RELIABILITY OF SAC405 AND SAC387 AS LEAD-FREE SOLDER BALL MATERIAL FOR BALL GRID ARRAY PACKAGES

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ABSTRACT

Solder joining is one of the interconnection methods in microelectronic packaging especially for the ball grid array (BGA) package type. The robustness of solder joint is directly related to solder ball alloy composition. In this paper, SAC405 & SAC387 were compared in terms of the following characteristics: alloy properties, solder ball surface morphology, solder ball shear strength (at time zero, after test, after multiple reflow, after high temperature storage, after moisture sensitivity level 3/260℃), Intermatellic Compound (IMC) thickness and morphology, missing ball after test and solderability. As a result, SAC387 reported better solder joint performance than SAC405 to be used in ball grid array packaging. This is supported by IMC thickness measurement that shows significant different in term of growth and consistency. Solder joint performance decreased with response to the increase number of multiple reflow and storage time.

Keywords: *reliability, lead-free material, solder joint, microelectronic packaging.*

INTRODUCTION

Sn based solders are the most attractive materials for the replacement of conventional Pb-Sn solder. Sn fulfils the metallurgical, environmental, economic and supply criteria and therefore most of the effort has been directed towards tin (Sn) containing binary or ternary alloys [1,2]. In Sn-Ag-Cu (SAC) system, metallurgical reactions between Sn and the minor elements (Ag and Cu) are the primary factors in determining the application temperature and solidification mechanism.

For the past several years many in the industry (NEMI, SOLDERTEC, CALCE, HDPUG, Intel, Dell, etc.) have been moving aggressively towards Sn-Ag-Cu (SAC). Lead-free alloy has been practically in used since countries such as Japan, USA and those in the European Union introduced the mandatory requirements for Pb-free imports [3]. The only drawback is that the melting point for most of the lead-free solder materials is higher than that of Sn-Pb eutectic alloy [4]. Table 1 shows the comparison of some physical properties of the lead-free solders and Sn-Pb solders.

Table 1: Physical property comparison of Lead-free solders and Sn-Pb solder

Physical property	**Sn63/Pb37**	**Sn96.5/Ag3.5**	**96.5Sn/3.8Ag/0.7Cu**
Melting point (°C)	183	221	217
Electrical resistivity (μΩ.cm)	14.5	12.3	13
Brinell Hardness HB	17	15	15
Density (g/cm3)	8.4	7.5	7.5
Tensile strength (MPa)	45.1	61.4	60

The inter-matellic compound (IMC) layer developed during the service time. Excessive thickness of IMC causes cracks at the solder joint area owing to brittleness and weakened the overall joint strength [5]. In Sn-Ag-Cu alloys, Cu_6Sn_5 and Ag_3Sn are in the equilibrium state, with distinct morphologies, platelets for Ag_3Sn and hollow, hexagonal rods for Cu_6Sn_5 [6]. In this study, SAC405 & SAC387 were compared in terms of the following characteristics: alloy properties, solder ball surface morphology, solder ball shear strength (at time zero, after test, after multiple reflow, after high temperature storage, after moisture sensitivity level 3/260°C), Intermatellic Compound (IMC) thickness and morphology, missing ball after test and solderability. The composition of both materials under studies is shown in Table 2.

Table 2: Solder ball composition comparison

	SAC 405	SAC 387
%Ag	4.0±0.1%	3.8±0.1%
%Cu	0.5±0.1%	0.7±0.1%

*Remark: Balance Composition is Sn 95.5% +/- 0.5%

EXPERIMENTAL WORKS

Figure 1 presented the experimental flow diagram applied in this study. The details on the samples and test information is given in Table 3. The Scanning Electron Microscope (SEM) was used to study ball surface morphology and IMC morphology underneath bulk solder with applied etching solution - 40hrs using 10ml HCl and 90ml ethanol as the etching agent. Follow by elemental depth profile analysis using Auger.

Ball attaches process started with the preparation of the test samples initiated by applying flux on the solder pads through pin transfer mechanism. The solder balls were placed on the solder pads by ball bump tool. The flux holds the solder balls in place until they are reflowed. The test sample was then reflowed whereupon the solder balls formed bumps. During reflow, the ball self centered on the substrate pad [7].

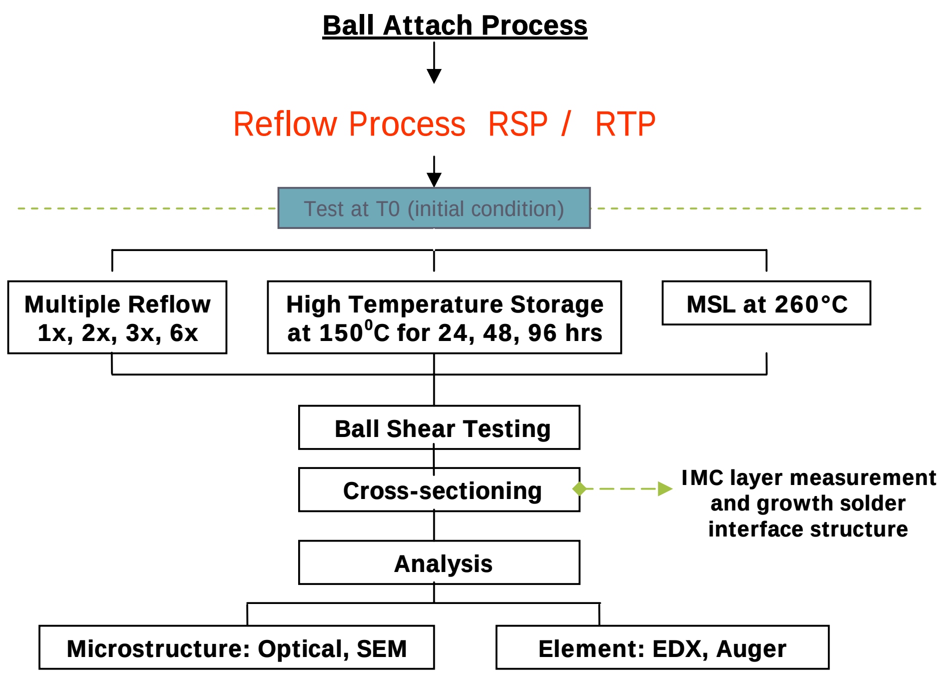
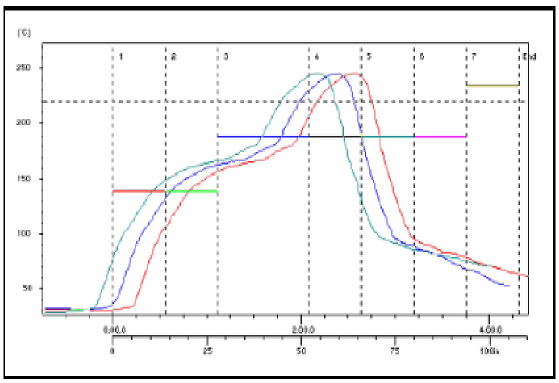


Figure 1: Experimental flow diagram

The reflow process was done using RSP profile (Figure 2) and conducted in a seven-zone forced convection oven at a peak reflow temperature of 235-250°C, with soak time between 130°C-170°C at ~55s.

Table 3: Test information

Condition	Sample size
Solder Ball Shear (SBS)(T0 & after test)	10 units/lot, 8 balls/unit
Multiple reflow (1x,2x,3x,6x) -SBS -Cross-section	5 units/lot/no. of cycles, 8 balls/unit 3 units/lot/no. of cycles, 2 balls/unit
High Temperature storage test (24,48,96 hrs) -SBS -Cross-section	5 units/lot/storage time, 8 balls/unit 3 units/lot/storage time, 2 balls/unit
Moisture Sensitiivity Level 3/260) -SBS -cross section	5 units/lot, 8 balls/unit 3 units/lot, 2 balls/unit
Solderability	45 units/lot



Current Profile Parameters	Current Spec	Actual		
		Rear TC	Center TC	Front TC
Ramp Rate (50 to 150^{0}C)	<3^{0}C/sec	2.41	2.41	2.38
Peak Temp	240 to 260^{0}C	245.5	245.5	246
Dwell Time > 220^{0}C	30 to 60 sec	35.5	35	34.5
Cooling Rate (240 to 210^{0}C)	<6^{0}C/sec	2.55	2.67	2.46
Additional Info :	Rec. Spec			
Soak Time btw 130 to 170 deg.C	max 90 sec	55	56	56
Dwell Time > 230^{0}C (liquidus temp @229)	30 to 40 sec	30	30	29

Figure 2: Ramp-Soak-Peak (temperature vs time) & reflow profile parameter

Test samples (Table 4) were subjected to ball shear test after assembly and after electrical test. Samples after test were also subjected to ball shear after multiple reflow operations of 1, 2, 3 and 6 times cycling at 260°C in accordance to JESD22-A113 [8]. Also, ball shear test was also performed on the test samples after high temperature storage at 150^{0}C for different storage time at 24, 48 and 96 hours. HTS is used to determine the effect of temperature and time under storage condition at elevated temperatures without electrical stress applied as stated in JESD22-A103B [9]. Moisture/reflow testing was performed at peak reflow temperatures of 260°C. The samples-10 units/lot was placed in a moist warm environment chamber according to JEDEC STD-020A [10]. The present moisture sensitivity standard contains six levels, the lower the level, and the longer a devices floor life. Then, it was proceed to solderability test to determine the wettability of the solder paste and solders balls at the SMT board level. Any failure on the solderability causes open solder joint. For inter-metallic thickness and area measurement, the units were cross-sectioned and polished for better observation and examination under Microscope and Image Analyzer. IMC elemental analysis was done using EDX.

Table 4: Package information

Item	Description
Package	480 TBGA
Packaging size	37.5 x 37.5 mm
Solder pad/Solder mask opening diameter	0.64 mm
Solder ball diameter	0.76 mm
Pad to ball ratio	0.84
Constant: Flux & Substrate vendor & profile	

Solder Ball Shear (SBS)Test

Ball shear test is a destructive method to determine the ability of BGA solders balls to withstand mechanical shear forces. Ball shear test were performed using *DAGE 2400 series* shear machine, as followed in JESD22-B117 [11].

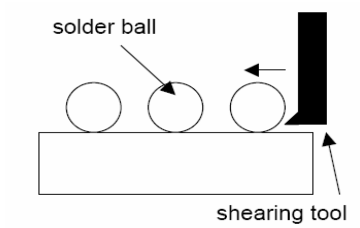


Figure 3: shear test diagram

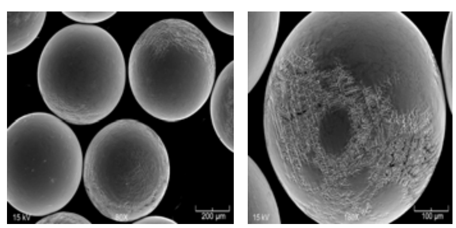
The shearing tool was aligned to the ball in the conventional manner as shown in Figure 3. The sample will then be moved away from the tool to create the acceleration distance. From this position, the sample is accelerated to the programmed test speed and the ball contacts the tool. Having a region of constant velocity (acceleration distance), the speed is held prior to and during impact with the ball. Lastly, the sample was decelerated to complete the test. The test parameters for the solder ball shear test are as follows:-

Ball diameter: 30 mils,
Ball shear speed: 300mm/s,
Ball shear height: 40 um from the substrate.

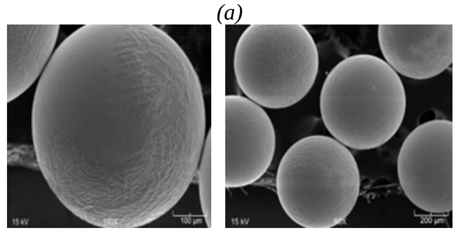
RESULTS AND DISCUSSION

Surface Morphology Comparison

Ball surface topography



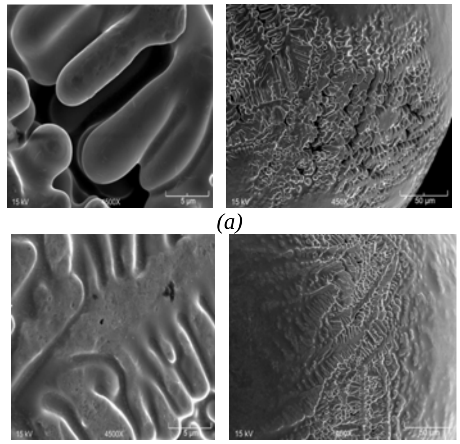
(a)



(b)

Figure 4: Ball surface topography for (a) SAC 405 and (b) SAC 387

Figure 4 and Figure 5 show the surface of ball SAC 387 is smoother than the SAC 405 ball. This is probably achieved by to a faster cooling process. This exhibited relationship between oxidation and topography as a function deployment of wetting and print ability of solder paste [12].



(a)

(b)

Figure 5: Detail ball surface topography for (a) SAC 405 and (b) SAC 387

The coarser dendrites on the SAC 405 ball surface forms notches and channels which may trap contamination and prevent the dispense of flux. [12] reported that the distribution of element on the surface probably had more impact of the surface roughness.

The finer dendrites on the SAC 387 ball surface provides better mechanical strength and prevent damage of the ball before attachment. It is agreed that Pb-free material will oxidize at a significant more rapid rate. When the temperature goes up, the oxidation process accelerates. In its turn, oxidation impacts both the topography of the solder particles as well as the surface tension of the solder. Changes in surface tension affect the wetting of the surface to be joined, ultimately impacting soldering performance. In fact, controlling and reduce oxide level is a parameter to achieve smoother particles surface.

Elemental depth profile-Auger analysis

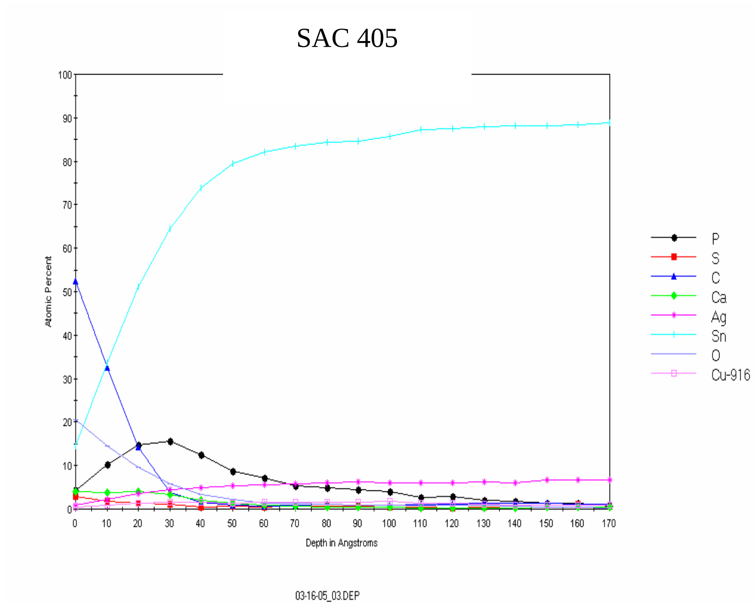


Figure 6: Profile for SAC 405 element

Phosphorus appears on the surface of SAC 405 Pb-free ball .The phosphorus will build up a brittle layer at the solder/pad interface and induce failure.

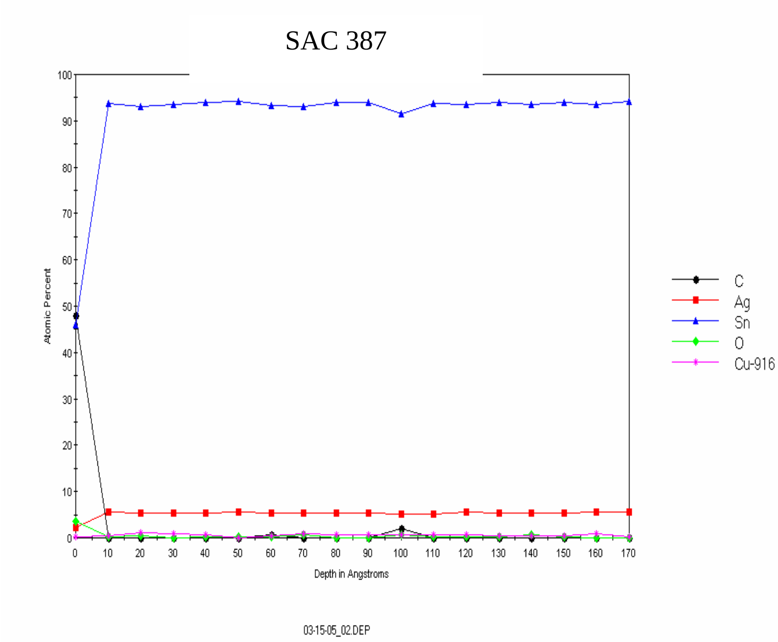


Figure 7: Profile for SAC 387 element

Differs with SAC 387 that is only Little O, no P or Ca is found on the surface of the ball. The sharp cliff in the profile suggests that the surface of this kind of solder ball is smooth.

Solder Ball Shear Comparison

Table 5: Previous Data –TBGA Ball Shear Comparison after assembly

Parameter	**SAC 405**	**SAC 387**
Max	2126.4	1972.9
Min	1213.5	1387.6
Mean	1814.6	1743.9
Std. Dev	182.7	134.3
Mean – 3SD	1266.6	1340.9
CpK	1.49	1.85
% of Mode 2	24%	4%

SAC 387 on different substrate has shown tremendous improvement in terms of SBS mode 2 failures. Mode 2 failure of SAC 387 is only 1.25% as compared to 24% in SAC 405, and it's comparable to SAC 387 has 0-4% mode 2 failure.

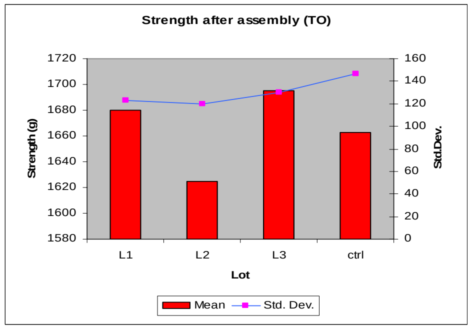


Figure 8: Shear strength at TO (after assembly) between SAC 405 & SAC 387

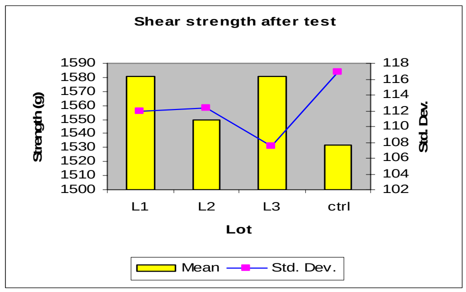


Figure 9: Shear strength after test between SAC 405 & SAC 387

After assembly, SAC 387 samples show highest average strength with lowest standard deviation. It is also proven to be different as compared to SAC 405 samples. After subjecting to electrical test, ball shear result shows slight decreasing of strength in all the samples, but SAC 387 samples still show highest average strength with lowest standard deviation.

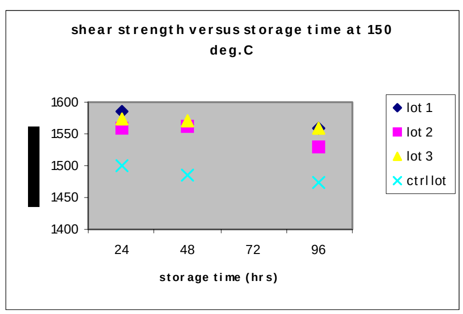


Figure 10: Shear strength versus storagetimes between SAC 405 & SAC 387

With increasing storage times, solder balls with composition SAC 387 & SAC 405 shows the decreasing of shear strength. It is proportional with IMC thickness where thicker IMC forms after longer storage times. However, SAC 405 shows lower shear strength against the other lots. This might be because of higher percentage of Ag presented in SAC 405 that leads to form large high Ag_3Sn and degrade the mechanical integrity of solder joint and supported by Figure 13.

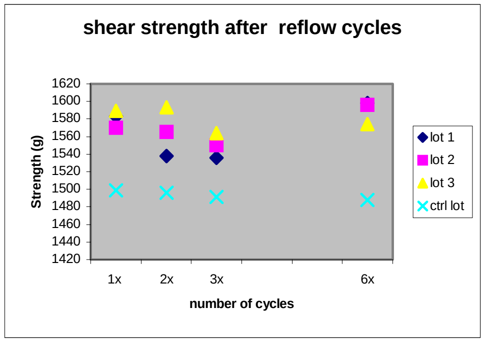


Figure 11: Shear strength versus reflow cycles between SAC 405 and SAC 387

Figure 10 shows that SAC 387 samples demonstrate increasing of strength up to 6x reflow while SAC 405 resulted no significant difference against number of cycles. It is also supported from Figure 12 that SAC 405 shows lower strength and higher Std. Dev when exposed under MSL/260 condition. But all test samples have passed MSL3 level at 260°C peak reflow temperature.

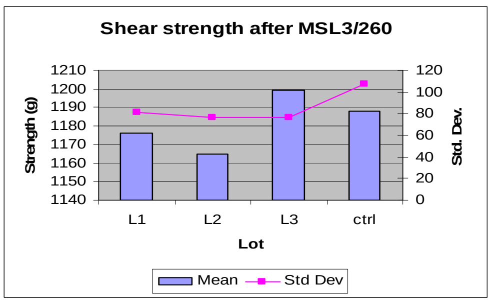
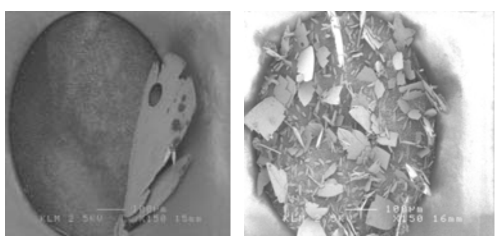


Figure 12: Shear strength after MSL3/260 between SAC 405 and SAC 387

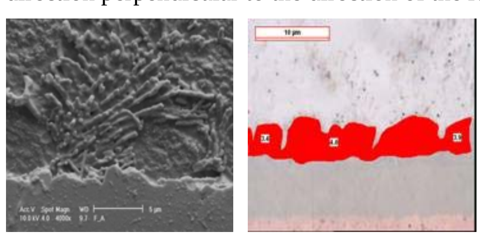
Solder Pad Analysis

The microstructure of reflowed solder joint is mainly controlled by the solidification process of a molten solder that is influences by the nucleation and growth phenomenon of the constituent phase.

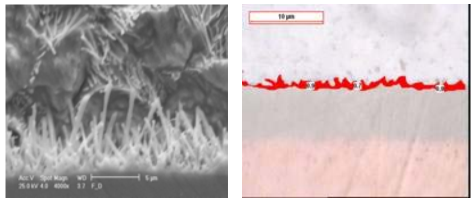


(a) (b)

*Figure 13: Solder pad examination (a) SAC 405: High Ag_3Sn Flakes and(b) SAC 387: Big Ag_3Sn Plate*Figure 13 (a) shows too many flakes/weak points that may result in low-ball shear. While SAC 387 has much lesser flakes/weak points, which gives better ball shear.Large proeutectic Ag_3Sn plates reported in SnAg/SnAgCu alloys solidified at a slow cooling rate. For SAC 387, the comprehensive deformation has also caused the dendrite structure to align and to be refined along the direction perpendicular to the direction of the loading.



(a)



(b)

Figure 14: (a) SAC 405 produced relatively huge and thicker IMC (b) SAC 387 produced fine and considerably uniform IMC, which is generally good for solder joint resist (SJR)

Table 6 below shows elemental analysis presented at IMC using EDX analysis.

Table 6: Analysis output done at IMC

Spot	SEM (IMC Morphology)	EDX (IMC Type)
Flake	Flake or plate type	Ag_3Sn
SAC 405 IMC	Scallop Type	Cu rich IMC, $(Cu,Ni)_3Sn_2$
SAC 387	Dendrite Type	Ni rich IMC,

Voids were found located above IMC layer. SAC 405 was previously observed to have rougher surface, the voids could be due to 2 reasons: 1) Flux entrapment and cause flux residue after reflow. 2) Ineffective flux cleaning action – Due to rough surface, flux could not reach certain point, leaving oxide and causing poor solder wetting.

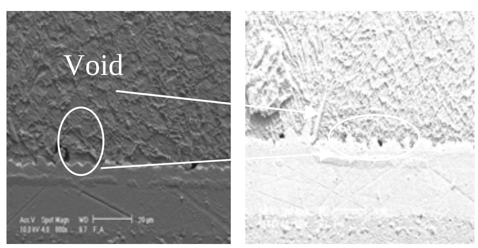
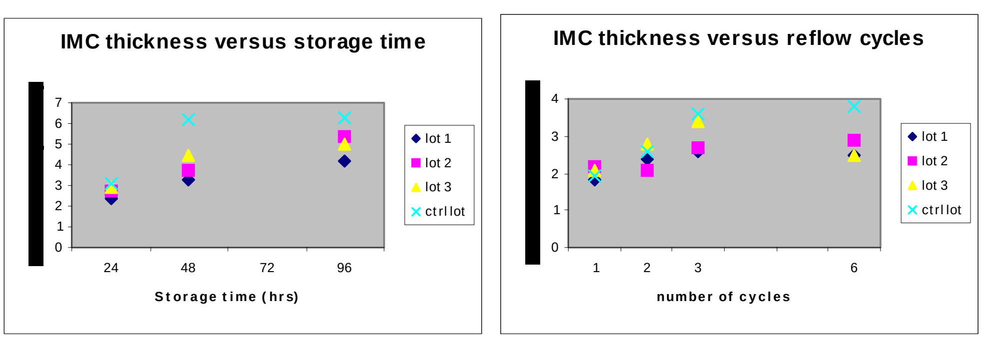


Figure 15: SAC 405

IMC layer Thickness Measurement



(a) (b)

Figure 16: IMC thickness measurement graph per (a) storage time (b) reflow cycles between SAC 405 and SAC 387

The thickness variation of the IMC layer against different storage time shows a linear relationship between the thickness of the IMC and the square root of aging time. The total thickness of IMC layer is the sum of the

Cu_6Sn_5 and Cu_3Sn layer [13]. Up to 48 hrs, SAC 405 shows thicker IMC more than 6 μm that is susceptible to crack and joint failure. Differ after multiple reflow cycles; there are no significant differences with response to number of cycles. But up to 6x reflow, SAC 387 shows thinner IMC against other lot.

Missing Ball Yield Loss at Final Test Comparison

Table 7: Missing ball yield loss results

Lot	Qty	Missing ball at final test	% defects
SAC387	130	0	0.00
SAC405	128	1	0.78

Characterization result with~130units test sample size shows that SAC405 has 0.78% missing ball yield loss at final test where at SAC387 has zero yield loss. It is supported that SAC387 helps to reduce missing ball risk and better solder joint strength.

Solderability Comparison

Table 8: Solderability results

Lot	Qtty	48hrs bake @150°c	72hrs bake @150°c
Lot 1	15unit/rdpnt	Pass	Pass
Lot 2	15unit/rdpnt	Pass	Pass
Lot 3	15unit/rdpnt	Pass	Pass
ctrl	15unit/rdpnt	Pass	Pass

From solderability, all test samples pass solderability test after 48 & 72 hrs dry aging.

CONCLUSION

From the results, we can conclude that SAC387 solder alloy reported better solder joint performance than SAC405. Solder ball surface morphology resulted SAC 387 have smoother surface than SAC 405. Therefore it is provides better mechanical strength and flux dispensing. It is supported by elemental depth profile analysis using Auger that Phosphorus appears on the surface of SAC 405 Pb-free ball. The phosphorus will build up a brittle layer at the solder/pad interface and induce failure.
Solder ball shear test presented SAC 387 have better performance when proceed to after assembly (TO), after test, after multiple reflow, after high temperature storage, after moisture level 3/260C). Solder joint performance decreased with response to the increase of number of multiple reflow and storage time.

This is supported by IMC thickness measurement and morphology analysis that shows significant different in term of growth and consistency. Followed by solderability test, all test samples pass after 48 & 72 hrs dry aging and SAC 387 resulted have no missing ball and % defects at final test.

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