Comprehensive Study on Thermal Aging and Ball Shear Characterization of SAC-X Solders

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Abstract

Ball Grid Array (BGA) is a surface mount chip package commonly used in many microelectronics products. It has solder balls array underneath the package provide electrical connection and mechanical support to the PCB. BGA is well-known for its low inductance, high lead count` and compact size. BGA chips are simpler to align to the printed circuit board. It is due to leads, which known as "solder balls" or "solder bumps," are further apart compare to the leaded packages. Tin-silver-copper (Sn-Ag-Cu) is a popular solder ball is also well-known as SAC, is a lead-free alloy [1, 2]. SAC is currently a dominant alloy system used to substitute tin-lead because of it adequate thermal fatigue properties and is close to eutectic with wettability and strength meeting require specification. However for more stringent reliability requirements such as in automotive applications, SAC solder will have difficulties to meet the reliability at board level when the footprint surpasses a certain dimension. This lead to the research and study for alternative solder alloys, such as SACQ and QSAC. The properties of the SAC305, SACQ and QSAC such as Tensile Strength, Elongation, and Hardness will be compared. Studies of the solder joint of various type of solder balls with BGA in terms of failure mode upon balls shear and measurement of the ball shear strength. These solder alloys need to subject to High Temperature storage (HTS) for extended duration up to 3000hrs under high temperature conditions. Details of the experimental results including the failure mode and the intermetallic characterization and correlations will be shared and discussed.

1. Introduction

Rapid development of electronics industry in the modern information age have lead products such as cell phones and computers to be progressively in demand. There is constantly growing demands requirements in terms of performance and functions of electronics products and at the same time, decreasing requirements in terms of weight and volume. Until now, multiple functions, miniaturization and light weight have become the main primary progress in the modern electronics products. To accomplish these requirement, downsizing of the feature size of integrated circuit chips is need and these will lead to complexity level continuously rising. Hence, I/O count and I/O density of packaging starts rising. BGA is an advanced high-density packaging technologies and it proves more competent advantages than the other packaging in term of requirement in miniaturization, high performance and light weight.

Solder alloy balls being used in BGA as interconnect sandwiched between the package substrate and the board on which the package is soldered. SAC solder ball family such as SAC305 is the common type of lead free solder ball use in BGA. It contained 3.0% tin (Sn), 0.5% silver (Ag) and 96.5% Copper (Cu). High Ag in SAC305 allow the solder material to flow and wet easily, excellent in electricity conductivity and melt at temperature of 217°C. SAC305 is a popular solder material in the electronic industries because of it solder-ability, mechanical properties and good reliability. Therefore, in the electronic industry, SAC alloys are prefer and main choice for the surface-mount lead free technology assembly. To further improve the board level reliability, SACQ & QSAC have been introduce to the market. Bi have been added to the SAC solder alloys to enhance the alloys wettability and spreading.

2. Types of Solder Ball's material

Three solder material are selected for this study. They are SAC305, SACQ and QSAC and their properties are tabulated in Table 1. Their main difference are hardness, tensile strength and elongation.

Table 1: Tensile Strength, Elongation, Hardness Comparison

Standard Alloy Property		Unit	SAC305	SACQ	QSAC
Melting Point	Solidus	°C	217	207	215
	Liquidus	°C	221	217	219
Density		g/cm³	7.4	7.5	7.5
Hardness (with Vickers Microhardness)		HV	14.1	30	23
Tensile Strength (Tensile test @ room temperature)		MPa	49	91	68
Elongation (Tensile test @ room temperature)		%	63	37	48
Thermal expansion coefficient (with TMA)		ppm - °C	23	22	22
Specific heat		J/g.K	0.23	0.24	0.21

3. Experimental Methods

3 types of solder ball's material with ball size of 300um, flux NC26A and BGA substrate are used for this experiment. Flux type NC26A is a halogen-free and no-clean flip-chip dipping flux is used. It is configure to leave an entirely benign and clear residue. BGA solder mask defined Cu pad with measurement of 200µm for bond pad size together with pitch at 400µm are used for this study. Image is as shown in Figure 1

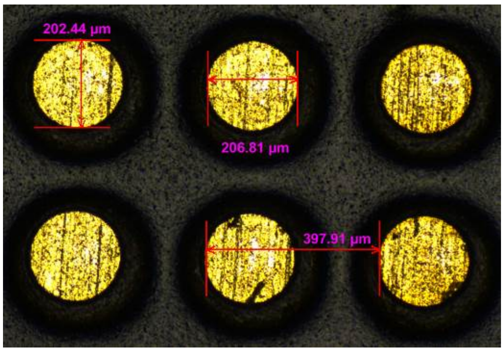


Figure 1: BGA Substrate Dimension

Flux printing process is required to apply NC26A flux using customized stencil made of stainless steel before solder ball is place onto the BGA substrate as shown in Figure 2. Samples then undergo reflow process which consist of 4 stages known as zones. The zones are known as preheat, thermal soak, reflow and cooling as shown in reflow profile as seen in the Figure 3. Each zones have a different temperature setting.

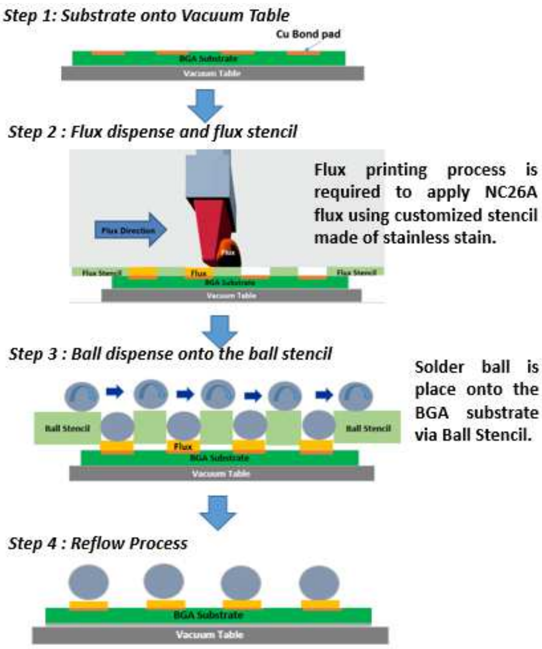


Figure 2: Flux Printing Flow to Ball Drop Process

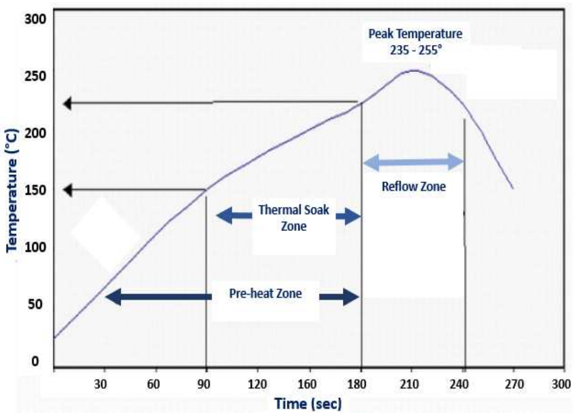


Figure 3: Reflow Profile

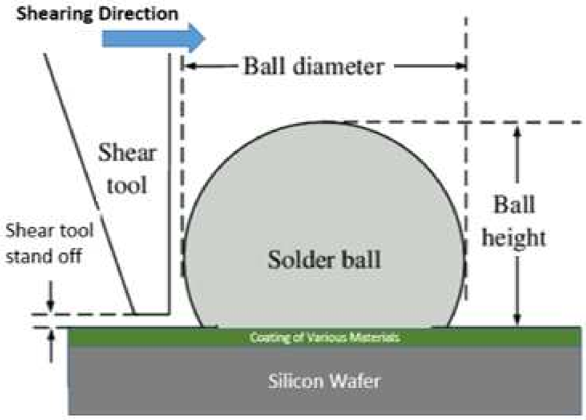


Figure 4: Ball Shear Test Schematic Diagram

The most popular and common method to test and evaluate the reliability of bond strength for BGA packages is ball shear test. In this study, shear tool height is set at 10% of an average ball height when collecting the ball shear measurement. 20 balls are collected from each set and failure mode were observed upon shearing via Nikon MM-80 optical microscope. IMC growth thickness will be measure via mechanical polishing and inspected with JEOL-JSM 5600LV scanning electronic microscopy (SEM) for 3 types of solder ball, after HTS from 0hr to 3000hrs.

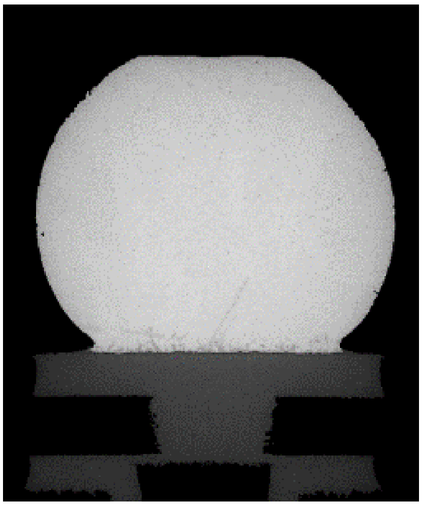


Figure 5: Cross section of 300um Solder Ball

3. Results and Discussion

3.1 Ball Shear Measurement & Failure Mode

Ball shear process is done using DAGE 4000HS bond tester. Time 0hr to 3000hrs HTS average ball shear strength summary for 3 types of solder ball are collected and data are shown below.

Observation are:

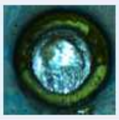
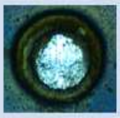
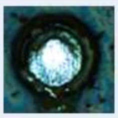
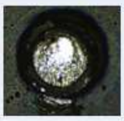
- Ductile failure observed using Nikon MM-80 optical microscope imaging on all the 20 balls for the 3 types of solder ball upon shearing at 0hrs to 3000hrs under HTS condition , as shown in Table 2

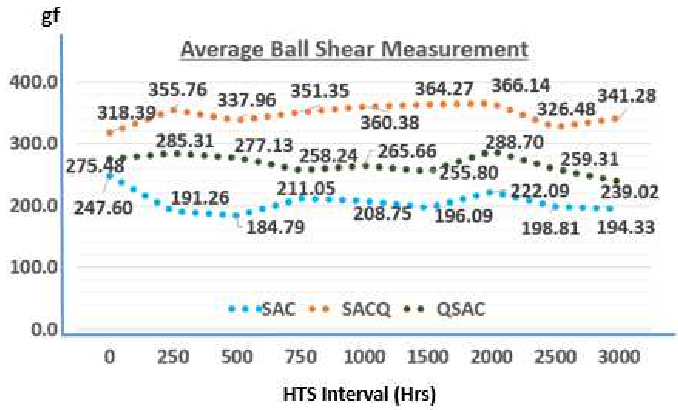
- All the 3 types of solder ball, SAC, SACQ and QSAC passed the required ball shear strength of >123gf based on 2.5g/mil2 industry standard.

- SACQ having the highest ball shear strength compared to SACQ and QSAC.
    - ✓ SACQ maintains an average ball shear strength of >300gf from 0hr to 3000hrs, throughout the HTS interval.

- Average ball shear strength of SAC, SAQ and QSAC does not witness significant drop as HTS interval increases from 0hrs to 3000hrs.
    - ✓ SAC average range from 146.24gf to 223.80gf
    - ✓ SACQ average range from 239.02gf to 288.70gf
    - ✓ QSAC average range from 318.39gf to 366.14gf

Table 2: Failure Mode after Ball Shear Process

Interval	SAC305	SACQ	QSAC
0hr			
250hrs			
500hrs			
750hrs			
1000hr			
1500hr			
2000hrs			
2500hrs			
3000hrs			



Graph 1: Comparison at HTS based on Ball Shear Measurement

3.2 IMC Growth

Cu_6Sn_5 is commonly observed IMCs when Cu substrate and Sn-based Pb-free solder reacted upon reflow. It is observed that Cu_6Sn_5 phase form very quickly. Cu_6Sn_5 initially produced a scallop-form at each interval temperature and transform to a prismatic-form as the time increases [4, 5].

Formation of scallop-liked Cu_6Sn_5 and planar-like Cu_3Sn IMCs types seen at solder/Cu interface once Sn-based solder alloy molten wets the pad of the Cu surface. A nanometer thin layer of Cu_3Sn formed between Cu_6Sn_5 and Cu at initial bonding stage for SAC, SACQ and QSAC at time 0hr as shown in Figure 6.

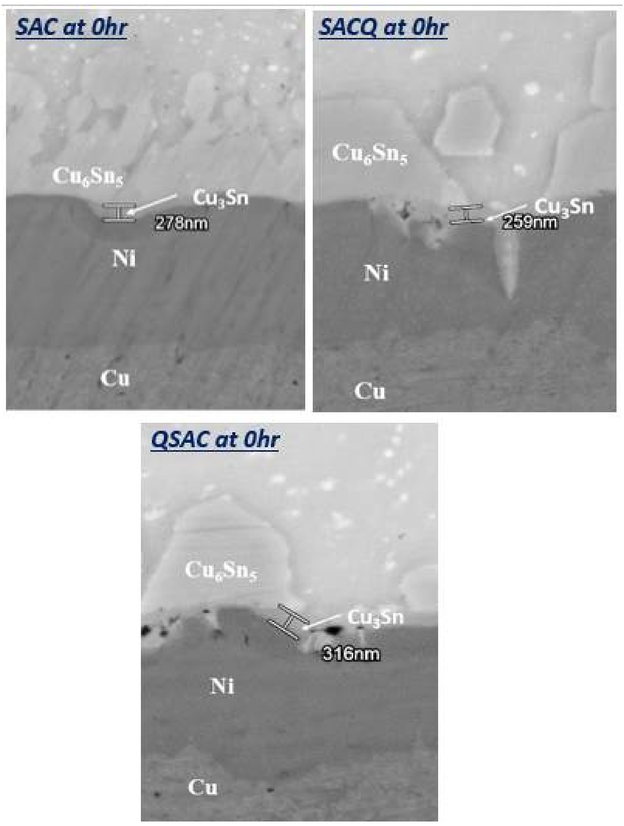


Figure 6: Cu3S IMC Growth

A thin layer and scallop-shaped Cu_6Sn_5 seen for SAC, SACQ and QSAC at time 0hr as shown in Figure 5. As the thickness is challenging to measure because of the scalloped nature of most IMC. An average of 10 measurements alongside the intermetallic layer positioned at right, center, and left of the whole solder ball were taken and summarize in Graph 2.

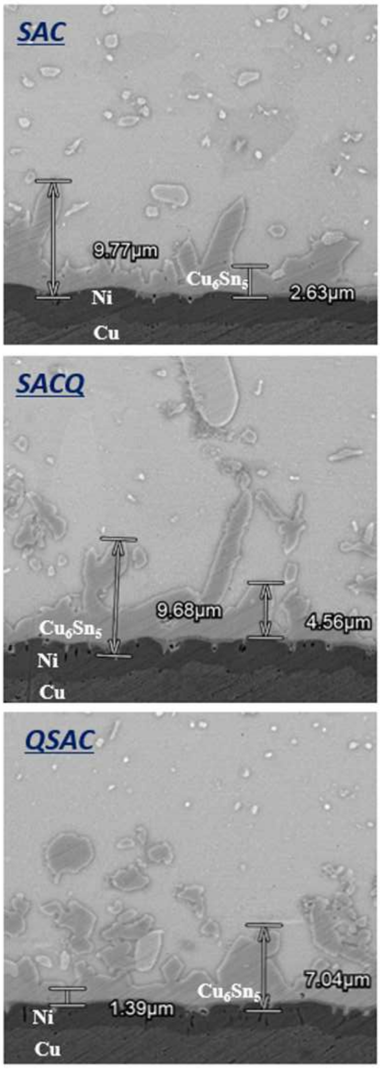
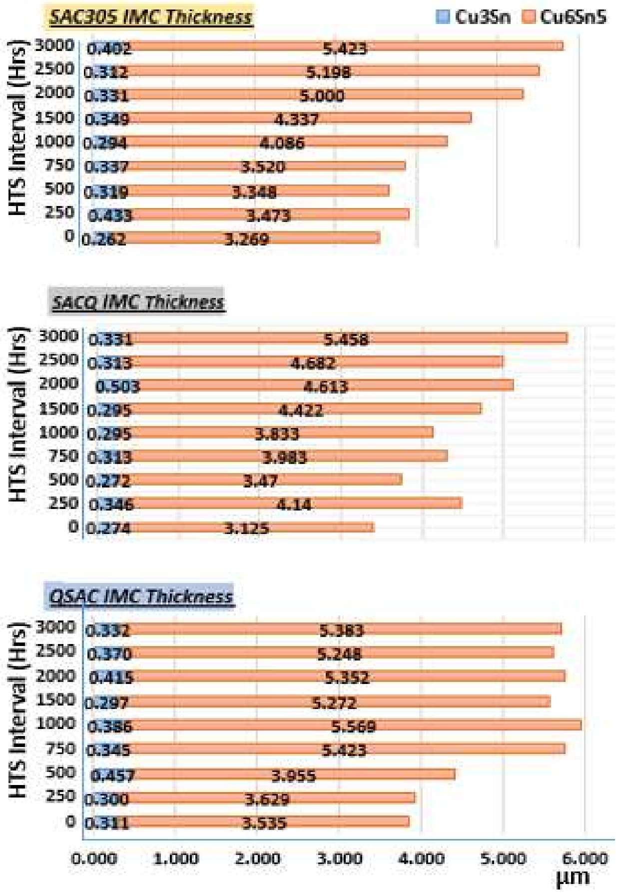


Figure 7: Scallop-shaped Cu_6Sn_5

Observation are:

- Steady increased for the Cu_6Sn_5 with increase in time for SAC305, SACQ and QSAC from 0hr to 3000hrs HTS
    - ✓ SAC Cu_6Sn_5 increase from 3.268µm to 5.423µm
    - ✓ SACQ Cu_6Sn_5 increase from 3.125µm to 5.468µm
    - ✓ QSAC Cu_6Sn_5 increase from 3.535µm to 5.383µm

- Cu_3Sn thickness does not increase significantly for SAC305, SACQ and QSAC from 0hr to 3000hrs HTS
    - ✓ SAC Cu_3Sn thickness range from 0.262µm to 0.433µm
    - ✓ SACQ Cu_3Sn thickness range from 0.272µm to 0.503µm
    - ✓ QSAC Cu_3Sn thickness range from 0.297µm to 0.457µm



Graph 2: IMC Thickness from 0hr to 3000hrs

3.3 Correlation between the IMC formations, shear strength and shear test failure mode

Ductile failure is observed until HTS of up to 3000hrs indicate that there is no correlation on the IMC thickness and ball shear strength. To achieve ductile failure, using solder mask define pad (SMD) is prefer compare to Non-solder mask define pad (NSMD) as SMD reduces the likelihood of the pad lifting.

As HTS interval increase, ball shear strength observation:

- SAC drop at every HTS interval from 247.60gf at 0hr to 184.79 gf at 3000hrs. The shear strength different about 62gf.
- QSAC ball shear strength maintain at 250hrs to 500hrs HTS interval with ball shear strength of 275gf – 285.31gf. The ball shear strength fluctuate at HTS interval from 750rs to 2500hrs ranging from 258.24gf to 288.70gf. At HTS 3000hrs, ball shear strength drop to 239.02gf.
- SACQ shows an increase in ball shear strength from 318.39gf at HTS 0hrs to 341.28gf at 3000hrs.

It is observed as IMC for SAC, SACQ & QSAC increase from 3um to 5um thickness after undergo HTS at 3000hrs,

- SACQ ball shear strength increase from 318g.39f to 341.28gf
- SAC ball shear strength decrease from 247.60gf to 194.33gf
- QSAC, ball shear strength decrease from 275.48gf to 239.02gf.

Conclusions

In this study, BGA solder mask defined Cu pad with measurement of 200µm for bond pad size together with pitch at 400µm with 300µm solder ball size with 3 different types of solder interconnect was discovered.

- Ductile failure observed using Nikon MM-80 optical microscope imaging on all the 20 balls for the 3 types of solder ball upon shearing at 0hrs to 3000hrs under HTS condition.

- Average ball shear strength of SAC, SAQ and QSAC does not witness significant drop as HTS interval increases from 0hrs to 3000hrs. SACQ having the highest ball shear strength compared to SACQ and QSAC with an average ball shear strength of >300gf from 0hr to 3000hrs, throughout the HTS interval.

- Steady increased for the Cu_6Sn_5 with increase in time for SAC305, SACQ and QSAC from 0hr to 3000hrs HTS whereas Cu_3Sn thickness does not increase significantly for SAC305, SACQ and QSAC from 0hr to 3000hrs HTS.

References

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