

Effect of temperature cycling parameters on the durability of Pb-free solders

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Solder joints provide critical electrical and mechanical connections in the electronic assemblies. To assure reliability of electronic hardware, it is important to understand the reliability of solder joints under use conditions. The conversion to RoHS-compliant materials has raised concerns about the reliability of lead-free solders used in electronic products. One of the primary mechanisms of solder joint failure is fatigue due to fluctuations in temperature resulting from operational and environmental conditions. Fatigue of solder arises from cyclic strain within the solder joint due to different rates of temperature expansion in the solder and interconnected structures.

To address the solder joint reliability concern of lead-free solder, a systematic set of experiments was conducted to examine the impact of dwell time and mean temperature on solder joint reliability. SAC305, SN100C, and SnPbAg solders were tested and compared with prior test results. The results indicated that lowering the mean cyclic temperature increased the thermal cycling durability of the solders dramatically. Results on the impact of cyclic mean temperature and dwell time revealed that dwell had a larger effect when the mean cyclic temperature was lower. Extended low temperature dwell for a temperature cycle of -25°C to 75°C was found to be more damaging than expected, particularly for SnPbAg. For a maximum temperature of 125°C, a dwell-time increase from 15 to 75 minutes did not have much effect. Results indicated that SAC305 was slightly less durable than SAC379 but was more reliable than SN100C and SnPbAg solders. SnPbAg was less durable than SnPb solder.

Introduction

The life expectancy of electronic hardware depends on the failure mechanisms that arise from the materials and technologies used in their construction as well as the operational and environmental conditions to which the hardware is subjected. With the transition from Pb-based solder to Pb-free solders, the life expectancy of solder has received renewed interest. Temperature cycle-induced fatigue is a major solder joint failure mechanism. Solder joint fatigue occurs due to inelastic deformation in solder induced by temperature changes and differences in temperature expansion between solder, component, and board. For qualification, electronics are subjected to standard temperature profiles [1,2]. Tin lead solder has been very well characterized based on the models and industry experience. Thus the reliability of electronic hardware using tin lead solder has been determined in terms of the number of standard temperature cycles it can survive. For lead-free solders, the models and experience are less mature.

While lead-free solders have been compared with tin-lead solder under standard temperature profiles, there have been fewer reports of lead-free solders being tested under non-standard conditions necessary to develop and verify predictive simulation models. Solder joint fatigue is a highly studied phenomenon that has been explored both experimentally and analytically [3-6]. One concern is the impact of mean cyclic temperature and cycle dwell time on the life expectancy of solder joints. To this end, several researchers [6-15] have conducted studies to analyze the effect of various temperature cycling

parameters. Pang *et al.* [7] in 2001 investigated the effect of temperature range and also proposed scale factors to correlate the high and low temperature changes. Yoon *et al.* and Osterman *et al.* reported on testing of SAC387 and Sn3.5Ag solder assemblies in 2005 [13] and 2006 [14], respectively. They provided experimental data to support the development of simulation models to estimate solder life expectancy under temperature cycling. Aoki *et al.* [12] in 2007 investigated the effect of ramp rate on the thermal cycling reliability of lead free solder joints. Along similar lines, Zhai *et al.* [9] in 2003 compared the effects of dwell time and ramp rate on the thermal cycling reliability of solder joints. They concluded that dwell time has more significant effect on solder joint reliability than the ramp rate. More recently, Bouarroudj *et al.* [15] in 2008 carried out both experimental and finite elements analysis to show the effect of dwell times on SnPb solder fatigue life.

In response to the widespread industry preference for SAC305 solder and the increased interest in SN100C solder, a new set of tests were planned and executed to obtain data for development of a model for solder joint reliability. This paper reports the experimental testing, results, and analysis of data on the effect of temperature cycling parameters on the thermal cycling reliability of solders.

Experiment

The test specimens consisted of two 84 IO Ceramic Leadless Chip Carrier (CLCC) and two 68 IO CLCC parts mounted on a 2.3 mm thick high temperature FR4 board. The pad finish on each of the

FR4 boards was organic solder preservative (OSP). The overall dimensions for each board were 130 mm × 93 mm. The 84 IO CLCCs were 30 mm × 30 mm, and the 68 IO CLCCs were 24 mm × 24 mm in size. The CLCC parts had adjacent corner terminals internally connected with wire bonds. The test specimens were assembled in a conventional surface mount reflow process. The solder pastes used in this study are listed in Table 1. Figure 1 depicts a representative test specimen.

Table 1 Solder Designations and Manufacturers

Designation	Paste Manufacture/Composition
SAC305	Indium SMQ92J Sn61.5/Pb 36.5/Ag2
SN100C	Aim Sn96.5Ag3.0Cu0.5 w/254 flux
SnPbAg	Aim Sn96.5Ag3.0Cu0.5 w/254 flux



Figure 1 Test specimen

Each assembled component formed an independent resistance net with metallization on the printed wiring board. The resistance net included the board traces to corner pads, which were completed internal to the CLCC part with wires connecting the corner terminals.

Test Protocol

In order to determine solder fatigue behavior, a systematic set of tests were conducted. For each test, eight test specimens per solder type were placed into a temperature chamber. During each test, the electrical resistance of each component resistance net was monitored using an Agilent 34970A data logger. Failure of the solder interconnects between the board metallization and component was expected to result in a measurable increase in electrical resistance. Due to the nature of solder interconnect failures, resistance changes were expected to be intermittent in nature, moving to a permanent open over time due to oxide formation and wear at the separated solder interfaces. For these tests, the failure criteria followed IPC-SM-785 standard [1], which defines failure as the first occurrence of a large resistance excursion (>300 ohms)

in a minimum set of ten consecutive resistance excursions in ten consecutive temperature cycles. All tests were conducted to 100 percent failure. Table 2 summarizes the test matrix.

Table 2 Test Matrix

Test	Min. Temp. (°C)	Max. Temp.(°C)	Dwell at Min. Temp. (min)	Dwell at Max. Temp. (min)
1	25	125	15	15
2	-25	75	15	15
3	-25	75	15	75
4	-25	75	15	120
5	25	125	15	75
6	-25	75	75	15
7	-50	50	15	15
8	0	100	15	15

Results

Upon completing each test, the cycles to failure were determined from the data logs and the source of failure was determined. In each case, failure analysis revealed that cracks in the solder interconnections resulted in increased electrical resistance. In some cases, parts fell off the boards when being removed from the test chamber. In other cases, low magnification optical examination was found to be sufficient to identify solder cracks. Figure 2 shows an optical microscope view of multiple fillets of a failed 68 IO package attached with SAC305 solder.

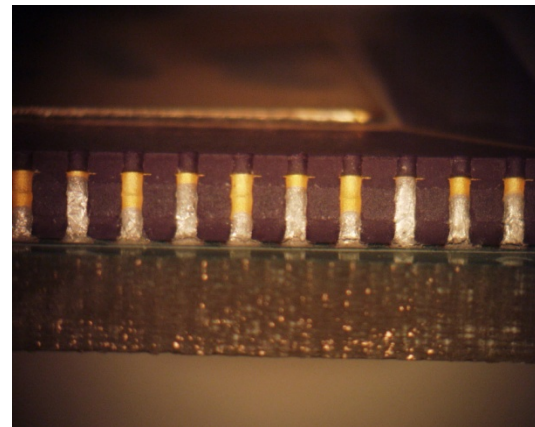


Figure 2 Optical image of cracked SAC305 solder interconnects

For further analysis, select failed test components were subjected to metallographic evaluation. Optical inspection of cross-sectioned joints confirmed complete

solder separation with cracks that ran under the component out to the outer edge of the solder fillet. Figure 3 provides a cross-sectional view of a failed SAC305 solder joint. Close inspection revealed the cracks were in the bulk solder.

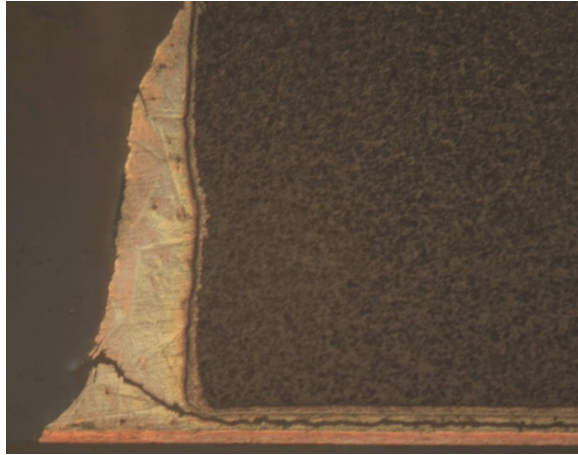


Figure 3 Cross-section of solder crack in SAC305 solder joint

Cycles to failure data were analyzed using a two-parameter Weibull distribution. A plot of cycles to failure for the 15 minute dwell, -25°C to 75°C test is presented in Figure 4.

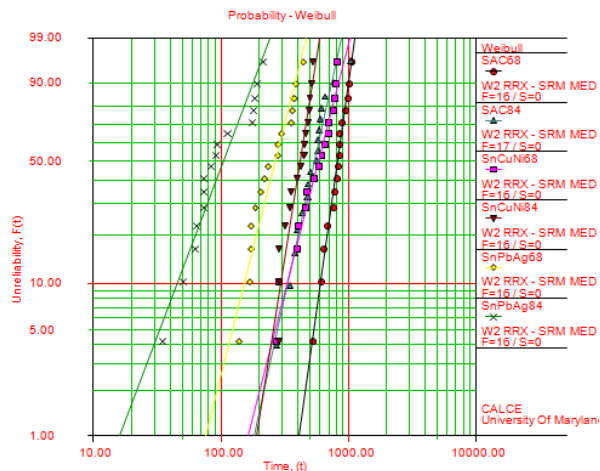


Figure 4 –Probability Plot Weibull Plot of Cycles to Failure for 25°C to 75°C (15 min dwell) Test

For all of the tests, the characteristic life of SAC305 solder interconnects was determined to be higher than both tin-lead-silver (SnPbAg), and SN100C solder. For all solders, the cyclic mean temperature was found to have a strong influence on cycles to failure. With the exception of SnPbAg, increasing the cyclic mean temperature was found to reduce cycles to failure. For tin-lead-silver, the characteristic life under 0°C to

100°C (15 minute dwell) was found to be less than that under 25°C to 125°C (15 minute dwell). The bar chart in Figure 5 shows the effect of cyclic mean temperature on the characteristic life of 68 IO packages normalized to the SAC305 with a cyclic mean temperature of 75°C.

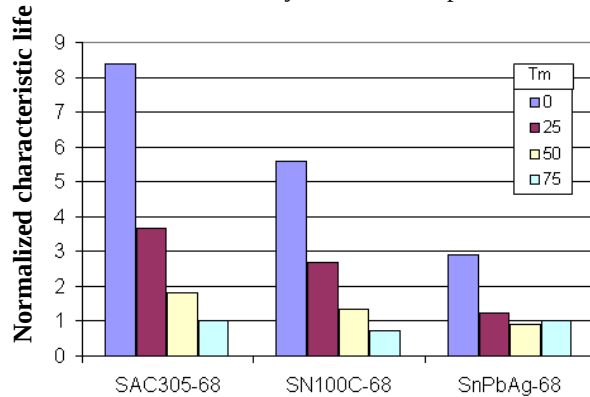


Figure 5 Mean temperature effect on characteristic lives of solders

Figure 6 presents the characteristic life for 68 IO packages under -25°C to 75°C and 25°C to 125°C temperature cycles with T_{max} dwells of 15 and 75 minutes, normalized to the tin-lead-silver under 25°C to 125°C with a T_{max} 15 minute dwell. By examining the impact of dwell time on cycles to failure, it was observed that the influence of dwell was reduced as the cyclic mean temperature increased for both SAC305 and SN100C. A similar finding was obtained for SAC387, Sn3.5Ag, and eutectic tin-lead (SnPb) in a prior study [14].

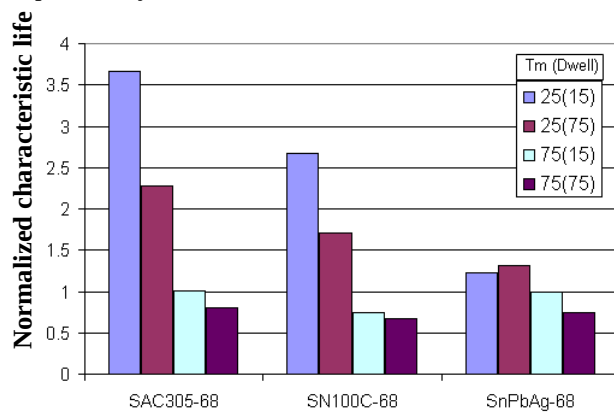


Figure 6 Dwell and mean temperature effect on characteristic lives of solders

Using test data for eutectic tin-lead (SnPb) reported in a prior study [14], the performance of SnPbAg can be compared with eutectic tin-lead (SnPb). Figure 7 provides the characteristic life for tin-lead (SnPb) and tin-lead-silver (SnPbAg) with mean cyclic temperatures of 25°C and 75°C and 15 and 75 minute dwells,

normalized to tin-lead data at 75°C cyclic mean and 15 minute dwell. Under the examined test conditions, SnPb was found to be more reliable than SnPbAg. When compared with the SnPb test results, the lower characteristic life under -25°C to 75°C (15 minute dwell) condition compared to -25°C to 75°C (75 minute dwell) condition appears to be an anomaly, and further testing should be considered to resolve this issue.

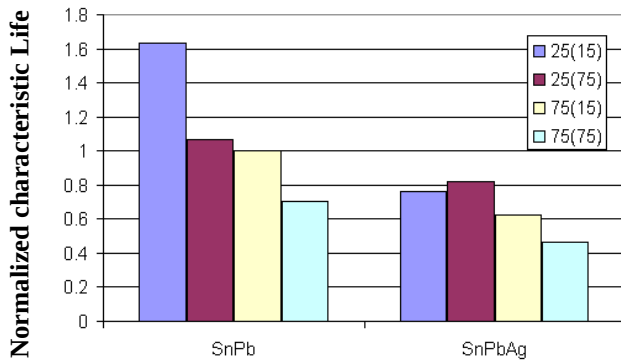


Figure 7 Comparison of characteristic lives of SnPb and SnPbAg solders

In addition to examining the impact of extended high temperature dwell, the effect of extended low temperature dwell was examined for the -25°C to 75°C test condition. Figure 8 depicts the difference in characteristic life due to extended 75 minute dwells at the low or high temperature normalized to SnPbAg with 15 minute dwell at both the low and high temperatures. From this plot, it can be observed that a low temperature extended dwell is nearly as damaging as high temperature dwells for SAC305 and SN100C. For SnPbAg, the low temperature dwell was found to be more damaging than the high temperature dwell.

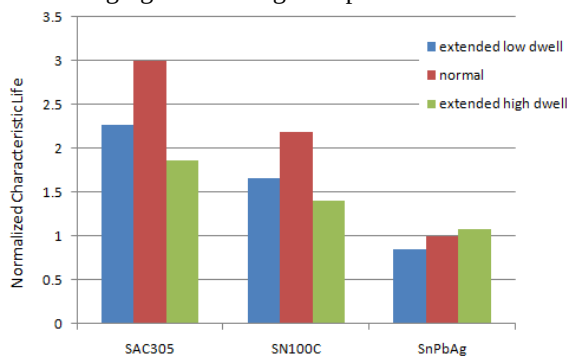


Figure 8 Low temperature and high temperature 75 minute dwell at -25 to 75°C

Using previously reported data for Sn3.9Ag0.7Cu (SAC397) [14], SAC305 was found to be less reliable than SAC397 under the tested conditions. Figure 13 compares the characteristic lives for the 68 IO package

with cyclic mean temperatures of 25°C and 75°C and T_{max} dwell times of 15 and 75 minutes, normalized to SAC397 under a 75°C cyclic mean temperature and a 15 minute dwell.

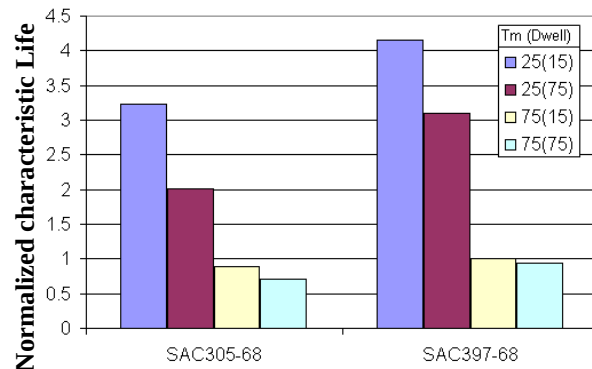


Figure 9 Comparison of characteristic lives of SAC305 and SAC397 solder

Figure 10 depicts the impact of extending high temperature dwell on a -25°C to 75°C temperature cycle from 15 minutes to 120 minutes. From this data, it was observed that extending the dwell from 75 minutes to 120 minutes for SAC305 results in only a slight reduction in characteristic life (6.6%) compared to a 37 % reduction that occurs by shifting from a high temperature dwell of 15 minutes to 75 minutes. For SN100C, the shift from a 15 minute to 75 minute dwell at the high temperature resulted in a 36% reduction in characteristic life. A shift from 75 minutes to 120 minutes resulted in a 14% reduction in characteristic life.

For SnPbAg, the impact of extended dwell was found to be negligible. It should be noted that for eutectic SnPb solder the impact of extending the dwell from 15 minutes to 75 minutes at the high temperature in the same -25°C to 75°C temperature cycle range resulted in a 35% reduction in characteristic life.

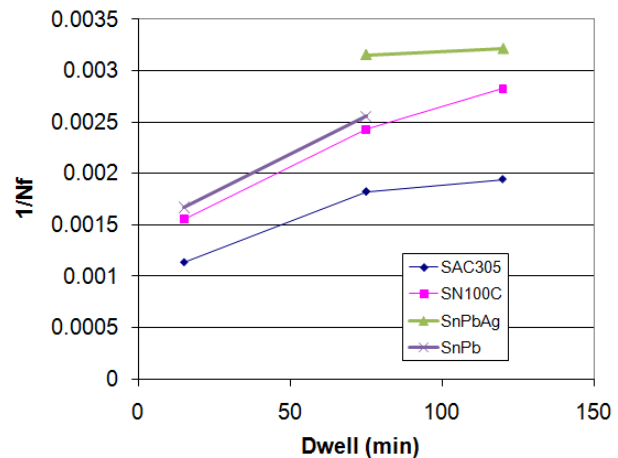


Figure 10 Impact of dwell on solder fatigue life (-25°C to 75°C)

The logarithm of the reciprocal of the characteristic life versus the dwell time for the -25°C to 75°C temperature cycle tests is presented in Figure 11. The regression fit of the plot indicates that the characteristic life is related to dwell through a logarithm function. This result indicates a diminishing effect as test dwell time is increased.

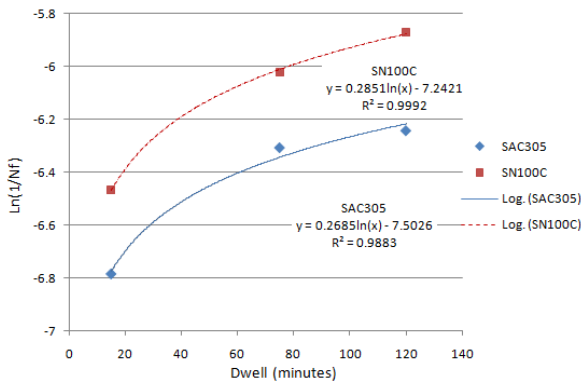


Figure 11 Dwell effect (-25°C to 75°C) on characteristic lives of solders

A plot of the reciprocal of characteristic life as a function of medium temperature with at fixed delta T of 100°C and dwell time of 15 minutes is depicted in Figure 12. Examining the impact of medium cycle temperature on the reciprocal of the characteristic life indicates that both SAC305 and SN100C correlate to a power law function. For the SnPbAg, which is not plotted here, the correlation does not hold.

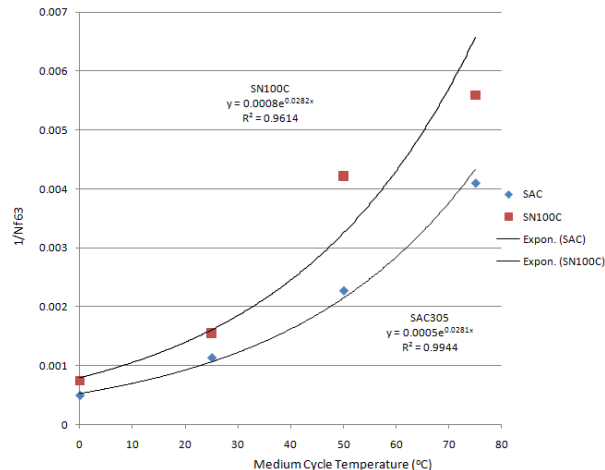


Figure 12 Medium Temperature Effect ($\Delta T=100$, dwell = 15 minutes)

Conclusions

This paper reports the effects of temperature cycling parameters on the solder interconnect fatigue reliability of lead-free solder joints. It was found that lowering the mean cyclic temperature increased the fatigue life of

SAC305 and SN100C. Leadless solder joints created with SN100C were found to have lower temperature cycling reliability than leadless solder joints created with SAC305 solder. Leadless tin-lead-silver solder joints were found to be less reliable than SAC305 solder under the tested conditions. SAC 305 solder was found to be slightly less durable than SAC379, whereas SnPbAg solder was observed to be slightly less durable than SnPb.

The tests revealed that extended low temperature dwell for the temperature cycle range of -25°C to 75°C was more damaging than expected, particularly for SnPbAg. For a maximum temperature of 125°C, a dwell time increase from 15 to 75 minutes was found to have little effect on the tested solders. The impact of dwell was found to be more significant when the median cyclic temperature shifted from 75°C to 25°C. Extending the dwell from 15 minutes to 120 minutes did not result in SAC305 having a lower durability than SnPbAg. Test data also supported the finding that dwell has a logarithmic response to dwell time.

Acknowledgements

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