

A Comparison Study on SnAgNiCo and Sn3.8Ag0.7Cu C5 Lead Free Solder System

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Abstract

A study was conducted on BGA lead-free C5 solder joint system to compare SnAgNiCo versus conventional Sn3.8Ag0.7Cu solder alloy. This study showed that SnAgNiCo C5 solder system performed better than Sn3.8Ag0.7Cu in terms of joint strength and brittle mode failure. Shear and pull strength was measured by Dage which is representative of the intermetallic (IMC) strength between the C5 solder sphere and Cu/Ni/Au pad finishing. Tray drop test and packing drop test were done to gauge solder joint performance against handling and impact force. A comprehensive study was done to study the effect of microstructure and interface intermetallics of both solder system after assembly, after test, after high temperature storage (HTS) at 150°C for 168 hours and 504 hours and after 6x reflow towards the joint integrity. Microstructure studies on SnAgNiCo solder reveals that formation of rod shape Ag₃Sn IMC distributed across the solder surface helps to act as dispersion hardening that increases the mechanical strength for the SnAgNiCo solder after thermal aging. EDX analysis confirmed that in SnAgCu solder/Ni interface, Cu-rich IMC formed on top of the Ni-rich IMC. For SnAgNiCo system, only Ni-rich IMC is found. Therefore, it is highly suspected that the presence of Cu-rich IMC posed a detrimental effect on the joint strength and tends to cause brittle joint failure. Both of the effect is then showed in ball pull result that after 6x reflow, SnAgCu solder has 100% brittle mode failure, where SnAgNiCo solder has only 5%. This result correlates with missing ball responses after packing drop tests. Thus, SnAgNiCo lead-free solder is a potential candidate for lead-free solder joint improvement for overall lead-free package robustness.

Keywords: BGA packaging, lead-free C5, brittle solder joint, intermetallics, SnAgNiCo, Sn3.8Ag0.7Cu, Shear and pull strength

Introduction

Eu RoHS Directive for environmental and health concerns have resulted in significant activities to find substitutes for lead-contained solders for microelectronics. The potential candidates such as Sn-Ag¹ and Sn-Ag-Cu¹ eutectic solders with melting temperatures of 221°C and 217°C, respectively are

the most prominent solders because of their excellent mechanical properties as compared with that of eutectic Sn-Pb solder². Other candidates as drop-in replacements for eutectic Pb-Sn solder, such as Sn-In-Zn alloys, may have melting point close to 185°C, though not eutectic, and an acceptable solidification range but have received only limited attention¹. Among the many possible lead-free solder alloy

candidates, three commonly used alloys to meet automotive thermal cycling requirement are Sn3.0Ag0.5Cu, Sn3.8Ag0.7Cu and Sn4.0Ag0.5Cu. However, industry has found these commonly applied solder alloys to have certain level of ball drop problem which affects production yield, product quality as well as customers satisfaction.

In this study, SnAgNiCo was being compared to conventional Sn3.8Ag0.7Cu solder alloy in terms of ball drop improvement. Shear and pull strength was measured by Dage which is representative of the intermetallic (IMC) strength between the C5 solder sphere and Cu/Ni/Au pad finishing. Tray drop test and packing drop test were done to gauge solder joint performance against handling and impact force. A comprehensive study was done to study the effect of microstructure and interface intermetallics of both solder system after assembly, after test, after high temperature storage (HTS) at 150°C for 168 hours and 504 hours and after 6x reflow towards the joint integrity. Microstructure studies on SnAgNiCo solder reveals that formation of rod shape Ag₃Sn IMC distributed across the solder surface helps to act as dispersion hardening that increases the mechanical strength for the SnAgNiCo solder after thermal aging. EDX analysis confirmed that in SnAgCu solder/Ni interface, Cu-rich IMC formed on top of the Ni-rich IMC. For SnAgNiCo system, only Ni-rich IMC is found. Therefore, it is highly suspected that the presence of Cu-rich IMC posed a detrimental effect on the joint strength and tends to cause brittle joint failure. Both of the effect is then showed in ball pull result that after 6x reflow, SnAgCu solder has 100% brittle mode failure, where SnAgNiCo solder has only 5%. This result correlates with missing ball responses after packing drop tests. Thus, SnAgNiCo lead-free solder is a potential candidate for lead-free solder joint improvement for overall lead-free package robustness.

2. Study Design

This study comprises 4 parts:

1. Assembly of samples with TBGA substrates from two different C5 lead free solder ball, namely SAC387 and SnAgNiCo.
2. Ball shear and cold ball pull measurement for after assembly, after test, after 168 hours and 504 hours high temperature storage and after 6x reflow.
3. Cross section and etching for IMC and solder microstructure analysis.
4. Tray drop test and packing drop test.

3. Subjects and Methods

3.1. Subjects

In this study, 35x35mm 672TBGA with electrolytic Ni/Au pas finishing was used as test vehicle for cold ball pull, ball shear and IMC study, while 37.5x37.5mm 740TBGA was used for drop tests study. This package was chosen because it has the smallest pad to ball ratio among all the BGA packages assembled in Freescale KL. Solder alloys were supplied by the same vendor. Solder composition and test vehicle details are shown on Table 1 and 2..

Table 1. Details of package used in this study

Solder Ball Composition	97.617%Sn2.3%Ag0.08%Ni0.003%Co and 95.5%Sn3.8%Ag0.7%Cu
Package Type	TBGA
Ball Count	672 & 740
Package Size	35x35mm & 37.5x37.5mm
Ball Pitch	1.00mm
Ball Size	0.66mm
Solder Mask Opening Diameter	0.45mm
Solder Pad to Ball Diameter Ratio	0.68
Cold Ball Pull LSL	550g

3.2 Methods

3.2.1 Samples Preparation

Two lots of samples were assembled, where one lot was attached with SAC387 and the other lot with SnAgNiCo. Solders are being reflowed on the TBGA substrate using Motorola Manufacturing System (MMS) machine with standard ramp-to-peak reflow profile for lead free TBGA. The reflow profile used in this study is displayed in Figure 1.

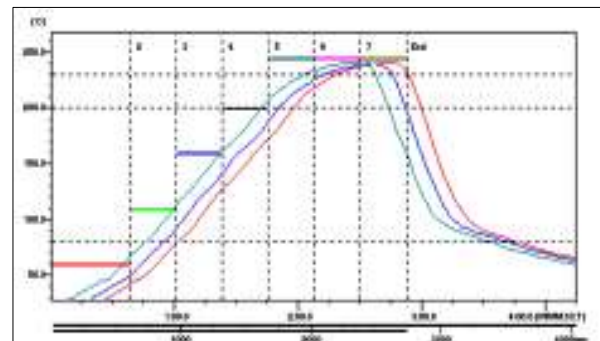


Figure 1. Ramp-to-peak reflow profile

Next, data at time zero was gathered after assembly and after test. Samples after test were also subjected to 168hrs and 504hrs high temperature storage baking at 150°C to study thermal aging effect on the solder system, as well as customers maximum reflow condition.

3.2.2 Cold Ball Pull (CBP) and Ball Shear (BS) Test

For the past few years, cold ball pull was found to be a more reliable outgoing metrology to gauge solder joint performance especially for leadfree products. Advantages of CBP were found to be 2 folds: 1. CBP test produces more IMC brittle failures which is more stringent to differentiate the performance of different elements within the lead-free solder ball alloy and the solder pad; 2. CBP brittle failures represent a measurement of joint strength under dynamic load conditions and it correlates to drop test results.

In this study, both cold ball pull and ball shear test were carried out using Dage 4000 system for each study condition. Details of the CBP test and ball shear parameters are displayed in Table 2 and Table 3 respectively.

Table 2. CBP test speed & jaw size used

	Parameter
CBP Speed	5mm/sec
Jaw Size	0.76mm

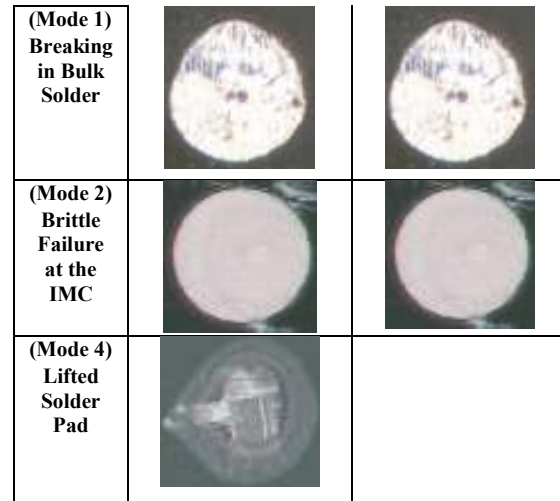
Table 3. Ball shear test parameters & shear tool used

	Parameter
Land speed	300um/sec
Test height	40 um
Test speed	300 um/s
Threshold/test load	1000 g
Over travel	100 um
Fall back	10%
Shear Tool Face Width	650um

Sample size for ball pull and ball shear test is 10 units. For each unit, 8 outer corner balls were tested per sample with 2 balls at each corner of the sample. The corner balls were perceived to have the weakest joints strength as they have the longest distance from the package center point. The common possible failure modes are listed in Table 4.

Table 4. CBP & ball shear test failure modes

CBP	Ball Shear
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3.2.3 Cross Section and Etching

Samples were mounted in cups using resin and left to harden overnight at room temperature. Then, the samples were cross-sectioned and polished to study the solder/alloy interfaces after resin had hardened. The microstructure observation can be well observed under Olympus BH3-MJL Microscope. For some samples, the solders were chemically etched by 100% of hydrochloric acid (HCl) for the range between two to five hours. Top-view morphology was then examined by JSM-6390LV scanning electron microscope (SEM).

3.2.3. Tray Drop Test and Packing Drop Test

In this study, two types of package level drop tests were performed. They were tray drop test and packing drop test. The purpose was to assess the solder joint robustness against vibration & impact shock. Tray drop test was done to assess package solder joint integrity during handling in the production floor, while packing drop test is to assess the handling during product shipment and transportation to customers. This was done using center pedestal support trays. Both drop testings were performed to obtain drop till fail data. During drop tests, if there is any broken tray, it will be replaced to prevent tray chips from inducing any ball drop.

Figure 2 illustrates the tray drop test method while Figure 3 illustrates the packing drop test method.

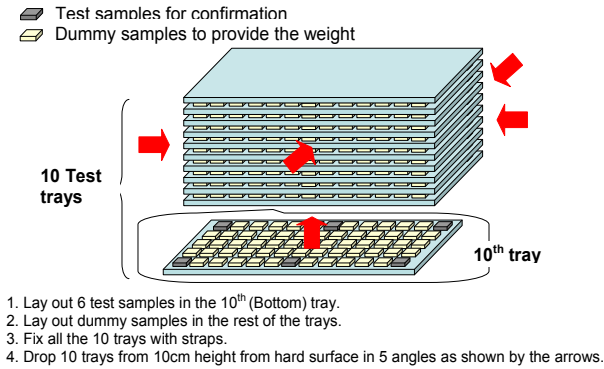


Figure 2. Schematic drawing of tray drop test

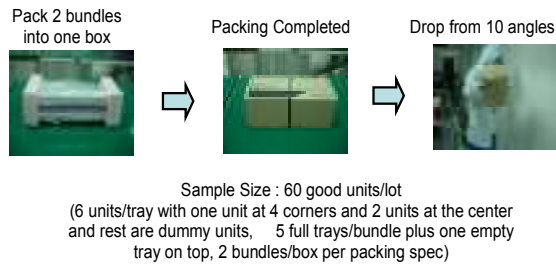


Figure 3. Schematic drawing of packing drop test

4. Results and Discussion

4.1 CBP and Ball Shear Results

Overall ball shear and CBP results are displayed in Figure 4 and Figure 5.

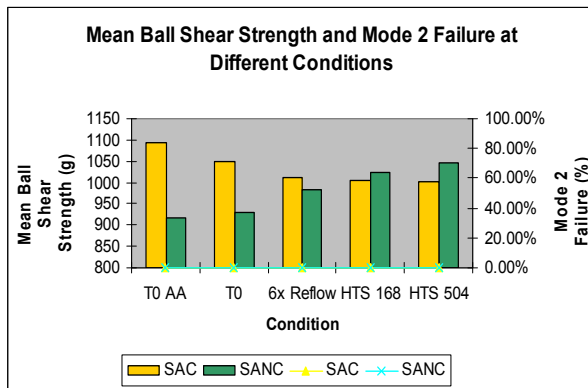


Figure 4. TBGA ball shear result

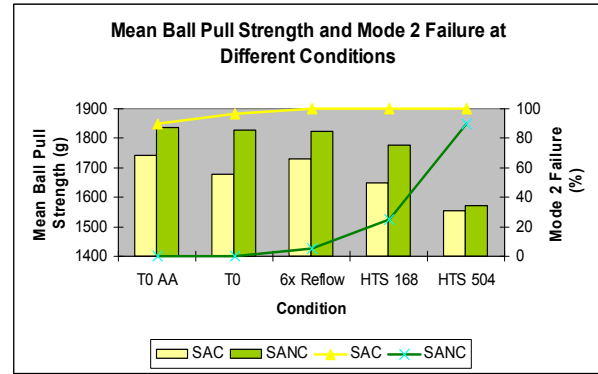


Figure 5. TBGA ball pull result

In ball shear test, only Mode 1 failure observed. It shows ductile failure through the bulk of solder for both alloy systems at all stress conditions. Therefore, ball shear with regular test speed (<1000 um/sec) is not an effective method to detect brittle interfacial failure but to provide information on the yielding behavior of the bulk solder. Ball shear at Time Zero after assembly and after test are lower for SnAgNiCo because the alloy has lower hardness than SAC387. This is a desired characteristic resembling the SnPb solder that enables the alloy to better absorb impact force and prevent ball drop. Ball shear strength for SnAgNiCo increases after thermal aging due to formation of rod shape Ag_3Sn IMC distributed across the solder surface that helps to act as dispersion hardening that increases the mechanical strength for the SnAgNiCo solder after thermal aging.

In CBP test, IMC brittle fracture (Mode 2) and lifted solder pad (Mode 4) are two failure modes that are normally observed. For SAC387 sample, 80~100% of the failures are mode 2 at T0. The mode 2 percentage increases with increased stressing and the pull strength decreases accordingly. In contrast, SnAgNiCo samples show significantly better solder joint robustness with no brittle failure observed at T0 and only 5% after 6x reflow with increasing pull strength compared to SAC387 after prolonged aging conditions. However, mode 2 failure for SnAgNiCo increases with longer storage time especially HTS 504 hours where percentage of mode 2 failure nearly equal to SAC387. This phenomenon is further examined through the study of interfacial microstructure in the following section.

4.2 Cross Sectioning Result

Microstructure analysis was conducted using cross-sectioning to study the intermetallic morphology at different condition. Figure 6 and

Figure 7 display the cross sectioned intermetallic area and thickness after high temperature storage.



Figure 6. Morphology of intermetallic compounds formed at the interfaces for SAC and SnAgNiCo after high temperature storage

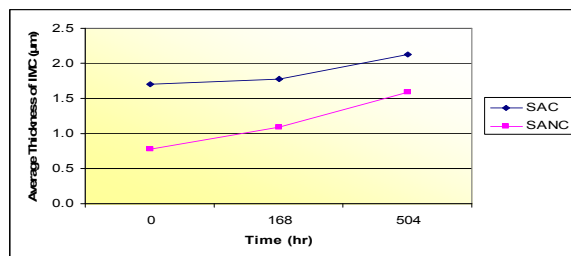


Figure 7. IMC thickness after high temperature storage

Figure 7 shows the increasing of average IMC thickness towards the longer storage time for both SAC387 and SnAgNiCo samples. Nevertheless, the solder joint IMC area for SAC387 is thicker compare to SnAgNiCo. According to Laurila *et al* (2005), thick IMC layer at the solder/metal interface may degrade the reliability of the solder joint due to their inherent brittle nature [11]. Therefore, SnAgNiCo has better solder joint strength but it deteriorates with longer temperature storage.

Figure 6 shows cross section of IMC morphology at different condition taken by optical microscope with magnification x1000. The stages of interfacial phenomena during soldering can refer to the report of Choi *et al* (2002) [10]. From figure 6, SAC387 shows initial separated grains at T0 stage. After storing for 168 hours under 150°C, bi-layer IMC was observed at the interface of solder joint shown at Figure 8. Formation of bi layer IMC can be

explained by Laurila *et al* (2005) [11]. The two layers are $(\text{Cu,Ni})_6\text{Sn}_5$ and $(\text{Ni,Cu})_3\text{Sn}_4$ examined by EPMA. The IMC layer continued to grows for longer storage time.

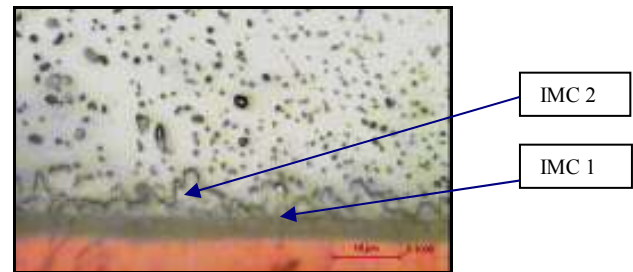


Figure 8. Observation of bi layer at IMC solder joint for SAC unit during HTS 168

For SnAgNiCo sample, small columnar grains observed at T0 stage which later became flatter and thicker after high temperature storage. After storing for 504 hours, it is interesting to find that some columnar structure joins with the columnar IMC at the solder matrix showed in Figure 6 above. Using EPMA, the identified columnar IMC structure at the solder matrix is Sn-Ni-Co with very little amount of Co. This phenomenon increases the brittle IMC layer at the solder joint which can degrade solder joint strength. Meanwhile, only one IMC layer found at the solder joint for SnAgNiCo sample which is Ni_3Sn_4 layer. This is supported by the study of Ho *et al* (2007) [12].

Figure 9, Figure 10 and Figure 11 below show comparison between cross section intermetallic morphology and thickness at T0 and 6x reflow for SAC and SnAgNiCo. After 6x Reflow, there was higher difference of IMC thickness for SAC sample where the IMC peaks have grown. For SnAgNiCo, no significant difference observed in the IMC area and thickness after 6x reflow. This is clearly observed through the IMC thickness showed in Figure 9 & 10. This shows addition of Ni and Co in solder is able to suppress IMC growth after 6x multiple reflow.

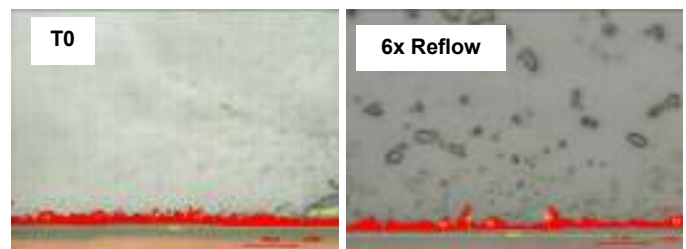


Figure 9. Side view morphology for SAC at T0 and 6x Reflow

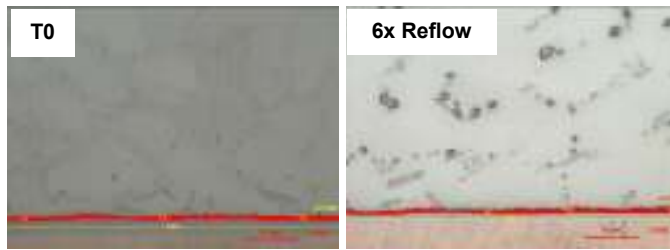


Figure 10. Side view morphology for SnAgNiCo at T0 and 6x Reflow

4.3 Etching and SEM Result

Top view morphology was taken by SEM on the etched samples under different conditions. Figure 12 and Figure 13 displayed the results.

From the SEM pictures, different top view morphologies were observed for SAC and SnAgNiCo samples. Morphology change under different stress condition.

Initially, SAC shows the irregular and needle-like IMC which is similar with the top view images obtained by Xu et al (2006) [13]. They are typically NiCuSn ternary IMC. After aging for 168 hours, it is observed that the growth and coalescence of original IMC needles resulted in lateral thickening and ripening [14].

For SnAgNiCo, the IMC grains consists of Sn-Ni-Co determined by EDX. At HTS 504, the growth of IMC grain size for SnAgNiCo unit becomes more pronounced. In the research of He et al (2004), extremely large Ni_3Sn_4 grains also found in a Sn-3.5Ag/sputtered Ni UBM system after reflowing for 20 min at 251°C. He speculated that the large grains form when a number of neighboring IMC grains happens to possess the same crystallographic orientation. These grains can easily coalesce to form a large grain and may result in similar solder joint strength as SAC387. [15]

Figure 13 shows the top view morphology after 6x reflow. For SAC, the grains show lateral thickening and ripening of needle-like shape after 6x reflow. Meanwhile, general grain size remains the same for SnAgNiCo sample but some rougher and larger grains observed. This is suspected to be the reason that contributes to 5% increment of mode 2 failure after 6x reflow. However, the effect of Ni and Co addition is clearly demonstrated here where overall grain size growth is greatly suppressed.

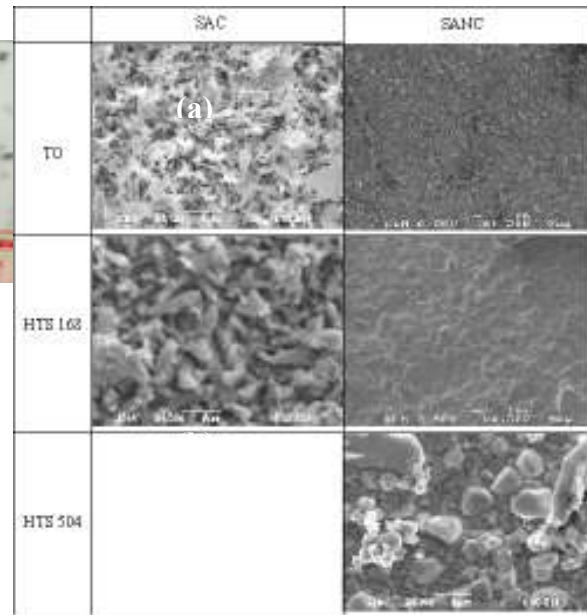


Figure 12. Top morphology at the interfaces for SAC and SnAgNiCo after high temperature storage taking by SEM with magnification x4300

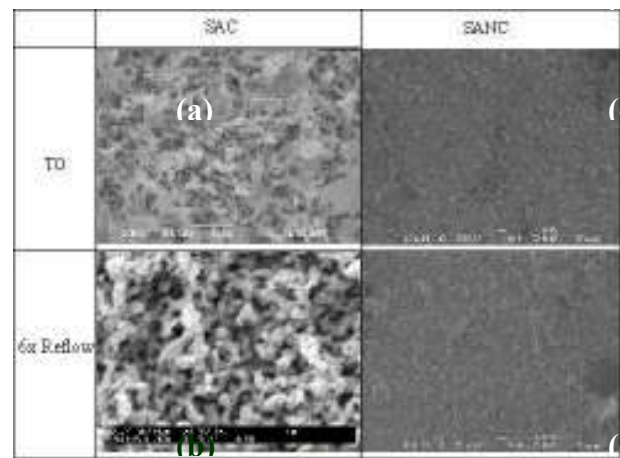


Figure 13. Top morphology at the interfaces for SAC and SnAgNiCo after 6x reflow taking by SEM

4.4 Drop Test result

Two drop tests were carried out to assess the solder joints robustness against vibration & impact shock. They were tray drop test (6 units sample size) & packing drop test (60 units sample size) as illustrated in Figure 2 & Figure 3, respectively. The most stringent package chosen for this test was 740TBGA (37.5x37.5mm) with 1mm ball pitch and 0.68 pad-to-ball ratio. The samples were dropped

through many cycles until dropped ball was found, with maximum 20 cycles tested. After every cycle, the samples were inspected for dropped balls and any broken trays were replaced to prevent dropped balls caused by chips from the trays. The number of cycles was recorded and shown in Table 5 for tray drop test and Table 6 for Packing Drop Test.

Table 5. Tray Drop Test Result

Solder Composition	No of Cycle tested	No of Cycle when ball drop happened	No of units with ball drop	No of balls drop
SnAgNiCo	13	13	1	3
SAC 387	2	2	1	4

Table 6. Packing Drop Test Result

Solder Composition	No of Cycle tested	No of Cycle when ball drop happened	No of units with ball drop	No of balls drop
SnAgNiCo	20	No ball drop seen	0	0
SAC 387	3	3	3	5

From the drop test result, it can be concluded that SnAgNiCo solder system is more robust than SAC 387 against vibration and impact shock.

5. Conclusions

Two kinds of lead-free solders (SAC387 and SnAgNiCo) on same electrolytic Ni/Au plating were studied. The major findings are as follows:

Overall, SnAgNiCo shows better solder joint strength and significantly lower brittle failure rate than SAC387 at time zero, after 6x reflow and after 168hrs HTS. Even though the solder joint strength for SnAgNiCo starts to drop after 504hrs HTS, but it still maintains better solder joint strength compare to SAC387.

After HTS, thickness of IMC layer for both SAC and SnAgNiCo increases. Bi layer IMC structures can be observed on SAC387 sample which consists of $(\text{Cu,Ni})_6\text{Sn}_5$ and $(\text{Ni,Cu})_3\text{Sn}_4$ that will degrade solder joint strength. For SnAgNiCo, only one thin Ni_3Sn_4 IMC was observed. However, at HTS 504, the growth of IMC layer joins with the

IMC phase on solder matrix and causes the sudden large drop of solder joint strength.

After 6x reflow, SnAgNiCo shows not much changes in ball pull strength due to no significant changes in morphology thus enhance solder joint strength.

From the drop test result, it can be concluded that SnAgNiCo solder system is more robust than SAC 387 against vibration and impact shock.

In summary, SnAgNiCo lead-free solder is a potential candidate for lead-free solder joint improvement for overall lead-free package robustness.

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