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RELIABILITY INVESTIGATION of Sn/Cu/Ni SOLDER JOINTS

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ABSTRACT

The electronics manufacturing industry has continued its search for a single alloy that can be utilized throughout the manufacturing line. To date, there is minimum success in the implementation of an alloy across the manufacturing process as compared to the tin lead based processes. The ability to employ one alloy will allow manufacturers to reduce complexity and cost while increasing yield.

The Sn/Cu/Ni alloy (SCN) has been widely used in wave soldering applications due to its applicability in achieving acceptable soldering results for many printed circuit board types. In addition, the SCN alloy is characterized by lower rates of reaction with base materials such as copper and iron [1]; the lack of precious metals makes the SCN alloy less expensive; and, the cosmetics of the final solder joint is similar to that of tin lead. However, the SCN alloy's focus and integration into reflow soldering applications has been hampered by its higher melting point temperature of 227°C. At temperatures required for complete and homogeneous mixing of the paste deposit with the component lead/bump, there are concerns such as possible damage of heat-sensitive components and joint reliability. Before widespread use of the alloy is adopted for surface mount applications, extensive qualification is required [2].

Through a previous study [3], it was shown that typical SAC assembly profiles achieved satisfactory SCN solder joints, and the vibration reliability results indicated similar performance of SCN solder joints to SAC305. In this study, the reliability is further quantified through both thermal cycling and further mechanical test. Drop testing was chosen as the mechanical test and a comparison in the solder's performance is made to SAC305 and SAC105.

The results show that, while SCN better matches SAC105 in solder ball strength testing, the performance in board level drop is very similar to SAC305. Thermal cycling results also appear very similar to SAC305.

Key words: Sn/Cu/Ni, Sn/Cu, SCN, Lead Free Solder Paste, Thermal Cycling, Drop Testing

INTRODUCTION

A large fraction of the microelectronics packaging industry has by now made the transition to lead-free soldering. This transition brings about many complications, including changes in the assembly process, material selection and concerns about reliability. The tin-silver-copper (SAC) based family of solder alloys has emerged as the popular lead-free choice for surface mount, while tin-copper-nickel (SCN) alloy is widely used in wave solder applications.

It is desirable to use a single alloy throughout the manufacturing line, which would reduce cost and complexity arising from material compatibility issues. While SCN is a popular alloy for wave solder applications, its use in surface mount has not been well documented. Recent work has shown that, even though the melting temperature of SCN is higher than for SAC, a SAC-based assembly reflow profile can achieve satisfactory SCN solder joints [3].

The objective of this study is to further evaluate the reliability of SCN based electrical interconnects. Thermal cycling was performed to compare SCN to SAC305. The potential use of SCN in portable product applications was examined through the use of drop testing, and the performance is compared to commonly used SAC solder joints.

EXPERIMENTAL

Materials

Two different test vehicles were used in this study. One test vehicle was used exclusively for drop/shock testing and solder joint characterization. The other test vehicle was used in thermal cycling. Three solder alloys were considered, which are described below.

- SAC305: Sn/3% Ag/0.5% Cu
- SAC105: Sn/1% Ag / 0.5% Cu
- SCN: Sn/0.7% Cu /0.05% Ni/Ge

Test Boards

The test board used for drop testing was of a modified JEDEC design [4]. It is a 1mm thick, 2 layer FR4 construction, using a Cu OSP surface finish. The board dimensions are 132 x 77 mm as shown in Figure 1. The pads are non-solder mask defined and have a nominal diameter 14.5 mils. Fifteen component locations were available, although only the four symmetric locations shown in Figure 1 were assembled for testing.

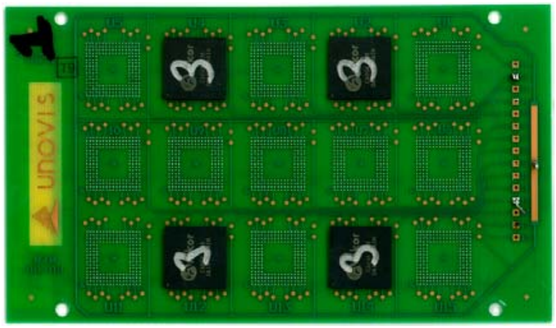


Figure 1. Drop Test Board

The test board used for thermal cycling was a 62 mil thick 4-layer board with Cu OSP surface finish (Figure 2). The board material was TU 722-5 resin with TAIYO PSR-4000 solder mask. The board dimensions were 5.2 by 9 inches. The pads were non-solder mask defined and have a nominal diameter of 16 mils. All sixteen component location were assembled and tested for each board.

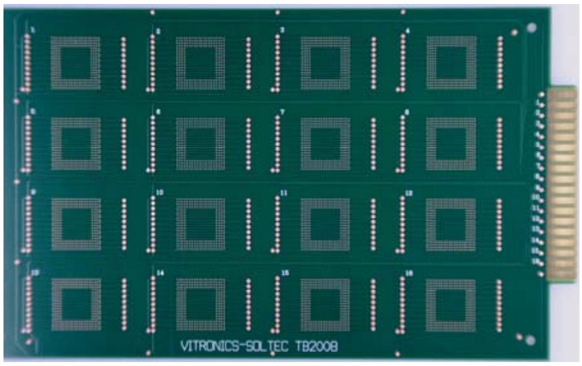


Figure 2. Thermal Cycle Test Board

Components

For drop testing, Amkor CABGA 208 components, using an ENIG surface finish, were supplied without solder balls, as shown in Figure 3. 500-micron (20-mil) diameter solder balls were attached in-house using a tacky flux. Alloys included SAC305, SAC105 and SCN. The peak temperature during solder ball attach was 250 °C.

Figure 3. BGA-CSP Components

Thermal cycling was performed on BGA-CSP components that were fabricated in-house for this application. Each component contained 256 I/O's arranged in a four-row perimeter array as shown in Figure 4. The components were bumped with either SAC 305 or SCN solder spheres using a tacky flux.

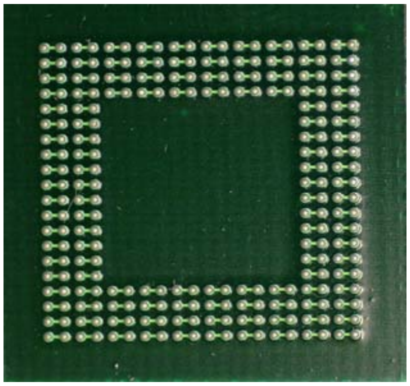


Figure 4. BGA-CSP Components for thermal cycling

Each package was constructed with a 0.5mm (20 mil) thick silicon die sandwiched between two 0.4mm (16 mil) thick FR4 substrates. The die was completely encapsulated by underfill. The components were cured in at 125°C for 1 hour. Solder balls were attached to the base with a peak temperature of 251 °C. The pad metallurgy of the substrates was immersion gold over electrolytic nickel. The layered structure of the components creates a package design which does not warp significantly during reflow and thermal cycling. Figure 5 shows the general schematic of the package design.

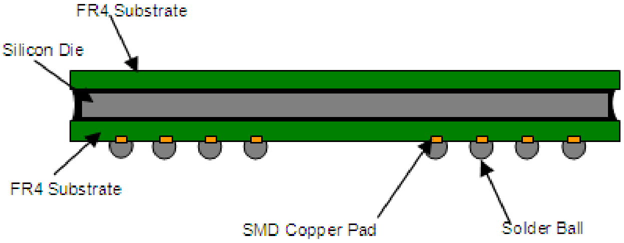


Figure 5. Schematic of the Package

ASSEMBLY PROCESS

A total of 16 drop test boards and 16 thermal cycle test boards were assembled. In drop testing, the alloy was considered as the only variable. SAC305 and SAC105 components were assembled with SAC305 paste, while SCN components were assembled with SCN paste. All drop test vehicles were assembled with a peak temperature of 246 °C and 60s above 217 °C.

For thermal cycling, factors such as reflow temperature, time above 217 °C and alloy were investigated. The DOE for thermal cycling is shown in Table 1.

Table 1. DOE for Thermal Cycling Tests

Factors	Level 1	Level 2	Level 3
Peak Temperature (°C)	238	248	N/A
TAL (above 217°C) (s)	50	75	N/A
TAL (above 227°C) (s)	30	50	N/A
Solder Paste/ Component Sphere	SAC305/ SAC305	SAC305/ SN100C	SN100C/ SN100C

RESULTS AND DISCUSSION

Cross Sectional Analysis

Cross sectional analysis was performed on the SCN/SCN, SAC305/SAC305, and SAC105/SAC305 assemblies used in drop testing. Good solder joint formation and collapse was observed in all cases. Cross-polarized light was used to examine the Sn-grain structures of each alloy. As shown in Figure 6, the grain structure of SAC105 and SAC305 is quite similar with only a few large grains visible. The structure of SCN, however, is a markedly different. There are several grains with irregular boundaries when compared to SAC. It has been shown that Sn-Grain orientations can have a large impact on the mechanical behavior of solder joints due to the anisotropy of the Sn-Grain properties [5].

Ball Shear Test

Portable products may experience high shock loading from mishandling, and the strain rates experienced within the solder joints may be on the order of 100 s^{-1}.Ball shear testing was performed on Amkor CABGA 208 components using both a Dage Series 4000 and 4000HS bond tester. The goal was to determine the solder strength as a function of shear speed, and observe failure mode differences between the alloys.

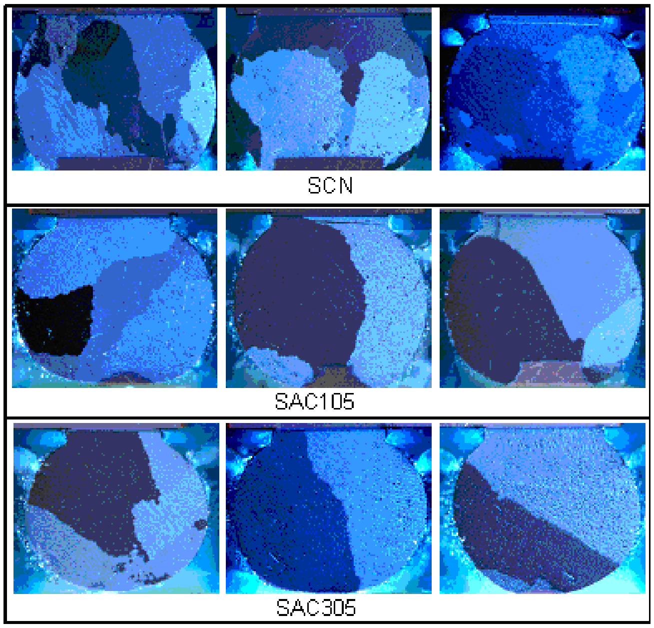


Figure 6. Cross Polarized Images of Solder Joints

Shear test speeds of 0.02 mm/s up to 2 m/s ($2x10^{-5}$ to $2x10^{0}$ m/s) were used. Testing was performed on 12-16 solder balls per condition. The data shown in Figure 7 illustrates that SAC305 is consistently the strongest alloy, followed by SAC105, while SCN is significantly weaker. As the shear speed increases, the strength of all alloys increases. At the highest test speed of 2 m/s, the strength of the three alloys appears to converge. Figure 8 shows the % difference in strength compared to SAC305. As the test speed increases, the difference in strength compared to SAC305 approaches zero.

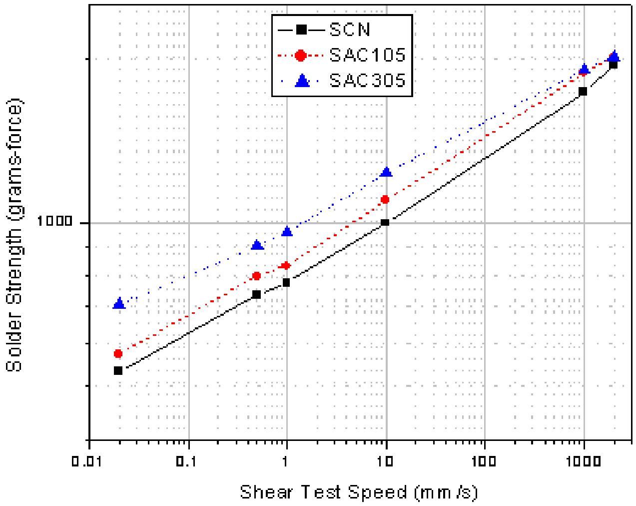


Figure 7. Shear strength as a function of test speed.

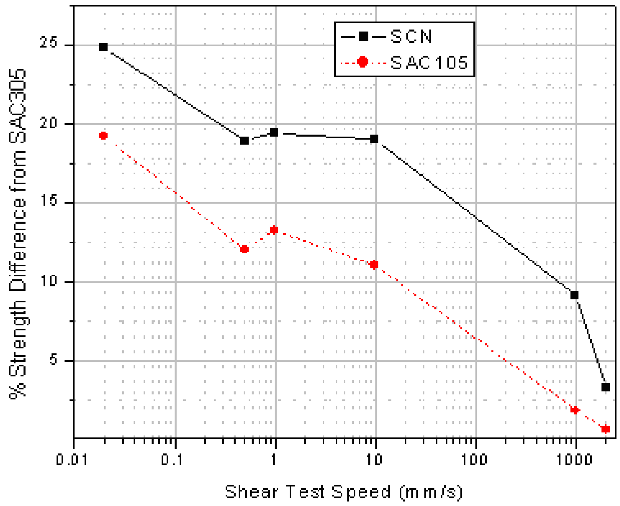
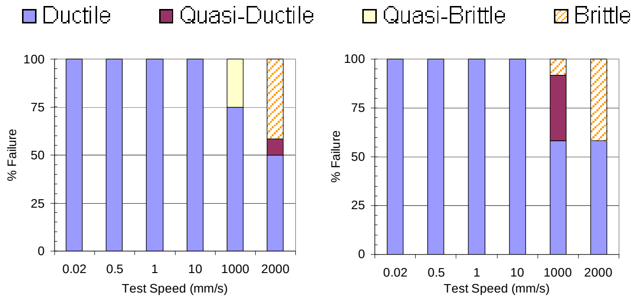
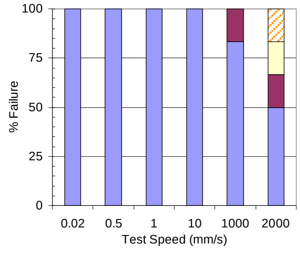


Figure 8. Difference in strength vs. SAC305.

Failure modes in shear test were primarily bulk solder failure. At the higher speeds, namely 1m/s and 2m/s, there were several interfacial (brittle) and mixed failure modes. The data shown in Figures 7 and 8 are for bulk solder failures only. Mixed failure modes were classified as quasi-ductile if greater than 50% of the fracture surface was through the solder, and quasi-brittle if greater than 50% of the fracture surface was through the interfacial or IMC region [6]. The distribution of failure modes is shown in Figure 9. All three alloys display similar trends in failure mode distributions with greater instances of brittle fractures occurring at the higher speeds.



(a) SCN (b) SAC105



(c) SAC305

Figure 9. Distribution of failure modes from Shear Testing.

Drop Test

Drop testing was performed per JEDEC JESD22-B111 [4]. The test boards were attached to the drop table at the four corners, with the components facing downward. A schematic of the setup is shown in Figure 10. The shock input was 1500-G with a 0.5 ms duration, as measured on the shock machine.

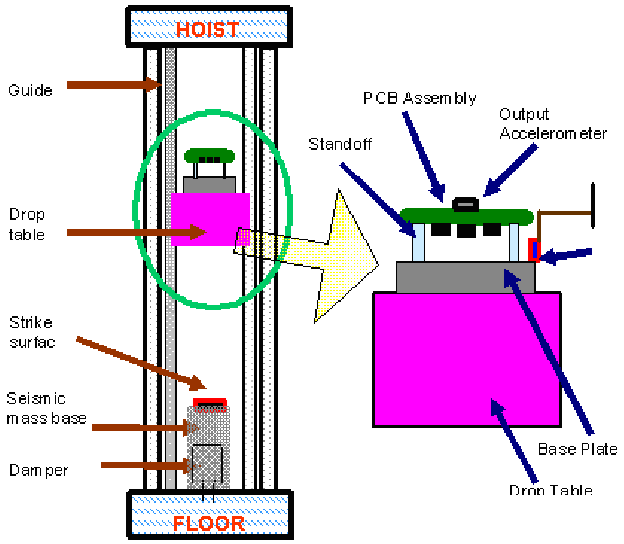
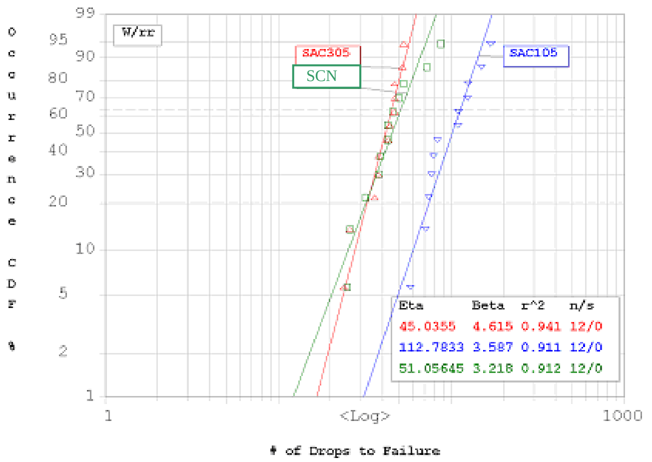


Figure 10. Drop Test Setup.

Each component was connected to an event detector to monitor for electrical failure during the testing. Electrical failure followed the JEDEC definition of “the first event of intermittent discontinuity followed by 3 additional such events during 5 subsequent drops” [4]. Each board was dropped until all components had failed. Failure data is plotted as a 2-parameter Weibull distribution in Figure 11.



Eta	Beta	r^2	n/s
45.0355	4.615	0.941	12/0
112.7833	3.587	0.911	12/0
51.05645	3.218	0.912	12/0

Figure 11. Drop test failure distributions.

Failure analysis was conducted on through the use of dye penetration and cross-sectional analysis. The primary failure location was the outside corner on each BGA, as indicated by the boxed regions in Figure 12. All tested components failed by pad cratering, as shown in Figure 13. Through failure analysis, there were no detected failures due to bulk solder fatigue or interfacial/intermetallic fracture. Therefore, direct comparisons between alloys are more readily made.

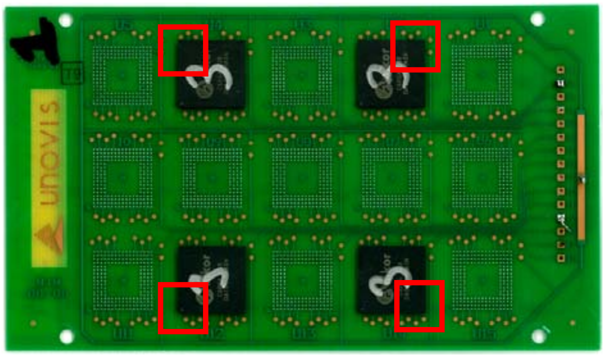


Figure 12. Failure locations on drop test board.

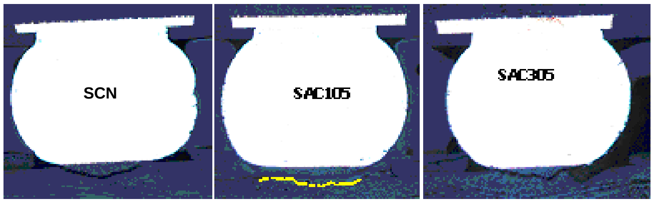


Figure 13. Pad cratering was seen on all samples.

It was has been suggested the increased ductility of lower-Ag alloys is desirable for high strain rate shock loading [7]. The SCN alloy has no Ag content, and therefore one would believe it to have even greater ductility than SAC105, thus making it more appropriate for shock loading. The solder ball strength testing shown in Figures 7-9 does suggest the same. However, strength testing is rarely an indication of the fatigue life of a material, and strength testing alone should not be used to determine how the alloy will perform in drop testing, especially when the failure modes do not correlate. Drop testing induces a cyclical stress at a high strain rate, and as yet we cannot duplicate this loading mode in solder ball testing. We also notice that the grain structure of SCN, shown in Figure 6, is markedly different than for SAC.

The failures observed in drop testing are PCB pad cratering. Here, a more ductile alloy under the given load, should increase the lifetime of this mode. It is likely that, under the given high strain rate cyclical loading, the stress/strain curve of SCN more closely resembles SAC305 than SAC105, even though the strength of the alloy is lower than either of the SAC alloys. Strength alone is not an indication of the stress/strain behavior.

Thermal Cycling

In the previous study [3], reflow processes were developed for the SCN solder paste using SAC305 and SCN bumped BGA-CSP components. The characterization of the assembly was done using cross sectional and SEM analysis, and board level vibration. The objective of the study was to characterize the performance of pure SCN joints to pure SAC 305 solder joint to a mixed SCN/SAC 305 solder joint. This was accomplished by designing reflow soldering profiles that reached the same peak temperatures and time above liquidus (above 217°C) optimized for typical SAC305 assemblies. Thermal cycling was also performed, but testing was not completed for publication.

Thermal cycling was performed with temperature ranges from 0°C to 100°C with a dwell time of 10 minutes and ramp up rate of 10°C/s. The boards were tested until 70% of the components failed. The test results for the three tested alloy combinations are shown in Figures 14-16, and the statistical data is tabulated in Table 2. The data tends to show similar behavior for the various reflow parameters within each alloy combination.

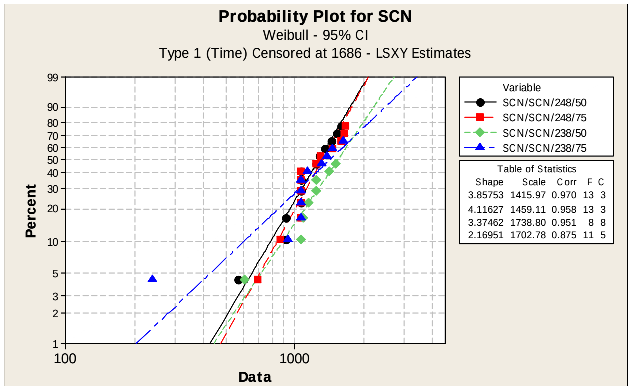


Figure 14. Weibull plot of failures for pure SCN assemblies in 0-100 °C ATC

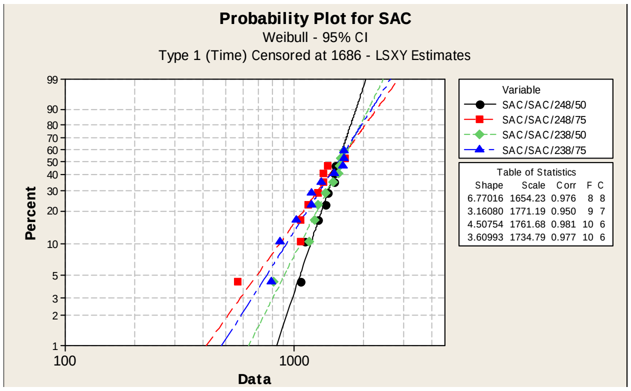


Figure 15. Weibull plot of failures for pure SAC305 assemblies in 0-100 °C ATC.

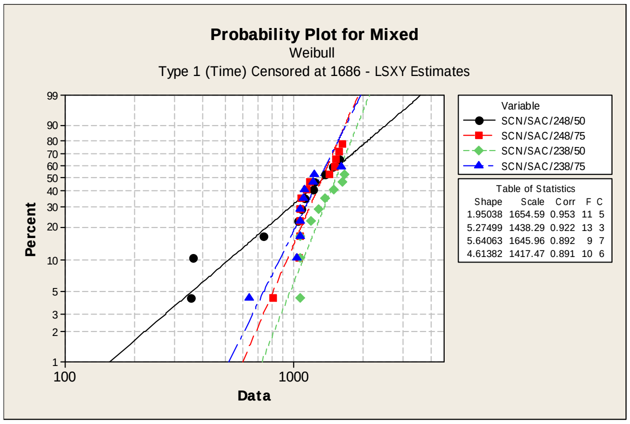


Figure 16. Weibull plot of failures for Mixed SCN/SAC305 assemblies in 0-100 °C ATC.

Table 2. Statistical data for 0-100 °C ATC

Combination	Peak (°C)	TAL (s)	N63	N01
SCN	248	50	1,416	430
SCN	248	75	1,459	477
SCN	238	50	1,739	445
SCN	238	75	1,703	204
SAC	248	50	1,654	839
SAC	248	75	1,771	413
SAC	238	50	1,762	635
SAC	238	75	1,735	485
Mixed	248	50	1,655	156
Mixed	248	75	1,438	601
Mixed	238	50	1,646	728
Mixed	238	75	1,417	523
SCN-N2	248	50	1,279	584
SCN-N2	248	75	1,465	378
SCN-N2	238	50	1,526	557
SCN-N2	238	75	1,537	827

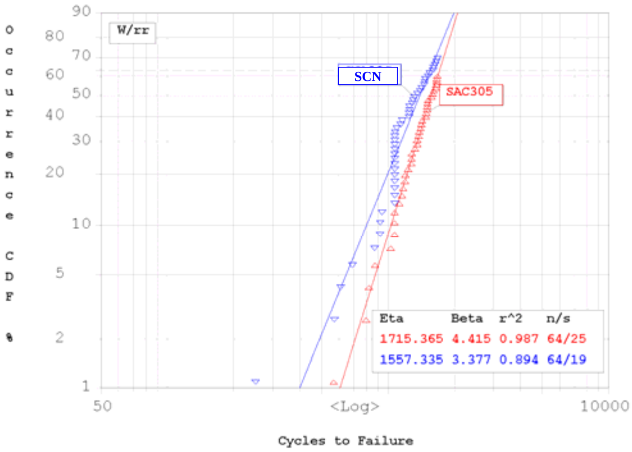


Figure 17. Weibull Plot of failures for all pure SCN and pure SAC305 assemblies in 0-100 °C Thermal Cycling

From the previous study [3], and results of this study, it was determined that the reflow temperature and TAL were not critical factors. Instead, the alloy and paste combination was determined to be most critical. Combined data for pure SCN and pure SAC305 systems is shown in Figure 17. From the data it can be observed that SCN joints had a similar behavior as SAC305 joints in 0-100 °C thermal cycling. The difference in N_{63} lifetime was only about 10%. These results tend to agree with literature data which found that SCN and SAC were found to be similar in -40 °C to 125 °C with 15 minutes cycles [2].

CONCLUSIONS

As a continuation to a previous study, the reliability of tin-copper-nickel solder alloy in surface-mount assemblies was examined. The results were compared to typical SAC based assemblies.

- Both studies showed that SCN solder paste can be reflowed using SAC profiles. Peak temperatures of 238^0C and TAL (227^oC) of 30 seconds are sufficient to obtain good solder joint formation.
- The appearance of SCN solder joints is similar to SAC joints.
- Ball shear testing showed that SCN solder joints are generally weaker than SAC305 and SAC105 joints, but at the highest test speeds the differences are negligible.
- Drop testing results showed that SCN assemblies were very similar to SAC305, however reliability of each was less than SAC105.
- Thermal cycling showed that SCN assemblies were very similar to SAC305.

The mechanical testing indicates that solder strength alone cannot indicate the reliability in a repeated high strain rate shock environment. Because the SCN alloy has a markedly different Sn-grain structure, the actual mechanical behavior and stress/strain relationships are also likely to be different from SAC based systems.

SCN alloy appears to be well suited to use in surface mount applications with minimal adjustments being necessary to the assembly process. Reliability can be expected to be similar to SAC305,

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