solders. Hai et al., [14] discussed the reliability of aged (1 year, 85^{o}C&125^{o}C) SAC BGAs with different surface finishes (ImAg, ENIG, ENEPIG) under thermal cycling. Significant degradation (over 50%, ImAg, 125^{o}C) was noticed for certain BGAs, and this is the general trend for all treatments. In all cases, ImAg was observed to perform behind ENIG and ENEPIG. Berni et al., [15] conducted a comparative study between surface finish combinations of different packages. The combination included different lead and SAC305 solder materials with two surface finishes (ImAg & ENIG). Among tested combination, SAC305-ENIG achieved hazard ratio value that reflects greater reliability.

Lead-free solder reliability has been significantly improved with introducing a doping technology. Since a decade, there has been much research concerning this effect on the solder joint reliability. The effect of adding Bi to Sn plating, in addition to other properties, were studied by Zhang et al.,. [16] It was found that Sn whiskers were mitigated significantly. Yang et al., [17] investigated the concentration effect of Ag & Cu on thermal properties of low Ag-SAC alloys. Doping with Bi was also examined for the same alloys. Adding Bi will significantly affect the solids of low-Ag SAC solders than the liquids state. Sridhar et. al, [18,19] investigated the reliability of several aged and non-aged components under thermal cycling. Newly doped alloys were used as solder pastes with OSP coating. The results showed improvement in reliability, especially the Ni-based ones. Hamasha et al., [20-22] studied the reliability of SAC based components under different conditions and aging durations. Innolot was used as a reference material. There were only a few materials that performed better than Innolot. Furthermore, a new research program was launched with industry to assess the reliability of newly doped materials as a replacement of Pb based material. Cai et al., [23] studied the reduction of aging effects of SAC alloys due to the doped elements. 0.1% of Bi was added to SAC307 alloy to get SACX0307. Standard SAC alloys (105, 205, 305, 405) were also used in this test. Several mechanical properties (modulus of elasticity, yield stress, ultimate strength, etc) were examined in this test under several aging temperatures (25, 50, 75, 100, 125^{o}C) and durations (0-6 months). SAC-X were the best among used alloys especially after 6 months of aging. In their following work, Cai et al., [24] continued the same work with more data in addition to microstructure analysis for new recorded results. Microstructure study shows less degradation and coarsening in SAC-X alloys compared to others. The effect of surface finish under thermal cycling for doped lead free solder alloys were examined. Studies [25-28] have been done on the effect of several combinations of surface finishes, solder spheres and solder pastes on the reliability of SAC (105&305)-based CABGA under thermal cycling. The effect of matched solder sphere-paste on reliability was obvious, especially in the case of Innolot. In most cases, ENIG was found to perform better than OSP and ImAg.

There has been a question of whether the matched solder spheres perform better than traditional SAC305 and SAC105 solder spheres. In this study, the reliability of several combinations of surface finishes (ImAg, OSP) and solder spheres (match, SAC105, SAC305) with Bi-based solder pastes, subjected to thermal cycling after a long term of aging (12 months) at elevated temperature are studied.

II. EXPERIMENTAL SETUP AND PROCEDURE

The test vehicle used for the experiment (Fig. 1) consists of Surface Mount Resistors (SMRs), Quad Flat No-Leads (QFNs), Chip Array Ball Grid Arrays (CABGAs) on Flame Retardant 4 (FR4-06) glass epoxy Printed Circuit Board (PCB) with a glass transition temperature of 170^{o}C. The Ball Grid Arrays (BGA) are of two dimensions, 15mm x 15mm (CABGA 208) and 6mm x 6mm (CABGA 36) with a pitch size of 0.8mm. The QFNs are of 5mm x 5mm with a pitch size of 0.65mm. The SMRs are organized into banks of six resistors connected in series. Each component is daisy chained to make sure that the signal passes through all the solder joints. The PCB is of 4.0 x 5.0 x 0.062 inches in dimension with non-solder mask defined pads.

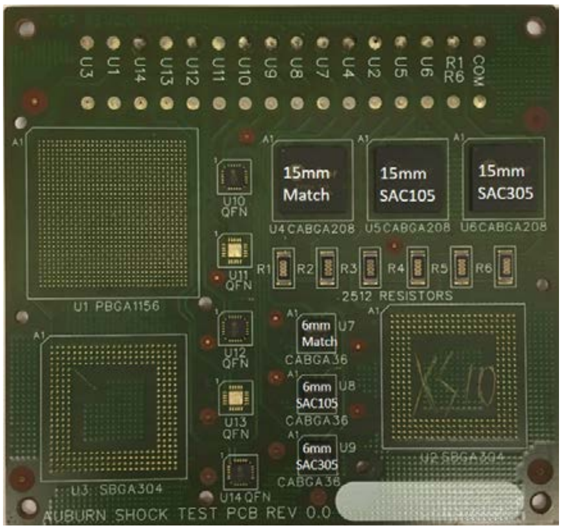


Fig. 1. Test Vehicle

The BGAs are mounted with SAC105, SAC305 and matched (solder sphere alloy with the same composition as solder paste) solder joints. The stencil thickness used for the printing is 6 mils. The reflow profile used for the package assembly is shown in Fig. 2. The profile is selected such that the solder joints have good wetting and least damage to the board.

This paper studies the effect of combining different types of solder spheres with Bi-based solder pastes, on the component reliability in accelerated thermal cycling. SAC

105, SAC 305 and match solder spheres are considered with immersion silver (ImAg) and organic solderability preserve (OSP) surface finishes. The solder pastes considered, with their composition is shown in Table I.

Table I. Composition of solder pastes

Solder paste	Composition
Innolot	Sn- 3.8Ag- 0.7Cu- 3Bi- 1.4Sb- 0.15Ni
MaxRel Plus	Sn- 3.8Ag- 0.8Cu- Bi- 3.0
Cyclomax	Sn- 3.4Ag- 0.50Cu-3.3Bi
Senju M758	Sn-3.0Ag-3Bi-0.8Cu-Ni

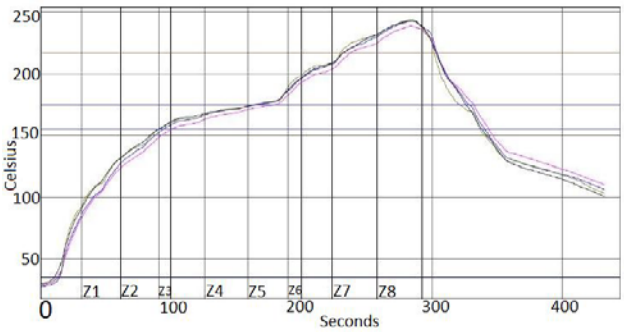


Fig. 2. Reflow Profile

The assembled boards were isothermally aged for twelve months at a temperature of 125°C after which they were thermal cycled using the profile shown in Fig.3 in Thermotron chamber. The cycling temperature was from -40°C to +125°C with up and down ramp times of 50 minutes each and dwell times at peak temperatures of 15 minutes each. The test boards were cycled for 5800 cycles.

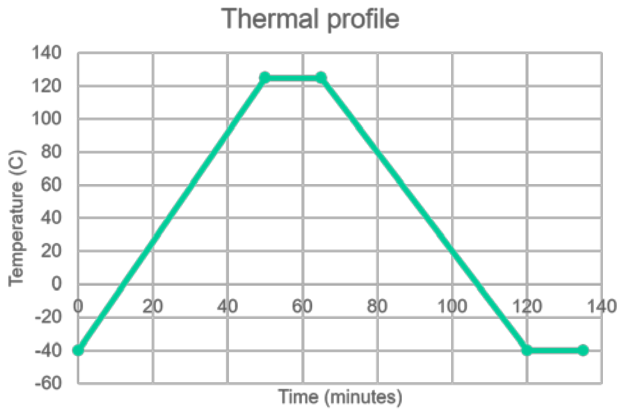


Fig. 3. Thermal Cycling Profile

The resistance values of the components are continuously monitored, by the monitoring system shown in Fig. 4, during the thermal cycling. The monitoring system consists of Keithley 7002 switch scanning system and Keithley 2001 digital multimeter interfaced with NI LabView. In the test, failure is defined as the five consecutive occurrences of increased resistance values by 100 Ohms than the baseline resistance.

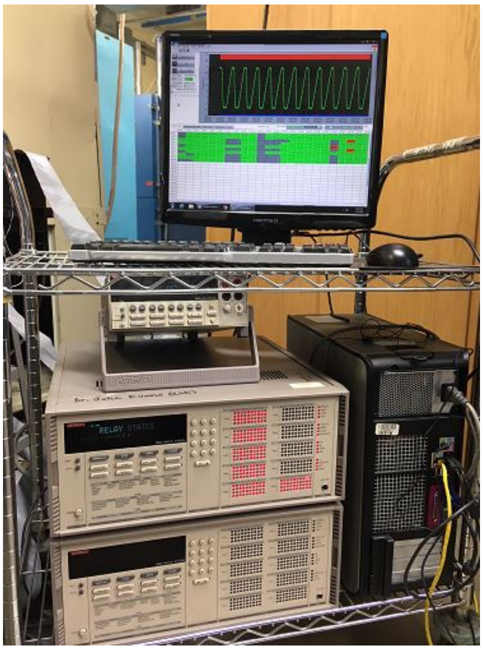


Figure 4. Test Monitoring System

III. RESULTS AND DISCUSSION

While 99% of CABGA208s failed, only 22% of the CABGA36s failed in the whole test. The percentage failure for QFNs and SMRs were 11% and 75% respectively. So, only CABGA208s are included in this study. Four Bi based solder pastes with common solder sphere alloys; namely SAC105, SAC305 and matched paste-sphere and two surface finishes; namely ImAg and OSP are used in the analysis.

A. Data Analysis

Two-parameter (β, η) Weibull plots were used for the analysis of reliability. The characteristic life (η) is the time (cycles in the study) at which 63.2% of samples failed and the shape parameter (β) represents the slope of the Weibull plot. ANOVA analysis is also done to understand the effect of each factors and their interactions. Main effects plot is calculated by considering the main factors in a level and disregarding the other levels. Interaction plots are constructed by considering the combination of one factor from each level. The data presented in the paper is based on the matrix shown in Table II.

Table II. Test plan matrix

Component	Solder Paste	Surface Finish	Solder sphere alloy
CABGA208	Cyclomax	ImAg	SAC105/305/match
		OSP	SAC105/305/match
	Ecolloy	ImAg	SAC105/305/match
		OSP	SAC105/305/match
	Innolot	ImAg	SAC105/305/match

		OSP	SAC105/305/match
	Senju M758	ImAg	SAC105/305/match
		OSP	SAC105/305/match

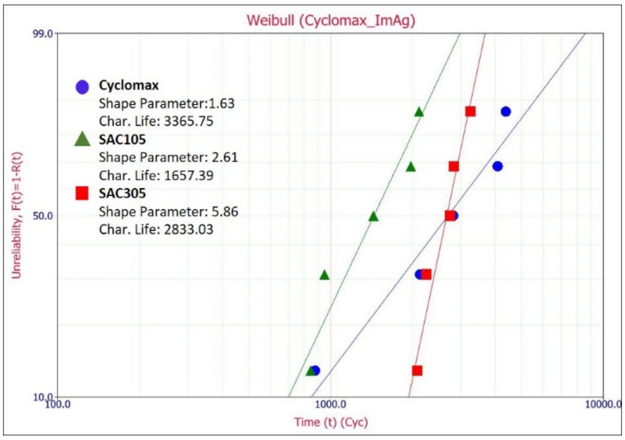


Fig. 5(a). Weibull analysis of solder spheres for ImAg finish with Cyclomax paste

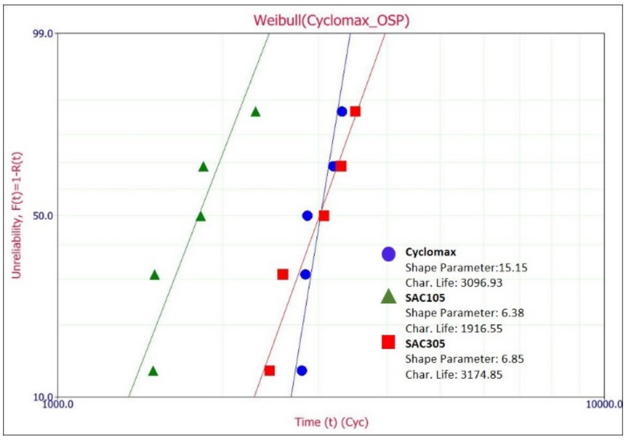


Fig. 5(b). Weibull analysis of solder spheres for OSP finish with Cyclomax paste

Fig. 5(a) shows the Weibull analysis for cyclomax solder paste with ImAg surface finish for different solder sphere alloys. Matching (Cyclomax) spheres has a better characteristic life than others even though it has early failures. SAC305 solder spheres doesn't perform as good as matched solder spheres with respect to characteristic life, but they don't have early failures. Fig.5(b) shows the analysis for cyclomax solder paste with OSP surface finish for different solder sphere alloys. Matched spheres and SAC305 spheres perform similarly, and SAC105 has the lowest characteristic life among the three. Fig. 5(c) shows the ANOVA analysis for the solder paste. From the main effects plot, it could be observed that the surface finish doesn't have a significant effect. In the interaction plot, it could be seen that OSP performs better with SAC105 and SAC305 while ImAg performs better with matched spheres. Fig.5(d) shows the summary of the results including different solder spheres for the surface finishes and cyclomax paste.

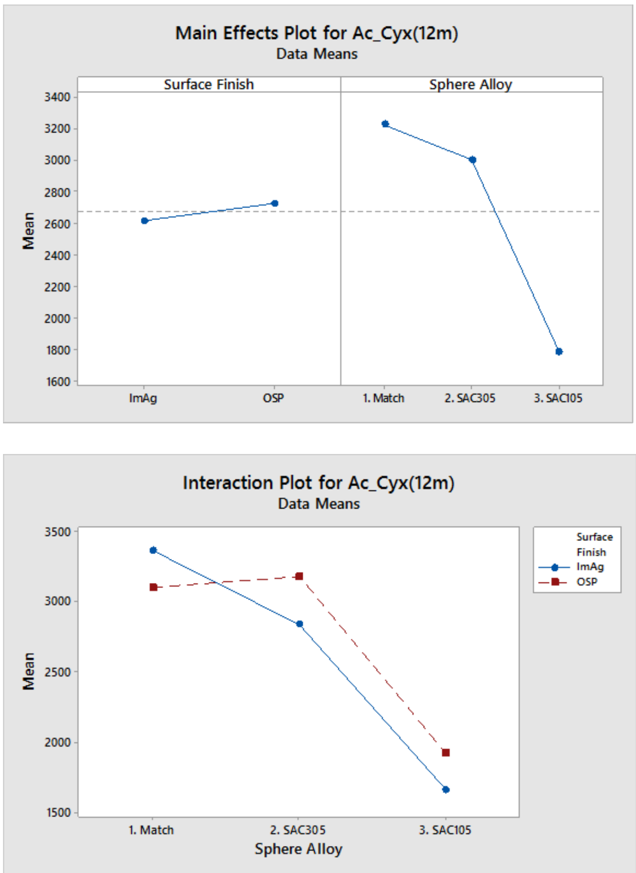


Fig. 5(c). ANOVA analysis for Cyclomax solder paste

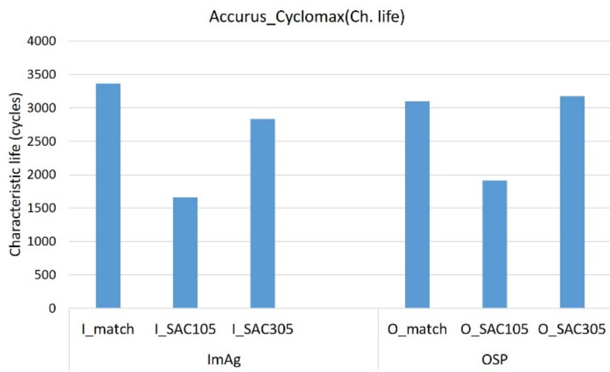


Figure 5(d). Comparison of solder spheres in different finishes for Cyclomax paste

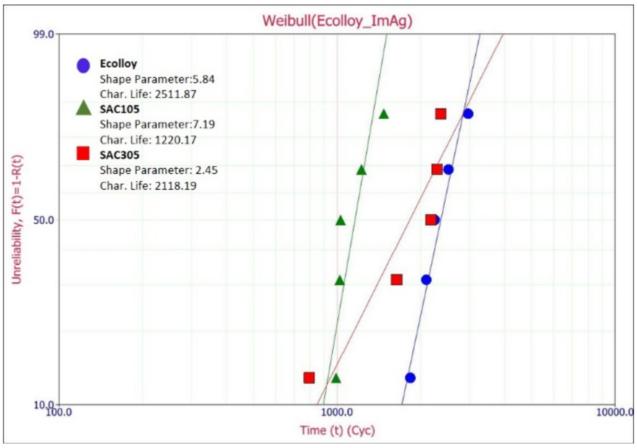


Fig. 6(a). Weibull analysis of solder spheres for ImAg finish with Ecolloy paste

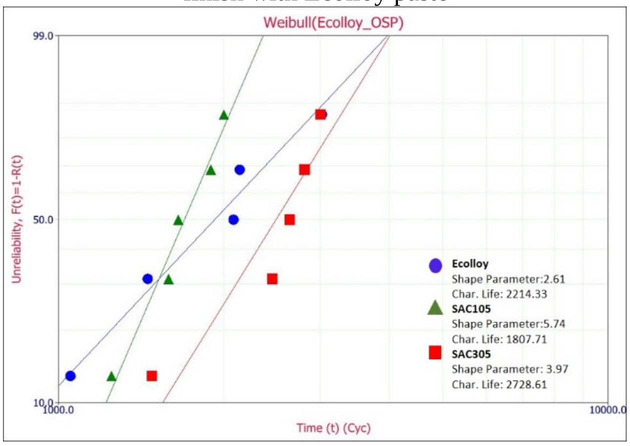
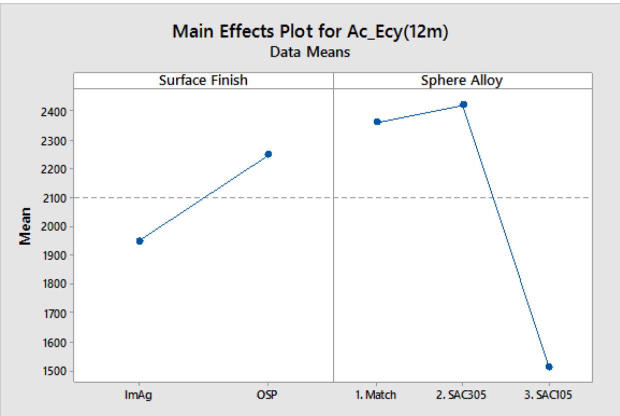


Fig. 6(b). Weibull analysis of solder spheres for OSP finish with Ecolloy paste

Fig. 6(a) shows the Weibull analysis for different solder sphere alloys for Ecolloy paste with ImAg finish. It could be seen that matched (Ecolloy) spheres perform the best, followed by SAC305. It could also be noted that SAC305 has early failures as well. However, when it comes to OSP finish, as shown in Fig. 6(b), SAC305 performs better than matched spheres and matched spheres have early failures as well. This indicates the effect of interaction between finish and spheres as observed in the analysis in fig. 6(c).



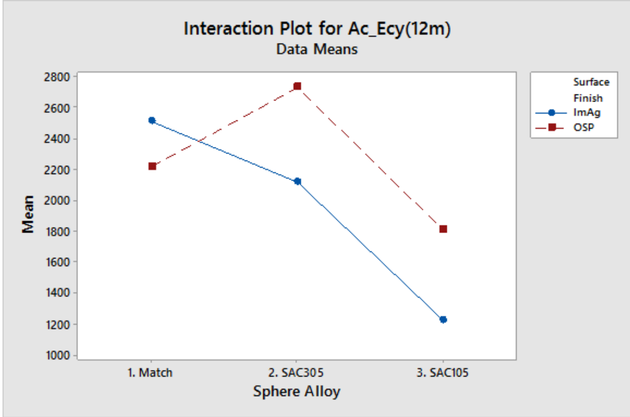


Fig. 6(c). ANOVA analysis for Ecolloy solder paste

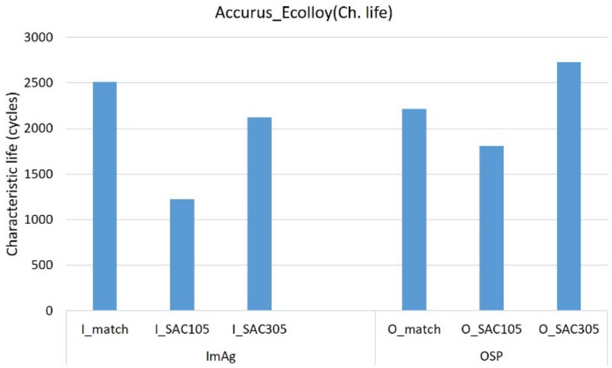


Figure 6(d). Comparison of solder spheres in different finishes for Ecolloy paste

From the main effects plot, it could be seen that OSP performs better than ImAg and that there is no significant difference between SAC305 and matched spheres. Regarding the interaction effect, it could be observed that OSP serves better with SAC305 and SAC105 and ImAg performed better with matched spheres. The characteristic life for different combinations of solder spheres and surface finishes for Ecolloy paste is shown in Fig.6(d).

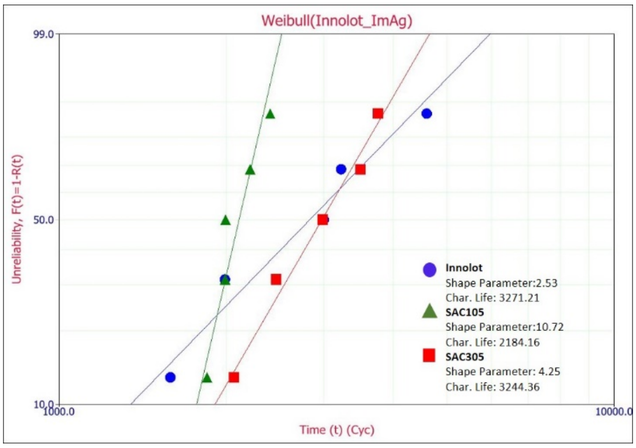


Fig. 7(a). Weibull analysis of solder spheres for ImAg finish with Innolot paste

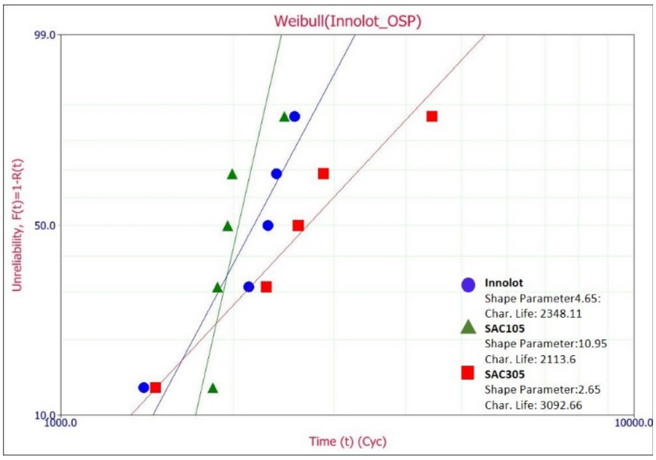


Fig. 7(b). Weibull analysis of solder spheres for OSP finish with Innolot paste

From the Weibull analysis for ImAg finish with Innolot paste as shown in Fig. 7(a), it could be seen that SAC305 and matched (Innolot) spheres perform the same with regards to characteristic life, but matched spheres have early failures. For OSP finish (Fig. 7(b)), SAC305 serves better with regards to characteristic life, but performs poorly when early failures are considered. From the ANOVA analysis as sown in fig. 7(c), it could be noted that surface finish and solder sphere alloys affect the reliability of solder joints. However, interaction effects couldn't be observed as ImAg performed better with all spheres, especially in the case of matched spheres. Fig.7(d) represents the summary of the results obtained for different combinations for Innolot solder paste.

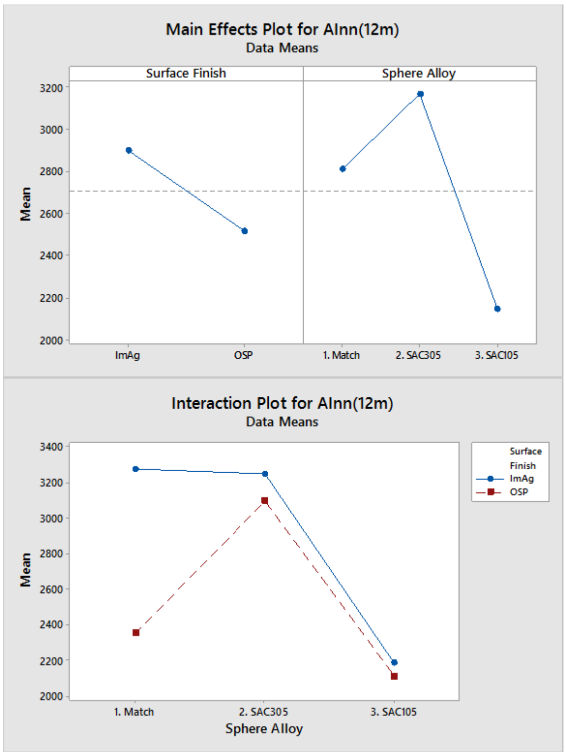


Fig. 7(c). ANOVA analysis for Innolot solder paste

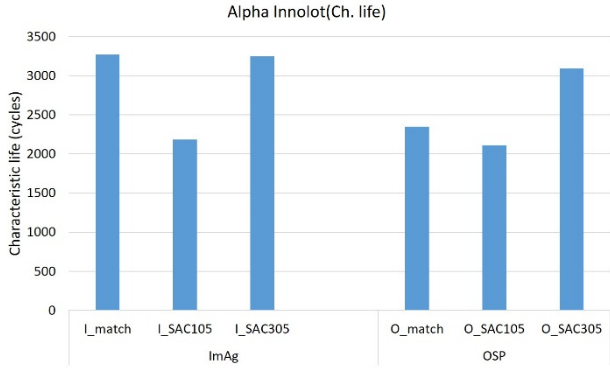


Figure 7(d). Comparison of solder spheres in different finishes for Innolot paste

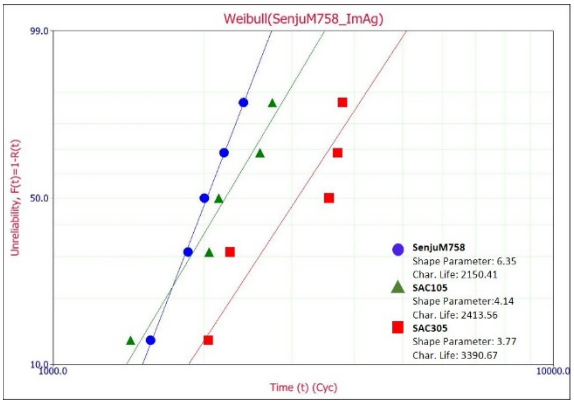


Fig. 8(a). Weibull analysis of solder spheres for ImAg finish with SenjuM758 paste

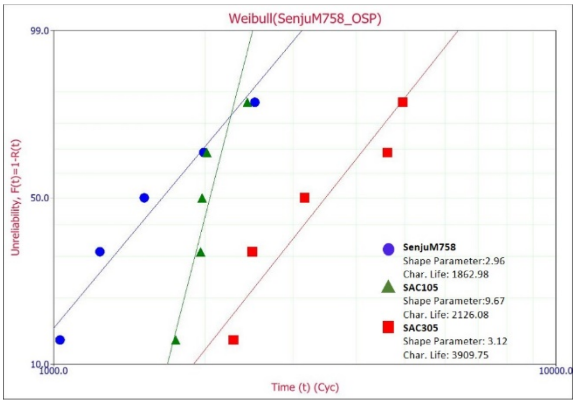


Fig. 8(b). Weibull analysis of solder spheres for OSP finish with SenjuM758 paste

For SenjuM758 paste with ImAg, as shown in Fig. 8(a), SAC305 performs the best, followed by SAC105 and matched (SenjuM758) spheres. A similar trend could be observed in the case of OSP finish as well. In the case of this solder paste, it is clear that the spheres need to be replaced with SAC305 or SAC105 for better reliability.

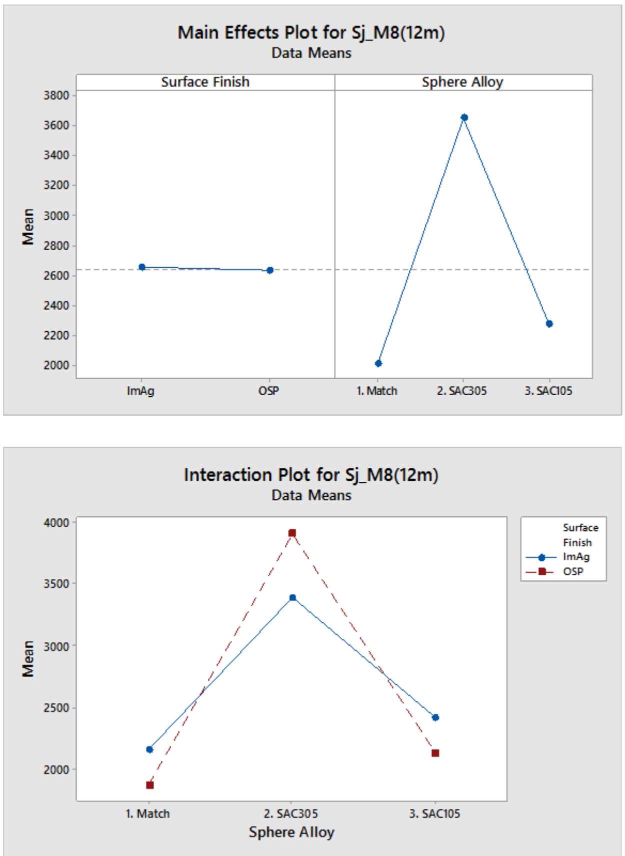


Fig. 8(c). ANOVA analysis for SenjuM758 solder paste

From the ANOVA analysis as shown in Fig. 8(c), it is clear that the surface finish doesn't have much effect, but the solder spheres have a significant effect. From the interaction plot, it was observed that the combination of OSP with SAC305 performed good, but not when OSP was combined with other solder spheres. Fig.8(d) shows the comparison of characteristic life for different combinations of solder spheres and finishes for SenjuM758 paste.

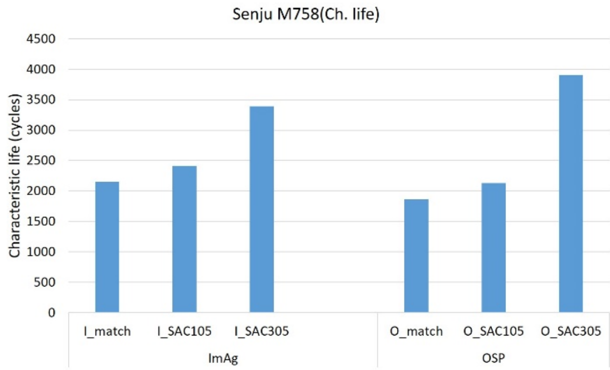


Figure 8(d). Comparison of solder spheres in different finishes for SenjuM758 paste

B. Microstructure

In the case of CABGA208, the solder joint consists of 16.8% solder paste and 83.2% solder sphere by volume. So, when matched spheres are used, solder joint is 100% solder paste material. When SAC105/SAC305 spheres are used, only 16.8% of the joint consists of solder paste material. Almost all the failures were on the component side along the IMC layer, which occurred as a result of local recrystallization. Bulk solder failures were found in the solder joints located at the corner of the component. SAC105 sphere was found to perform worse than the matched and SAC305 spheres. SAC105 spheres were observed to have a lot of recrystallization when compared to other spheres. A representative case of cyclomax paste with OSP finish is mentioned here. Fig.9(a) shows cyclomax sphere for the combination. Fig.9(b) and Fig.9(c) show SAC105 and SAC305 spheres for the cyclomax-OSP combination.

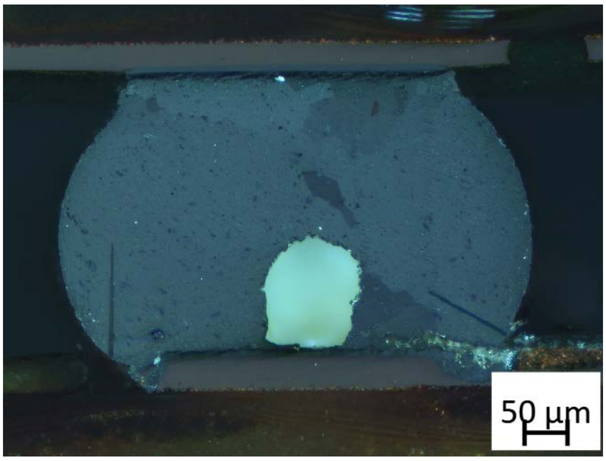


Figure 9(a). Polarized image of cyclomax sphere with OSP finish and cyclomax paste

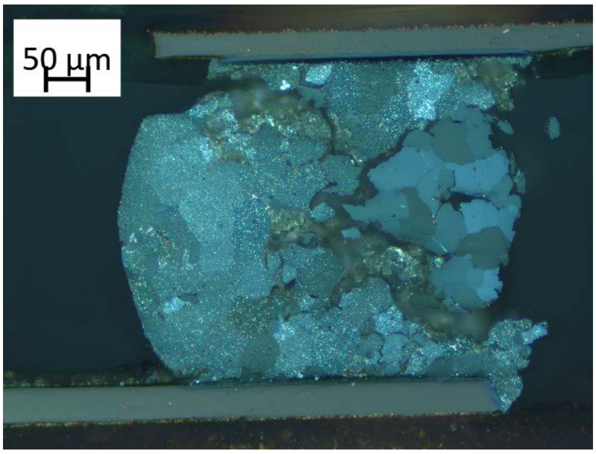


Figure 9(b). Polarized image of SAC105 sphere with OSP finish and cyclomax paste

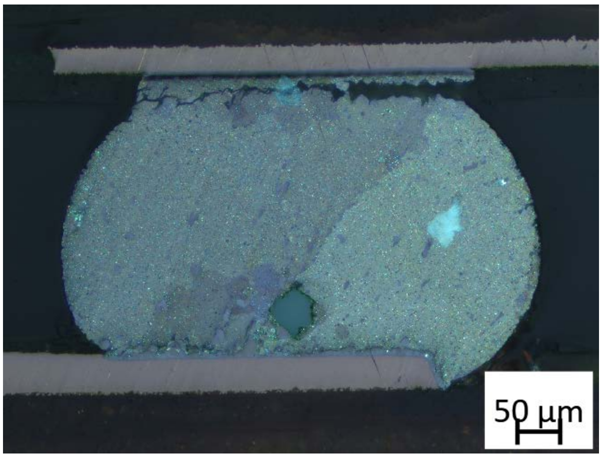


Figure 9(c). Polarized image of SAC305 sphere with OSP finish and cyclomax paste

It was also observed that matched spheres did not perform well in the case of SenjuM758 paste unlike other pastes, rather it performed poorer than SAC105. Fig.10(a), Fig.10(b) and Fig.10(c) show microstructure for matched, SAC105 and SAC305 spheres, respectively. As it could be seen, the matched sphere has a lot of precipitates, when compared to SAC105 and SAC305 spheres. Low characteristic life in the case of SenjuM758 spheres could also be attributed to its brittle nature due to the high silver content.

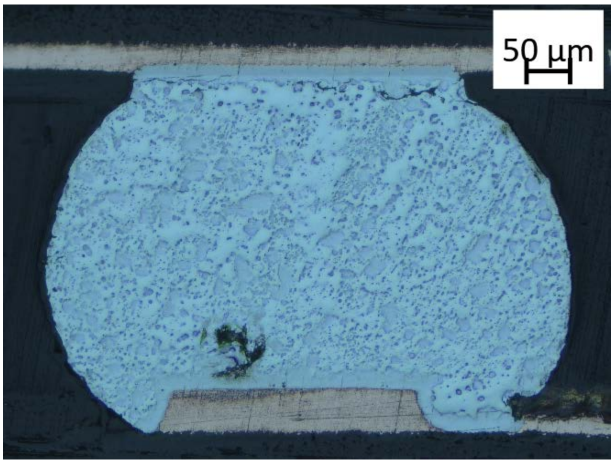


Figure 10(a). Brightfield image of SenjuM758 sphere with ImAg finish and SenjuM758 paste

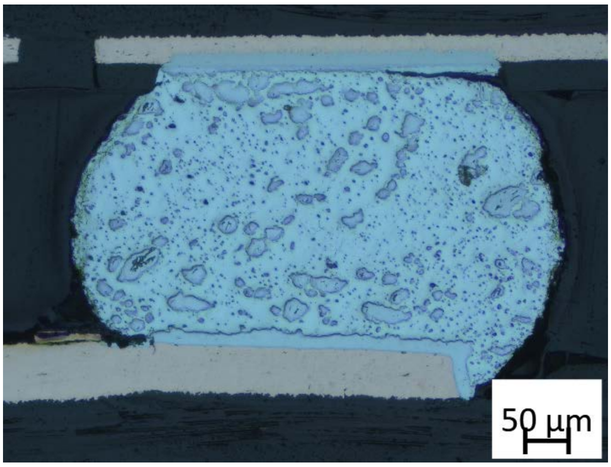


Figure 10(b). Brightfield image of SAC105 sphere with ImAg finish and SenjuM758 paste

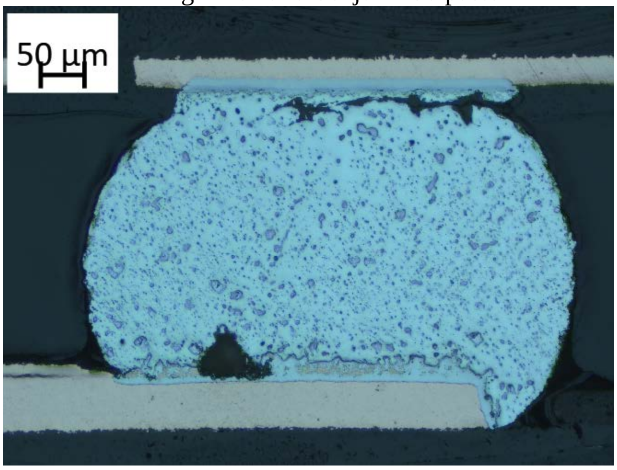


Figure 10(c). Brightfield image of SAC305 sphere with ImAg finish and SenjuM758 paste

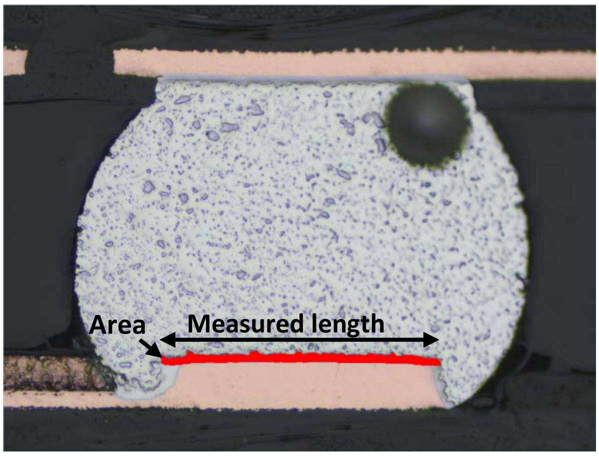


Figure 11. IMC layer thickness measurement

The intermetallic layer thickness on the board side was measured for all cases and tabulated in Table III. The area of the IMC layer was calculated and was divided by the length of the layer along the copper pad to obtain the IMC layer thickness as shown in the fig. 11.

Table III. Intermetallic layer measurment

Solder paste	Surface Finish	Solder Sphere	IMC Thickness (μm)
Cyclomax	ImAg	SAC105	9.14
		SAC305	15.8
		Match	11.11
	OSP	SAC105	7.89
		SAC305	8.07
		Match	8.74
Ecolloy	ImAg	SAC105	25.58
		SAC305	17.28
		Match	21.51
	OSP	SAC105	6.67
		SAC305	11.55
		Match	7.48
Innolot	ImAg	SAC105	19.83
		SAC305	8.6
		Match	16.73
	OSP	SAC105	8.99
		SAC305	17.29
		Match	9.47
SenjuM758	ImAg	SAC105	17.37
		SAC305	13.18
		Match	23.88
	OSP	SAC105	11.5
		SAC305	9.97
		Match	9.58

IV. CONCLUSION

The effect of using different solder spheres with different solder pastes and surface finishes were studied in the paper. In most of the cases, the failures were due to recrystallization and precipitate formation. It was observed that solder spheres, indeed had a significant effect on the reliability than the surface finish. This fact was clear from the ANOVA analysis and from the observation that the cracks, which led to failure were on the component side and not much cracks were found on the board side. EDX analysis needs to be done in order to understand more about the precipitates.

REFERENCES

[1] H. Beyer, V. Sivasubramaniam, M. Bayer and S. Hartmann, "Reliability of Lead-free Large Area Solder Joints in IGBT Modules with Respect to Passive and Active Thermal Cycling," CIPS 2016; 9th International Conference on Integrated Power Electronics Systems, Nuremberg, Germany, 2016, pp. 1-6.

[2] Y. Qi, H. R. Ghorbani and J. K. Spelt, "Thermal Fatigue of SnPb and SAC Resistor Joints: Analysis of Stress-Strain as a Function of Cycle Parameters," in IEEE Transactions on Advanced Packaging, vol. 29, no. 4, pp. 690-700, Nov. 2006.

[3] Y. Zhang, Z. Cai, J. C. Suhling, P. Lall and M. J. Bozack, "The effects of SAC alloy composition on aging resistance and reliability," 2009 59th Electronic Components and Technology Conference, San Diego, CA, 2009, pp. 370-389.

[4] J. Zhang et al., "Thermal Aging Effects on the Thermal Cycling Reliability of Lead-Free Fine Pitch Packages," in IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 3, no. 8, pp. 1348-1357, Aug. 2013.

[5] Thirugnanasambandam et al., "The study of vibrational performance on different doped low creep lead free solder paste and solder ball grid array packages", *14th Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, pp. 920-923, 2014.

[6] Thirugnanasambandam et al., "Proportional Hazard Model of doped low creep lead free solder paste under vibration", *15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, pp. 1209-1217, 2016.

[7] Thirugnanasambandam et al., "Component Level Reliability For High Temperature Power Computing with SAC305 And Alternative High Reliability Solders", *Proceedings of SMTA International*, 2014.

[8] Sanders et al., "Component Level Reliability For High Temperature Power Computing with SAC305 And Alternative High Reliability Solders", *Proceedings of SMTA International*, pp. 144-150, 2015.

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

[10] Raj, A et al.,"Comparative Study on Impact of Various Low Creep Doped Lead Free Solder Alloys", *Proceedings of SMTA International*, pp. 820-826, 2017.

[11] M. Motalab et al., "Correlation of reliability models including aging effects with thermal cycling reliability data," 2013 IEEE 63rd Electronic Components and Technology Conference, Las Vegas, NV, 2013, pp. 986-1004.

[12] Akkara et al. “Effects of long term aging on SnAgCu solder joints reliability in mechanical cycling fatigue”, *SMTA International, pp. 419-425, 2017*

[13] Su S, Fu N, Akkara F, Hamasha S. “Effect of long term room temperature aging on the fatigue properties of SnAgCu solder joints. ASME. *J. Electron. Packag*. 2018;

[14] Z. Hai et al., "Reliability Comparison of Aged SAC Fine-Pitch Ball Grid Array Packages Versus Surface Finishes," in IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 5, no. 6, pp. 828-837, June 2015.

[15] R. Berni, M. Catelani, C. Fiesoli and V. L. Scarano, "A Comparison of Alloy-Surface Finish Combinations Considering Different Component Package Types and Their Impact on Soldering Reliability," in IEEE Transactions on Reliability, vol. 65, no. 1, pp. 272-281, March 2016.

[16] R. Zhang et al., "Tin-bismuth plating for component finishes," 2011 IEEE 61st Electronic Components and Technology Conference (ECTC), Lake Buena Vista, FL, 2011, pp. 2060-2066.

[17] Liu Yang, Sun Fenglian, Zhang Hongwu and Wang Yang, "Influence of Ag, Cu and additive Bi elements on the thermal property of low-Ag SAC solder alloys," Proceedings of 2011 6th International Forum on Strategic Technology, Harbin, Heilongjiang, 2011, pp. 72-75.

[18] Sridhar, S., Raj, A., Evans, J., Bozack, M., Johnson, W., Hamasha, S., "Reliability Study of doped Lead Free Solder Paste Alloys by Thermal Cycling Testing" SMTA International, Chicago, IL, September 2017.

[19] Sridhar, Sharath et al., "Drop impact reliability testing of isothermally aged doped low creep lead-free solder paste alloys", *15th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*. pp. 501-506, 2016.

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

[21] Hamasha, S., Evans, J.L., Bozack, M.J., & Johnson, W.R. (2018). Long-term isothermally aged concerns for SAC lead-free solder in harsh environment applications. 2018 Pan Pacific Microelectronics Symposium (Pan Pacific), 1-7.

[22] S. Hamasha, F. Akkara, S. Su, H. Ali and P. Borgesen, "Effect of Cycling Amplitude Variations on SnAgCu Solder Joint Fatigue Life," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*.

[23] Z. Cai, Y. Zhang, J. C. Suhling, P. Lall, R. W. Johnson and M. J. Bozack, "Reduction of lead free solder aging effects using doped SAC alloys," 2010 Proceedings 60th Electronic Components and Technology Conference (ECTC), Las Vegas, NV, USA, 2010, pp. 1493-1511.

[24] Z. Cai, J. C. Suhling, P. Lall and M. J. Bozack, "Mitigation of lead free solder aging effects using doped SAC-X alloys," 13th InterSociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, San Diego, CA, 2012, pp. 896-909.

[25] 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," *2018 17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, San Diego, CA, 2018, pp. 1374-1380.

[26] S. Hamasha *et al*., "Effect of Surface Finish and High Bi Solder Alloy on Component Reliability in Thermal Cycling," *2018 IEEE 68th Electronic Components and Technology Conference (ECTC)*, San Diego, CA, USA, 2018, pp. 2032-2040.

[27] C. Zhao, C. Shen, Z. Hai, M. Basit, J. Zhang, M. J. Bozack, J.L. Evans, J. C. Suhling , "Long Term Aging Effects on the Reliability of Lead Free Solder Joints in Ball Grid Array Packages with Various Pitch Sizes and Ball Arrangement," Journal of Surface Mount Technology, Vol. 29 (2), pp. 37-46, 2016

[28] Cong Zhao, Thomas Sanders, Zhou Hai, Chaobo Shen, and John L. Evans (*2016*) Reliability Analysis of Lead-Free Solder Joints with Solder Doping on Harsh Environment. International Symposium on Microelectronics: FALL 2016, Vol. 2016, No. 1, pp. 000117-000122.