JCAA/JG-PP No-Lead Solder Project: -55ºC to +125ºC Thermal Cycle Testing Final Report for the CSP, Hybrid & SMT Resistor/Capacitor Components

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Abstract

The use of conventional tin-lead (Sn/Pb) solder in circuit board manufacturing is under ever-increasing political scrutiny due to environmental issues and new regulations concerning lead, such as the Waste Electrical and Electronic Equipment (WEEE) and the Restriction on Hazardous Substances (RoHS) Directives in Europe. In response to this, global commercial electronic manufacturers are initiating efforts to transition to lead-free assembly. Lead-free (Pbfree) materials may find their way into the inventory of aerospace and defense assembly processes under government acquisition reform initiatives. Any potential banning of lead compounds could reduce the supplier base and adversely affect the readiness of missions led by National Aeronautical Space Agency (NASA) and the Department of Defense (DoD). The Joint Council on Aging Aircraft (JCAA)/ Joint Group on Pollution Prevention (JG-PP) Pbfree Solder Project, a partnership between DoD, NASA and OEMs, was created to examine the reliability of component solder joints using various Pbfree solders when exposed to harsh environments representative of NASA and DoD operational conditions. This paper documents final results of the JCAA/JG-PP consortia -55ºC to +125ºC thermal cycle testing. The goal of testing was to generate reliability data for test boards that are representative of IPC Class III High Performance Electronic Products.

Background

The JCAA/JG-PP Consortium was the first industry group to test the reliability of Pbfree solder joints against the requirements of the aerospace/military community. The initial round of JCAA/JGPP testing with the primary test vehicle was completed in July of 2006 [1]. The -55C to +125C thermal cycle testing was conducted by Rockwell Collins Inc. for the JCAA/JG-PP No-Lead Solder Project. This report documents an additional -55C to +125C thermal cycle testing set for CSP/Hybrid components not included on the initial (e.g. primary) test vehicle.

The solder alloys included in the test were:

Sn3.9Ag0.6Cu (SAC) for reflow and wave soldering
Sn3.4Ag1.0Cu3.3Bi (SACB) for reflow soldering
Sn0.7Cu0.05Ni (SNIC) for wave soldering
Sn37Pb (SnPb) for reflow and wave soldering

Test vehicles were assembled using these solders and a variety of component types. Thermal cycle testing was then conducted on the test vehicles using a -55ºC to +125ºC temperature range in accordance with the IPC-9701 specification.

Objective

The objective of the study was to compare the solder joint integrity of selected Pbfree solder alloys to Sn63/Pb37 solder alloys for a -55ºC to +125ºC temperature range.

Procedures

Test vehicle

Figure 1 illustrates the secondary test vehicle used in the thermal cycle testing; it was 14.5 inches wide by 9 inches high by 0.090 inches thick and contained 6 layers of 0.5 ounce copper. The test vehicle was designed to meet IPC-6012, Class 3, Type 3 requirements. The laminate was FR4 per IPC-4101/26 with a minimum Tg of 170ºC with an immersion silver surface finish. This laminate was selected to represent “Manufactured” printed wiring assemblies that were designed for use in Pbfree soldering processes. The secondary test vehicle was procured due to a number of CSP/Hybrid pad design problems on the primary test vehicle. The secondary test vehicle is identical to the primary test vehicle except for the component types tested. Figure 2 shows the primary test vehicle for comparison purposes.

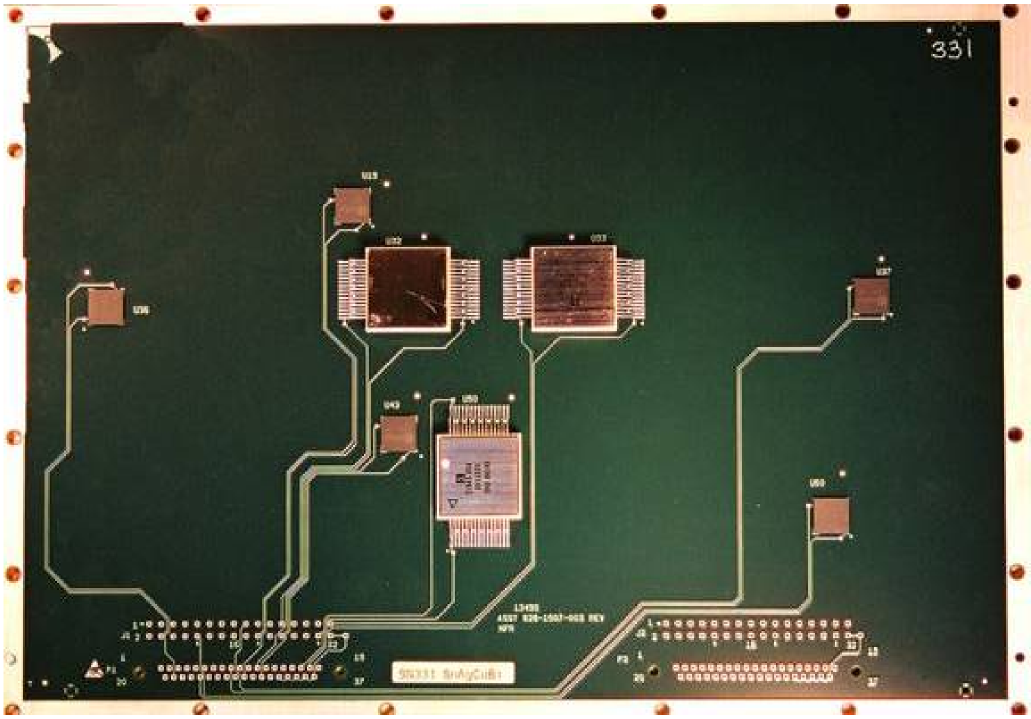

Figure 1 Secondary test vehicle design

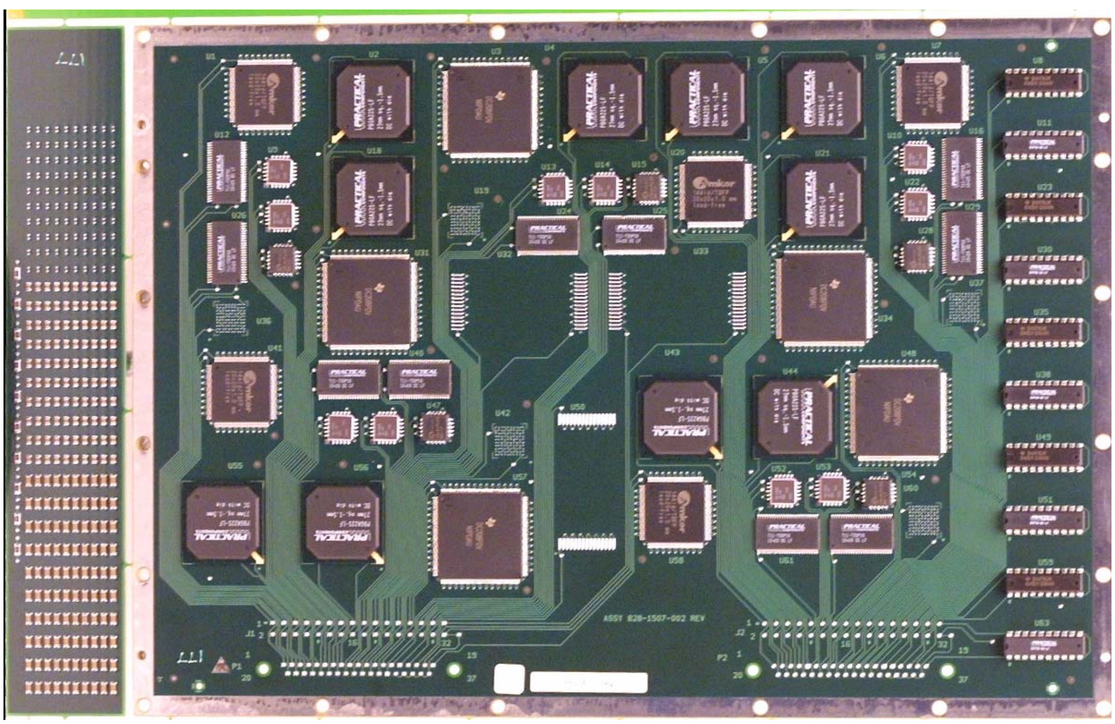

Figure 2 Primary test vehicle

Test Components

Two components were included on the test vehicle. A chip scale package (CSP) was selected because it is representative of the newest types of component technologies currently found in printed wiring assembly production. The specific CSP solderball solder alloy used in the investigation was SAC405. A hybrid component was selected because it was representative of the oldest component types found in printed wiring assembly production, most notably on Class III High Performance legacy electronic products. The hybrid components were subjected to a pretinning operation using the three primary solder alloys (e.g. SnPb, SAC, SACB) so that the hybrid surface finish and solder alloy were matched. The hybrid components were recessed and staked in the test vehicles in accordance with standard mounting practices. Table 1 lists the component types and their surface finishes. The surface mount chip capacitors and resistors on the primary test vehicle break-away edge coupon (which were not tested in the primary test vehicle thermal cycle conditioning) were tested with the secondary test vehicle.

Component Type	Component Finish
Hybrid	SnPb
	SAC
	SACB
CSP	SnPb
	SnAgCu
0402 Capacitors	Sn
0805 Capacitors	Sn
1206 Capacitors	Sn
1206 Resistor	Sn

Table 1 Component types and finishes

Test Vehicle Assembly

The 30 secondary test vehicles were assembled at the BAE Systems Irving Texas facility. A detailed description of the specific tin/lead and Pbfree soldering processes was presented in an earlier publication [2]. The solder joint quality of all test vehicles was confirmed with X-ray inspection and visual inspection in accordance with the IPC-JSTD-001/IPC-A-610 specifications.

Thermal Cycle Parameters and Methodology

The temperature cycle range used in the investigation was -55ºC to +125ºC with a 30 minute dwell at the high temperature extreme and a 10 minute dwell at the low temperature extreme. A maximum temperature ramp of 10°C/minute was used in the testing. The continuity of the components was continuously monitored throughout thermal cycle testing by an event detector in accordance with the IPC-9701 specification, with each component treated as a single resistance channel. An 'event' was recorded if the resistance of a channel exceeded 300 Ω for more than 0.2 μsec. A failure was defined when a component either:

- Recorded an event for 15 consecutive cycles,
- Had five consecutive detection events within 10% of current life of test, or
- Became electrically open.

Once a solder joint was designated a failure, the event detection system software excluded it from the remainder of the test. Detailed temperature profiling was conducted prior to the beginning of the thermal cycle conditioning to insure that each test vehicle was subjected to uniform, consistent exposure to the test chamber temperatures. In the Rockwell Collins consortia testing effort, a total of 15 secondary test vehicles were placed in the chamber. Figure 3 illustrates the thermal cycle temperature profile for the -55ºC to +125ºC testing and the resulting measured test vehicle temperatures with a time lag due to thermal inertia. Note that the 30 and 10 minute dwell durations at the temperature extremes were the durations experienced by the test vehicles. The programmed chamber dwell durations had to be longer to account for the thermal inertia.

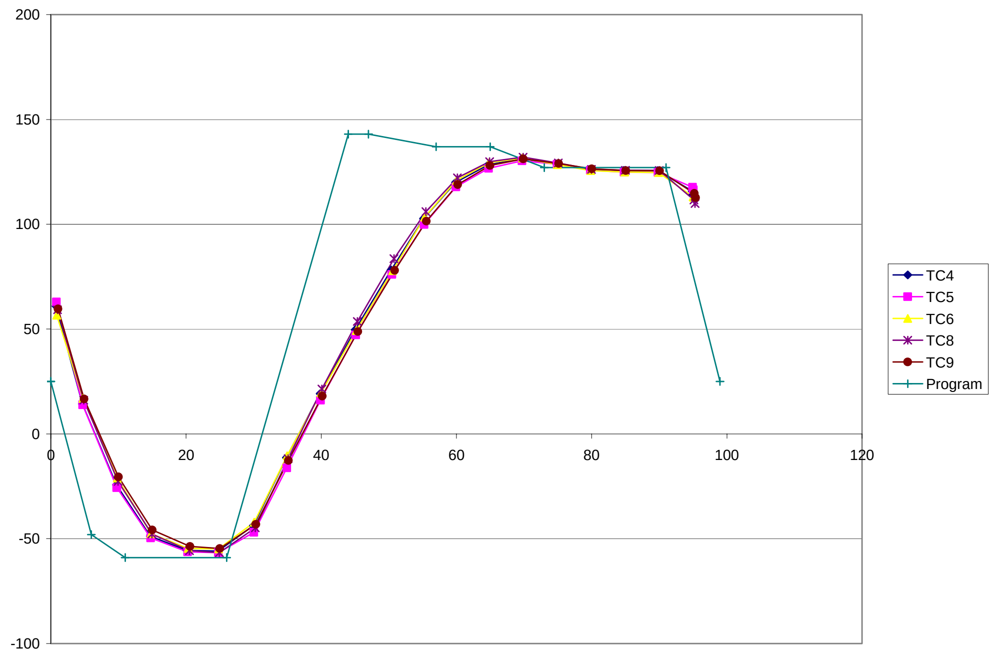

Figure 3 Thermal cycle profile for the -55ºC to +125ºC conditioning CSP/Hybrid Test Vehicle

Test Results – Statistical Analysis

The test vehicles completed a total of 4698 thermal cycles during the 12 month test duration. Table 2 lists the final component population failure rates after completing 4698 thermal cycles. A statistical analysis for each component type was completed with the following sections summarizing the results for each specific component style. It should be noted that the capacitors were not continuity tested

Component Type	Total Failures	Total Population	Percent Failed
Hybrid	4	45	8.8
CSP	74	74	100
SMT Resistor	107	170	63
SMT Capacitor	NA	NA	NA

Table 2 Component population failure rates after 4698 thermal cycles

Chip Scale Package (CSP) Results

The CSP components failed 100% (74 of 74) of the total test population within 2000 thermal cycles. The SnPb solder alloy had better overall solder joint integrity performance than either the SAC or SACB solder alloys with respect to the first failure and failure rate (Weibull slope). The SAC and SACB solder alloys had equivalent solder joint integrity performance. Figure 4 illustrates the CSP Weibull data and Table 3 lists the two parameter Weibull characteristics.

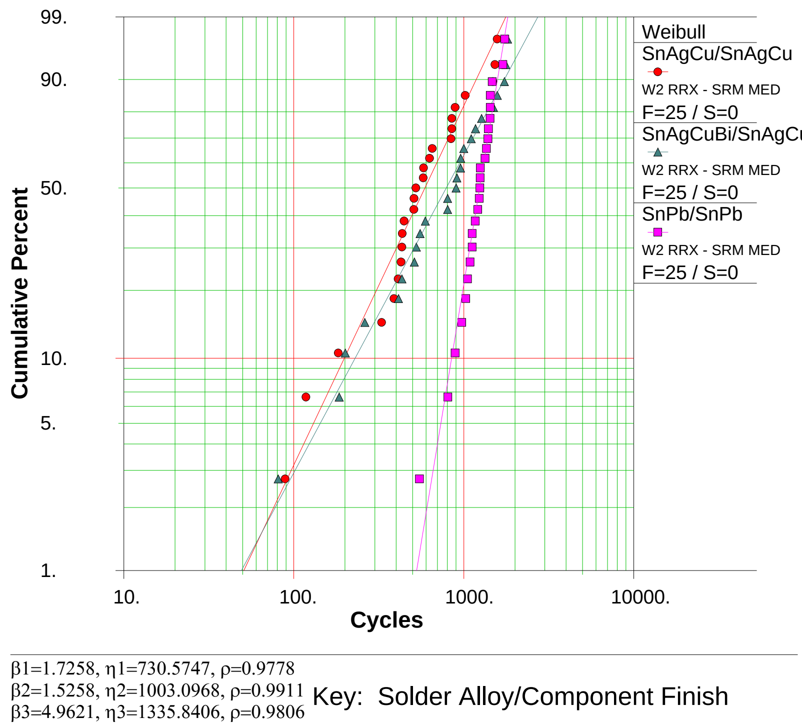

Figure 4 CSP Component Weibull Plot

Solder Alloy	JCAA/JGPP Data	
	slope	N_63
SnPb	5.0	1335
SAC	1.7	730
SACB	1.5	1003

Table 3 CSP Component Two Parameter Weibull Characteristics

Hybrid Component Results

The hybrid components failed only 8.9% (4 of 45) of the total test population after 4698 thermal cycles. The four failures were for the SnPb finish soldered with a SnPb solder alloy (Figure 5). No other hybrid combinations recorded failures.

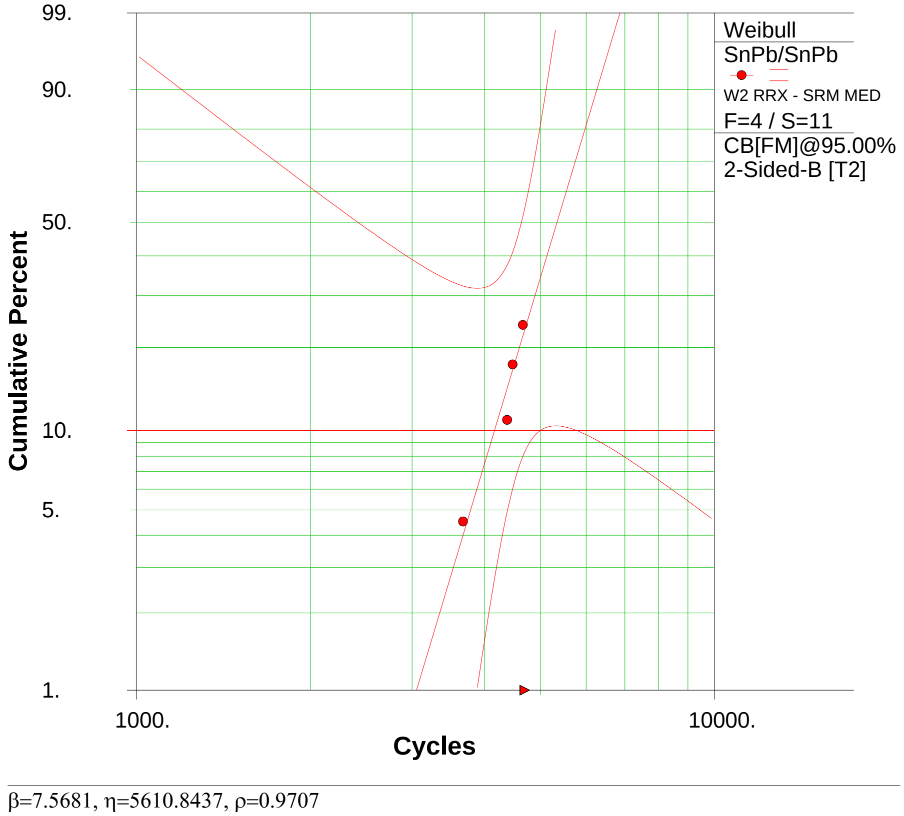

Figure 5 Weibull for SnPb finish/ SnPb Solder Alloy Hybrid Components

Surface Mount Resistor Results

The surface mount resistor components failed 63% (107 of 170) of the total test population after 4698 thermal cycles. The SACB solder alloy had the best thermal cycle performance, followed by the SAC solder alloy with the SnPb solder alloy with the lowest performance. In practical terms, the thermal cycle performance of all three solder alloys was acceptable for high performance electronics with very high N63 values and only two failures below the 2000 thermal cycle milestone (one SAC solder joint at 1702 cycles and one SnPb solder joint at 1871 cycles). A review of the results illustrated in Figure 6 reveals a reduction in thermal cycle performance when comparing the SnPb Manufactured test vehicles and the SnPb Reworked test vehicles. The Manufactured test vehicle laminate Tg was 170°C and the Reworked test vehicle laminate Tg was 140°C – the difference in Tg values resulted in an increased solder joint stress that reduced the SnPb solder joint integrity. Hunt and Wickham investigated the -55°C to +125°C thermal cycle solder joint integrity of 0603 and 1206 resistors [3]. They reported a failure rate for the 0603 and 1206 resistors of 0.24% and 0.0% respectively after 4380 cycles. The investigation test results are in good agreement with their reported failure rates. Woodrow investigated the -55°C to +125°C thermal cycle solder joint integrity of SMT 1206 capacitors using a SAC387 solder alloy [4]. Table 4 lists the Weibull slope and characteristic life (N63) values from the Woodrow investigation and this investigation. A comparison of the two data sets reveals good correlation with consideration being given for the lower slope value and the 140°C Tg laminate test vehicle in the Woodrow data set. Table 5 lists the 2 parameter Weibull values for each of the solder alloys for the investigation.

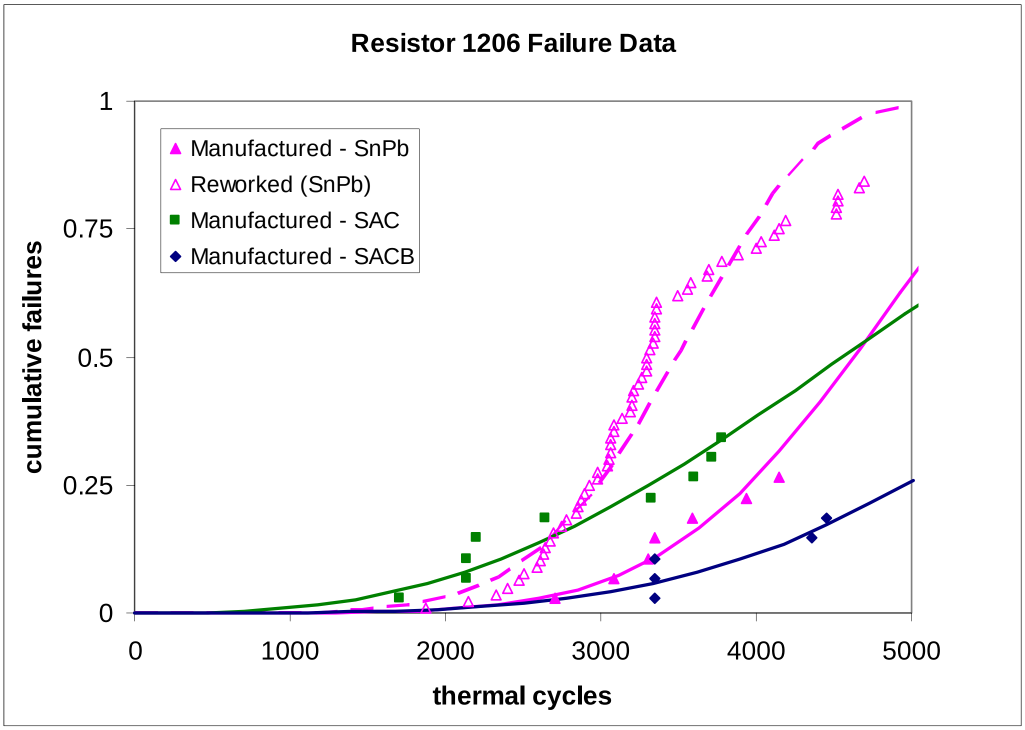

Figure 6 SMT Resistor Weibull Manufactured and Reworked Test Vehicles

Solder Alloy	JCAA/JGPP Data		Woodrow Data	
	slope	N_63	slope	N_63
SnPb	5.56	4943	5.15	5540
SAC	2.76	5199	1.98	3866

Table 4 JCAA/JGPP versus Woodrow Weibull Data Comparison

Solder Alloy	Manufactured		Reworked	
	slope	N_63	slope	N_63
SACB	3.98	6775	NA	NA
SnPb	5.56	4943	5.59	3734
SAC	2.76	5199	NA	NA

Table 5 Two Parameter Weibull Values for SMT Resistors Test Vehicles

Surface Mount Capacitor Results

The surface mount capacitors were not continuously monitored due to the incompatibility of the event detector, which measures resistance, and the capacitive component. Instead, subsets of the SMT capacitor population were periodically removed for metallographic cross-sectional analysis at regular intervals over the 4698 thermal cycles test duration. Statistical analysis was not conducted on the SMT capacitor components due to their lack of daisy chain circuits for event detection monitoring, which prevented the collection of cumulative failure distribution data. Metallographic cross-sectional analysis revealed the SMT capacitors began failing between 2203 thermal cycles and 3342 thermal cycles.

The Appendices contain summary/comparison tables of the N1, N10 and N63 statistical analysis for each component on the test vehicles and all of the alloy specific Weibull plots generated from the statistical analysis.

Test Results – Physical Failure Analysis

In addition to conducting statistical analysis to determine the solder alloy/component finish solder joint thermal cycle fatigue life, extensive failure analysis was conducted. The following sections summarize each of the physical phenomena investigated during the failure analysis effort.

Failure Analysis – Hybrid Components

Optical and metallographic microscopy documentation was completed on the hybrid samples. Only four failures were recorded for the hybrid components population. Those failures were confined to Sn63/Pb37 solder test vehicles with failures being recorded at cycles 3676, 4381, 4478, and 4664. Optical microscopy examination revealed that solder joint cracks originated at the possible locations: the solder joint toe, the solder joint heel and the Hybrid lead/solder joint interface. Figure 7 illustrates a typical optical microscopy observation.

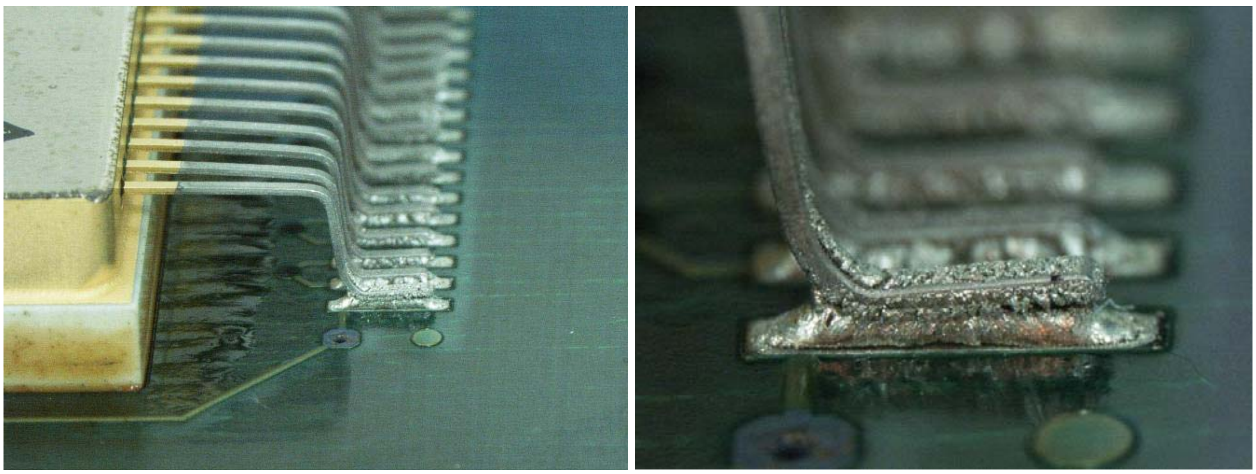

Figure 7 a/b Hybrid Component U33, Sn63/Pb37 Test Vehicle 307, 4478 Total Thermal Cycles

Metallographic microscopy examination revealed failure of the solder joint in the heel and toe regions. Figure 8 and Figure 9 illustrate the solder joint cracks observed.

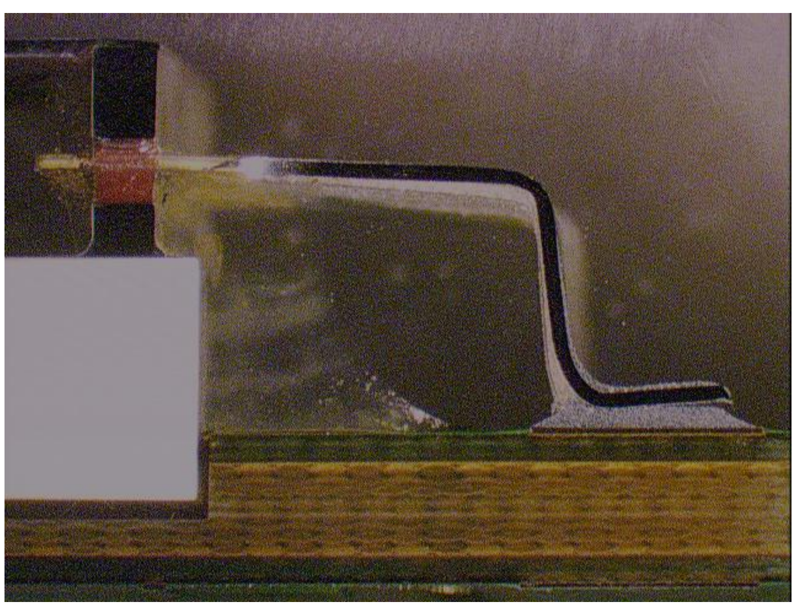

Figure 8 Metallographic View, Hybrid Component U33, Sn63/Pb37 Test Vehicle 307, 4478 Total Thermal Cycles

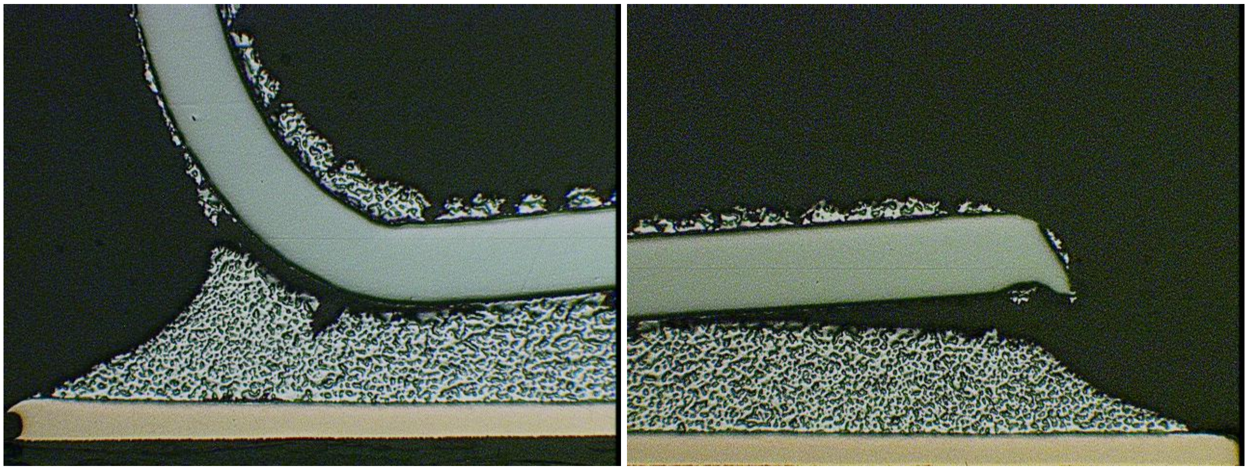

Figure 9 a/b, Solder Joint (a) Heel & (b) Toe, Hybrid Component U33, Sn63/Pb37 Test Vehicle 307

Failure Analysis – CSP Components

Optical and metallographic microscopy documentation was completed on a selected set of CSP components. Figure 10 and Figure 11 illustrate the failed solder joints observed on the Sn63/Pb37 solder alloy CSPs. Initial examination of the failed Sn63/Pb37 solder joints pointed to a manufacturing root cause as it appear that a poor solder joint was created at the test vehicle pad location. However, examination of a number of other Sn63/Pb37 solder alloy CSP joints revealed solder on both sides of the failure crack; therefore it appears that the failures were in fact due to typical solder joint fatigue.

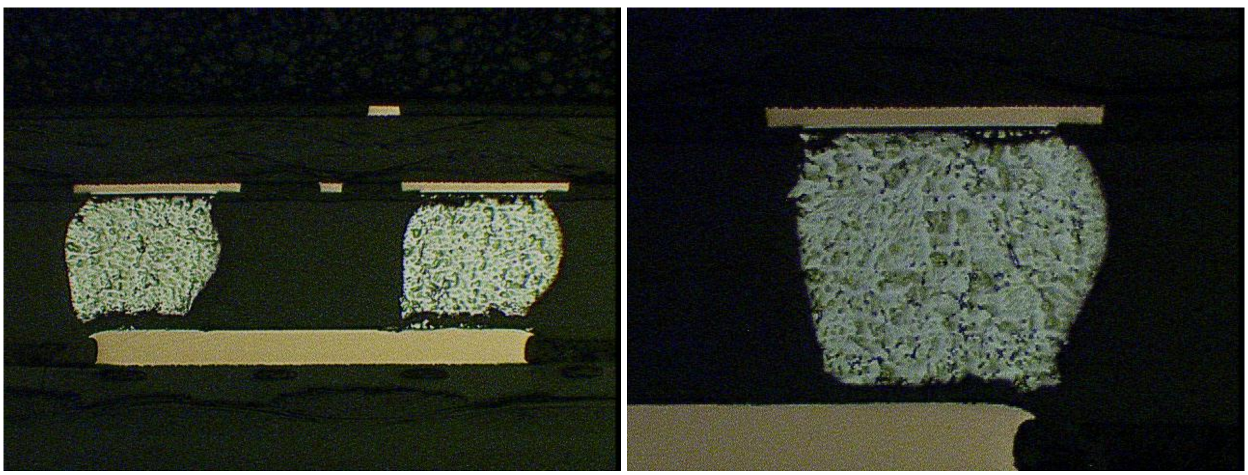

Figure 10 Metallographic View, CSP Component U36, Sn63/Pb37 Test Vehicle 310, 549 Total Thermal Cycles

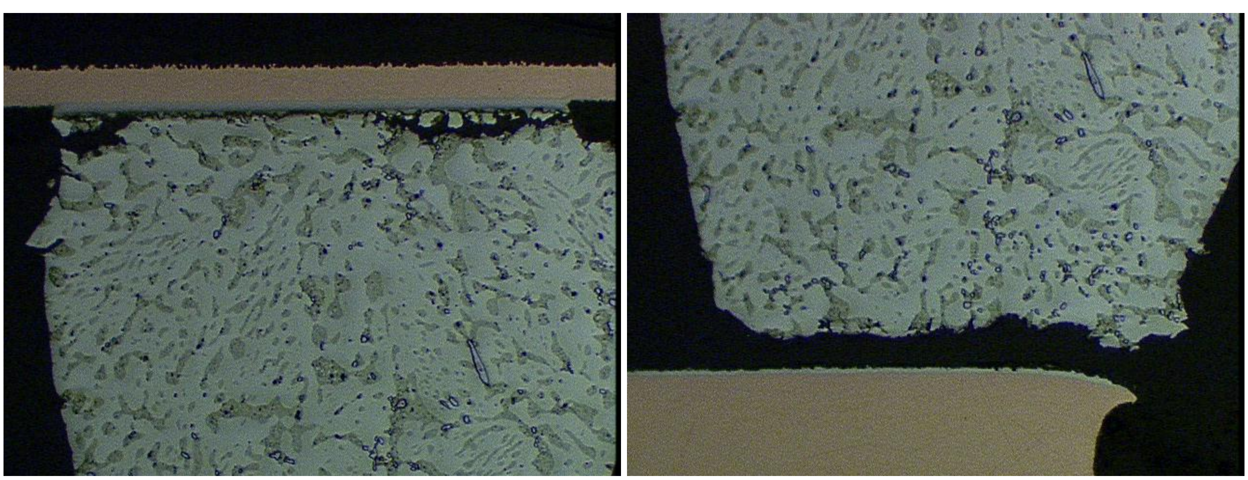

Figure 11 Metallographic View, CSP Component U36, Sn63/Pb37 Test Vehicle 310, 549 Total Thermal Cycles

Figure 12 and Figure 13 illustrate the failed solder joints observed on the SAC solder alloy CSPs. No unusual observations were recorded.

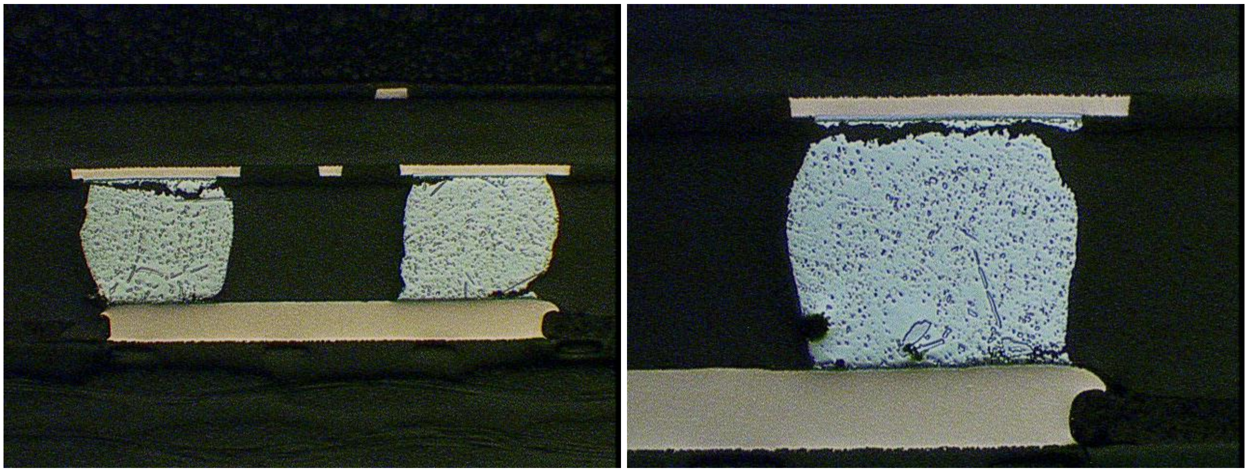

Figure 12 Metallographic View, CSP Component U36, SAC Test Vehicle 317, 89 Total Thermal Cycles

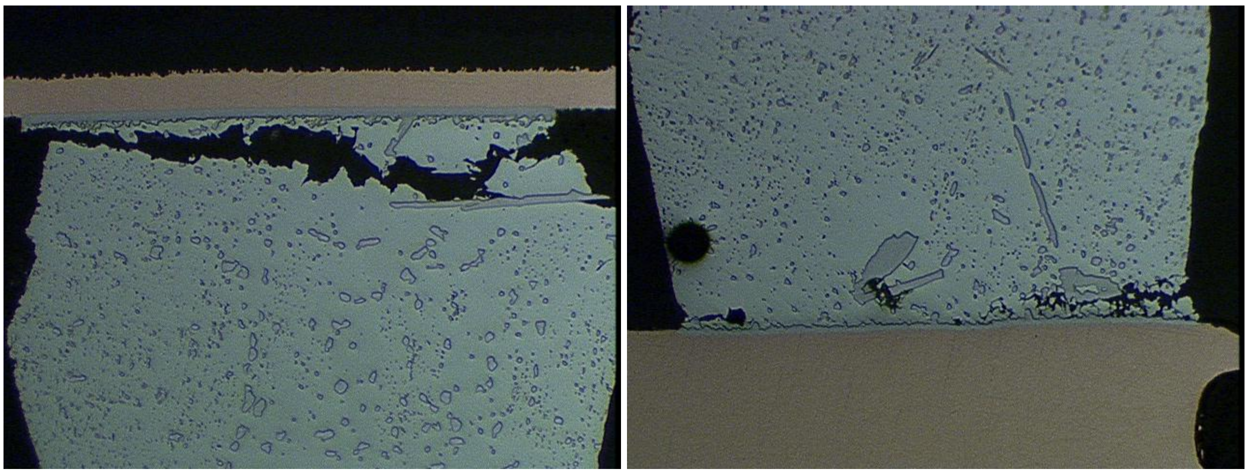

Figure 13 Metallographic View, CSP Component U36, SAC Test Vehicle 317, 89 Total Thermal Cycles

Figure 14 and Figure 15 illustrate the failed solder joints observed on the SACB solder alloy CSPs. No unusual observations were recorded.

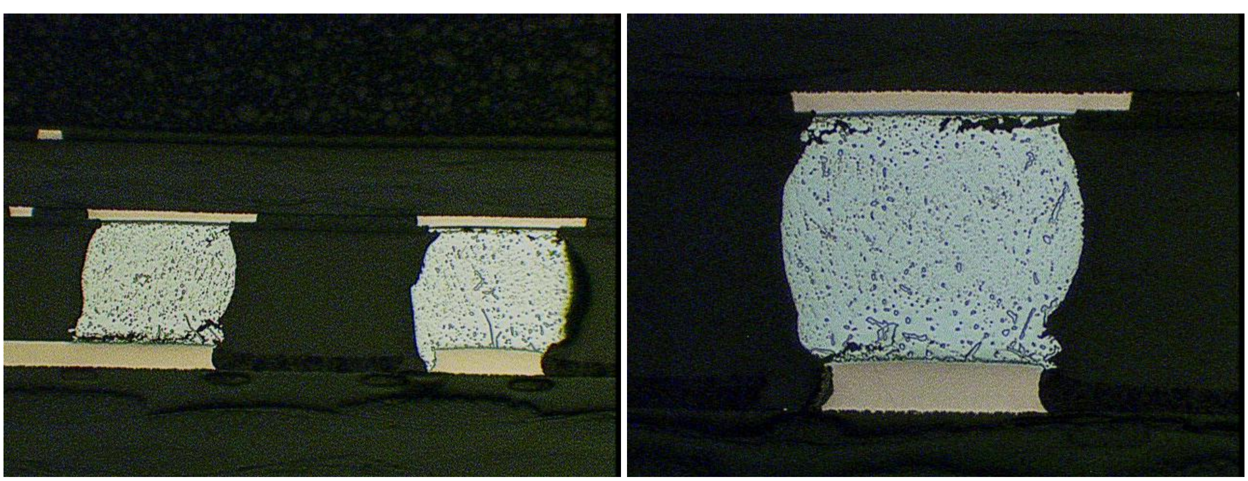

Figure 14 Metallographic View, CSP Component U19, SAC Test Vehicle 343, 158 Total Thermal

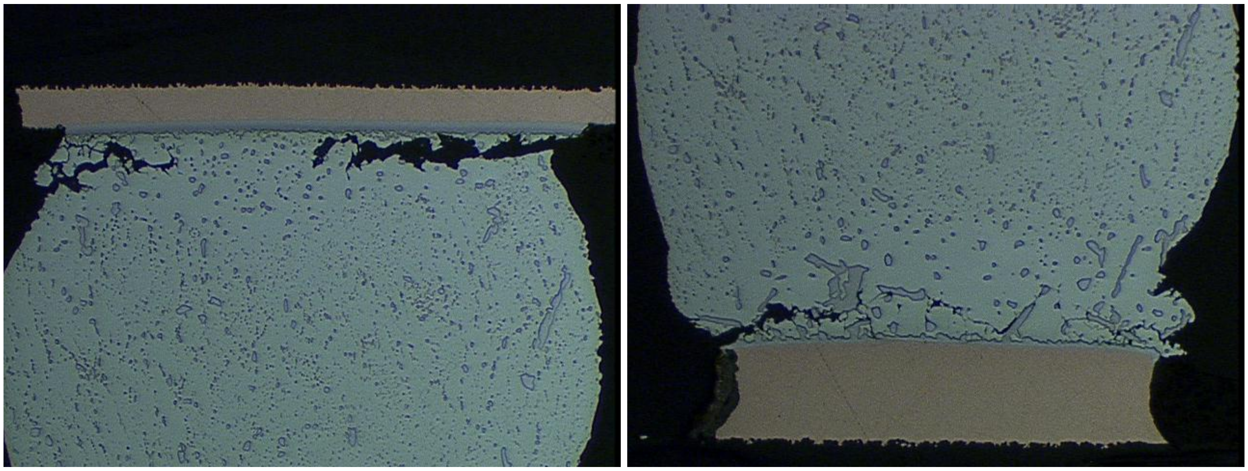

Figure 15 Metallographic View, CSP Component U19, SAC Test Vehicle 343, 158 Total Thermal

Failure Analysis – SMT Resistors Components

Optical and metallographic microscopy documentation was completed on a selected set of SMT resistor components. A representative SACB solder alloy SMT resistor solder joint is illustrated in Figure 16 and Figure 17. The SACB solder alloy had the best thermal cycle performance with an N63 value exceeding 6000 cycles. However, the SACB solder joints do reflect the accumulated damage of the thermal cycle induced stresses even when they did not fail.

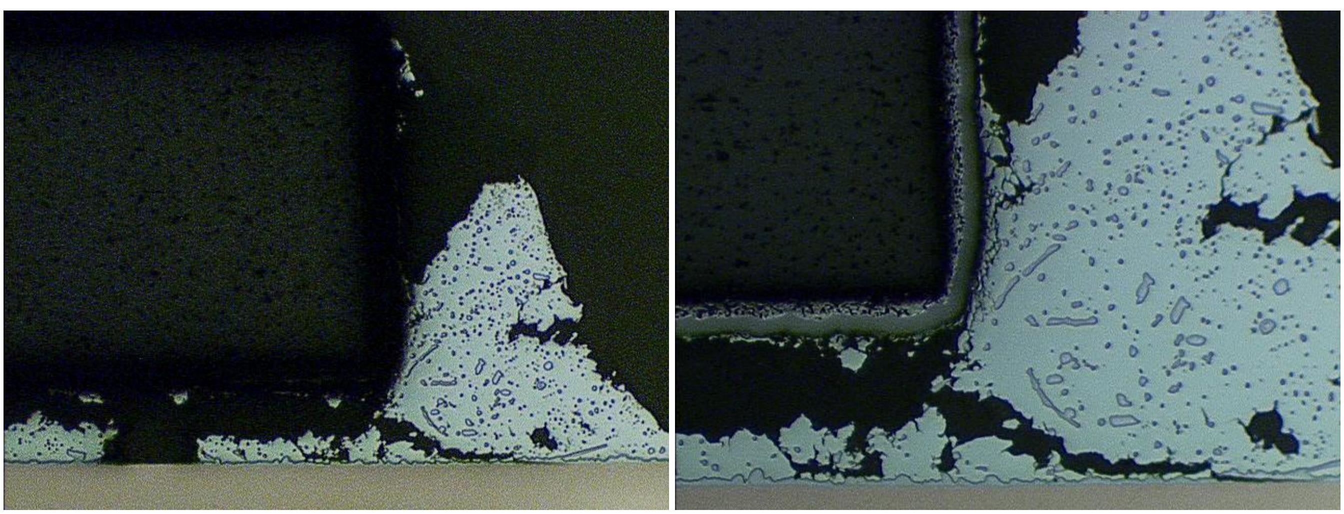

Figure 16 Metallographic View, SMT resistor, SACB Test Vehicle 128, 4698 Total Thermal Cycles

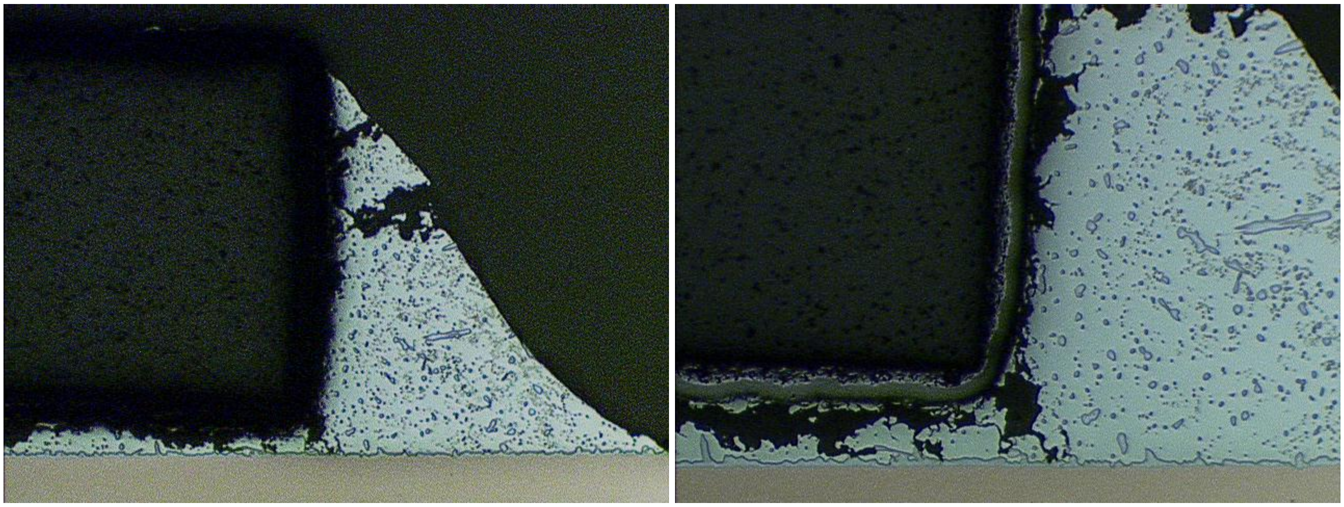

Figure 17 Metallographic View, SMT resistor, SACB Test Vehicle 128, 4698 Total Thermal Cycles

The first recorded solder joint failure for the SAC solder alloy was at 1702 thermal cycles. The metallographic examination of this resistor revealed no anomalies or manufacturing induced defects. Figure 18 and Figure 19 shows the solder joint microstructure and cracked solder fillets. Metallographic examination of a resistor that failed at 2644 thermal cycles (Figure 18 and Figure 19) and at 4698 thermal cycles (Figure 20 and Figure 21) reveals the thermal cycle stresses resulting in additional solder joint cracking as the number of thermal cycles were accumulated. A comparison of the SACB solder joints versus the SAC solder joints reveals more extensive cracking in the SAC solder joints.

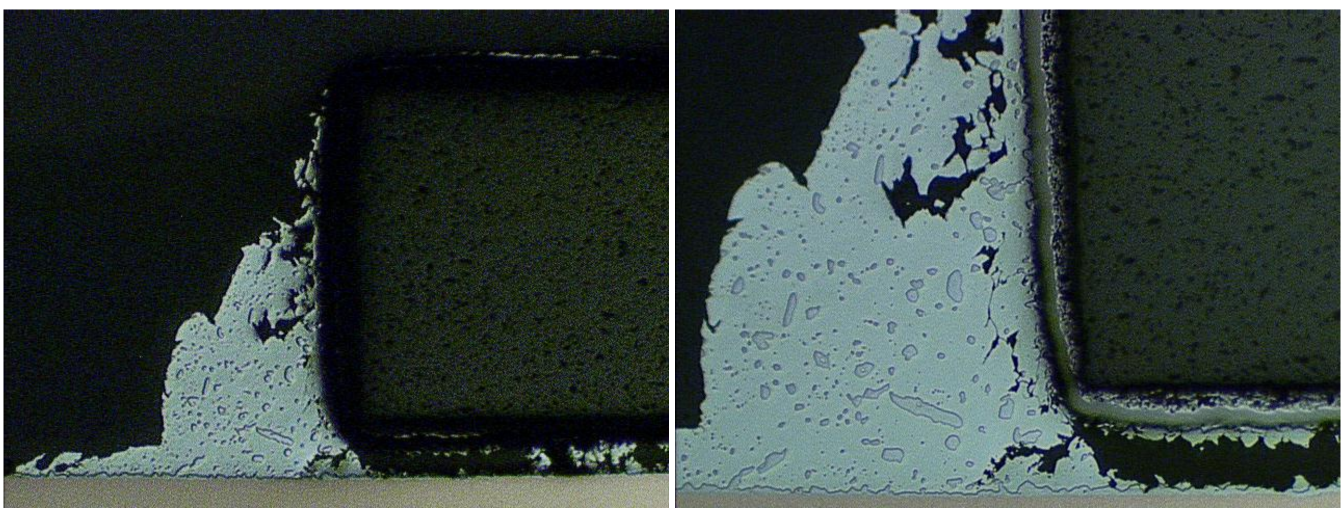

Figure 18 Metallographic View, SMT resistor, SAC Test Vehicle 85, 1702 Total Thermal Cycles

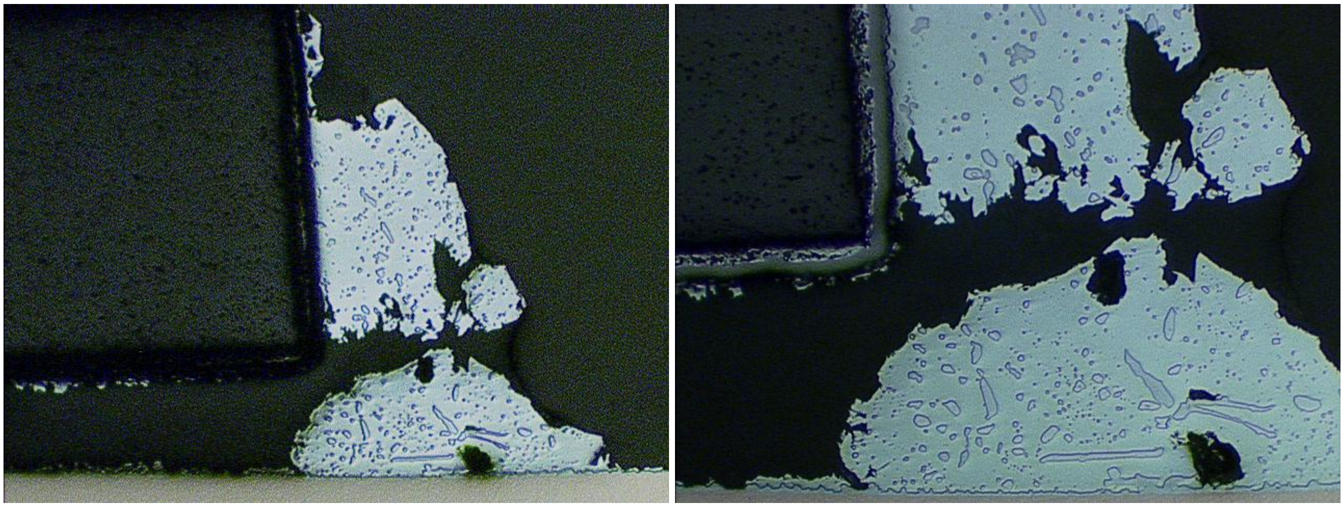

Figure 19 Metallographic View, SMT resistor, SAC Test Vehicle 85, 1702 Total Thermal Cycles

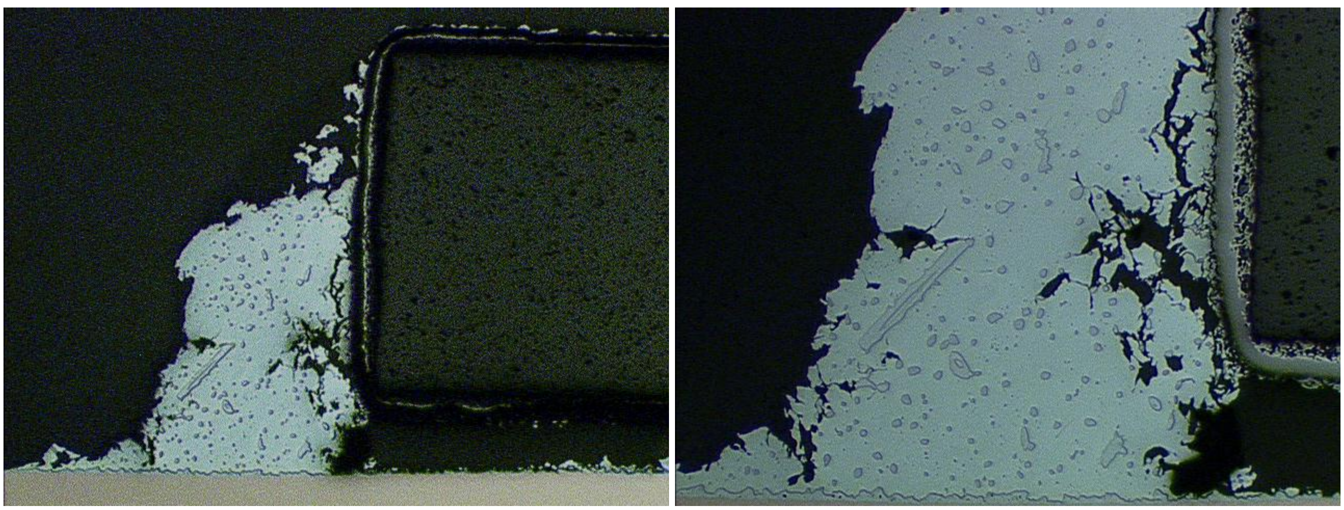

Figure 20 Metallographic View, SMT resistor, SAC Test Vehicle 87, 2644 Total Thermal Cycles

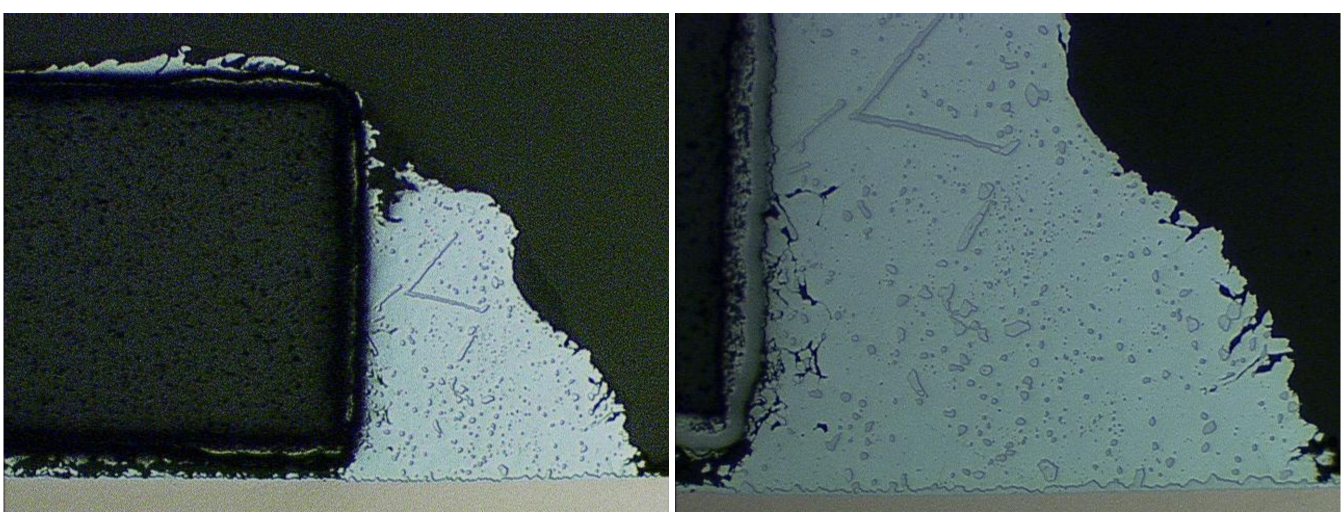

Figure 21 Metallographic View, SMT resistor, SAC Test Vehicle 87, 2644 Total Thermal Cycles

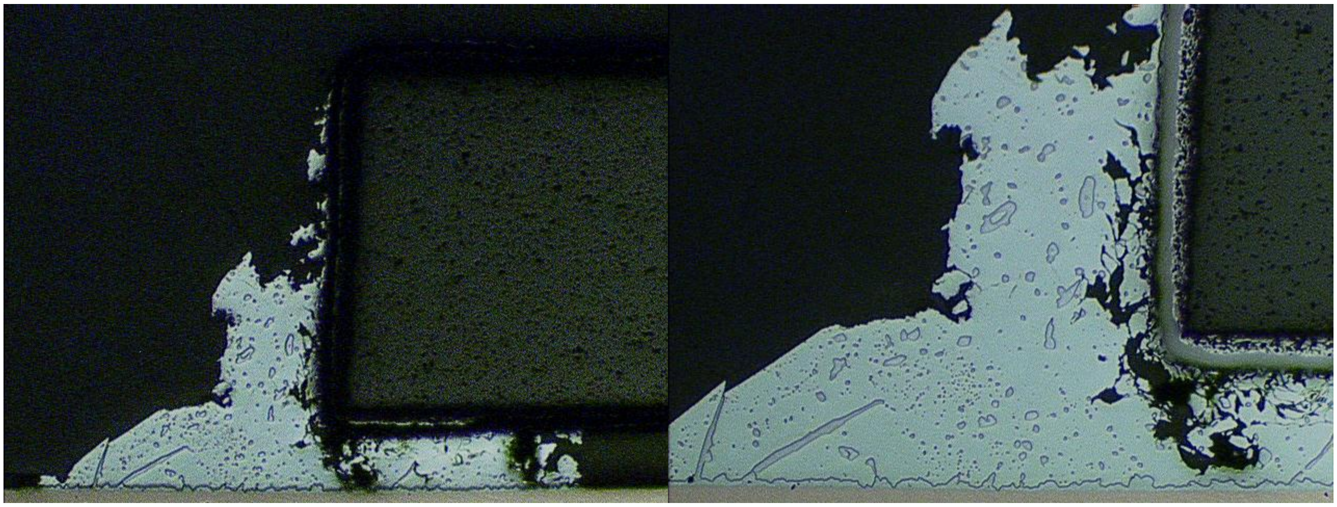

Figure 22 Metallographic View, SMT resistor, SAC Test Vehicle 85, 4698 Total Thermal Cycles

The first recorded solder joint failure for the Manufactured SnPb solder alloy test vehicle was at 2702 thermal cycles. The metallographic examination of this resistor revealed no anomalies or manufacturing induced defects. Figure 23 and Figure 24 shows the solder joint microstructure and cracked solder fillets. The second recorded solder joint failure for the Reworked SnPb solder alloy test vehicle was at 2143 thermal cycles (the first recorded resistor failure fell off the test vehicles during the course of thermal cycling). The metallographic examination of this resistor revealed no anomalies or manufacturing induced defects. Figure 25 and Figure 26 shows the solder joint microstructure and cracked solder fillets.

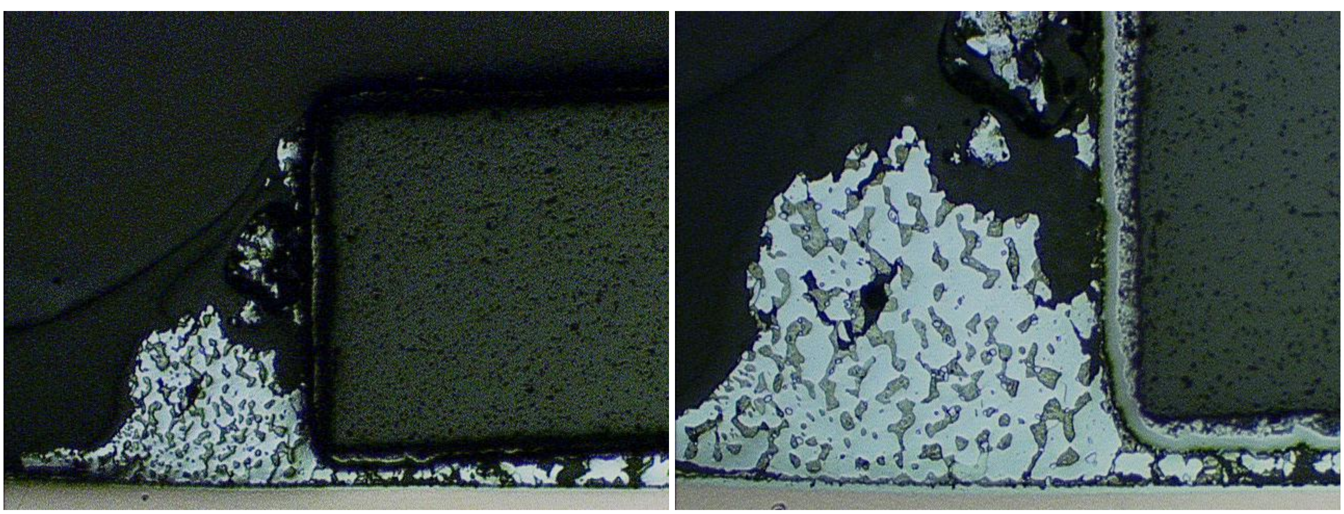

Figure 23 Metallographic View, SMT resistor, SnPb Test Vehicle 17, 2702 Total Thermal Cycles

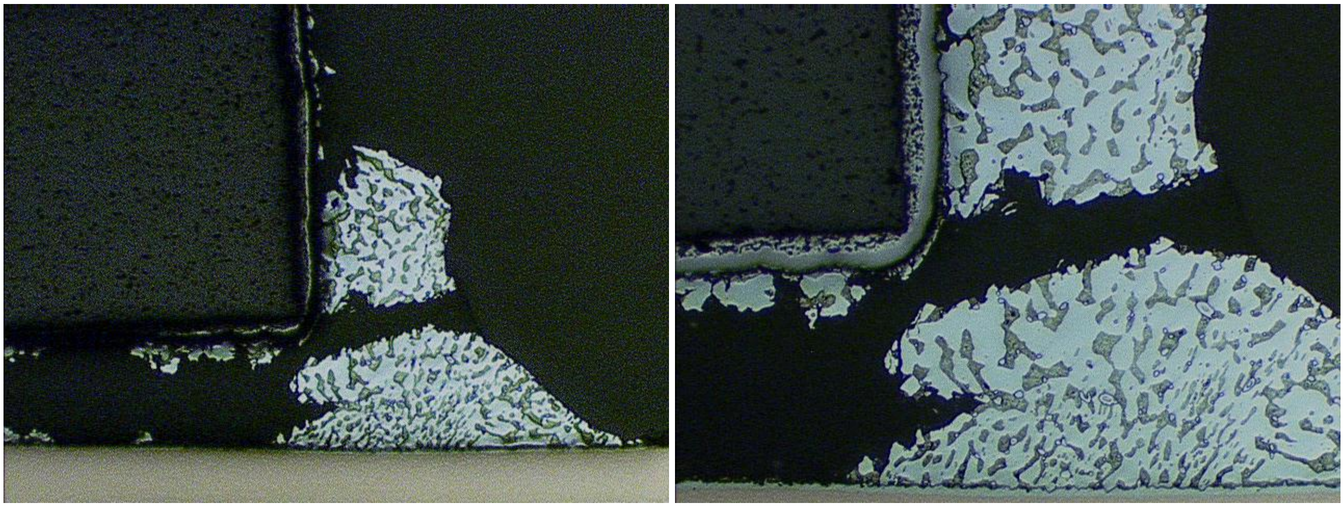

Figure 24 Metallographic View, SMT resistor, SnPb Test Vehicle 17, 2702 Total Thermal Cycles

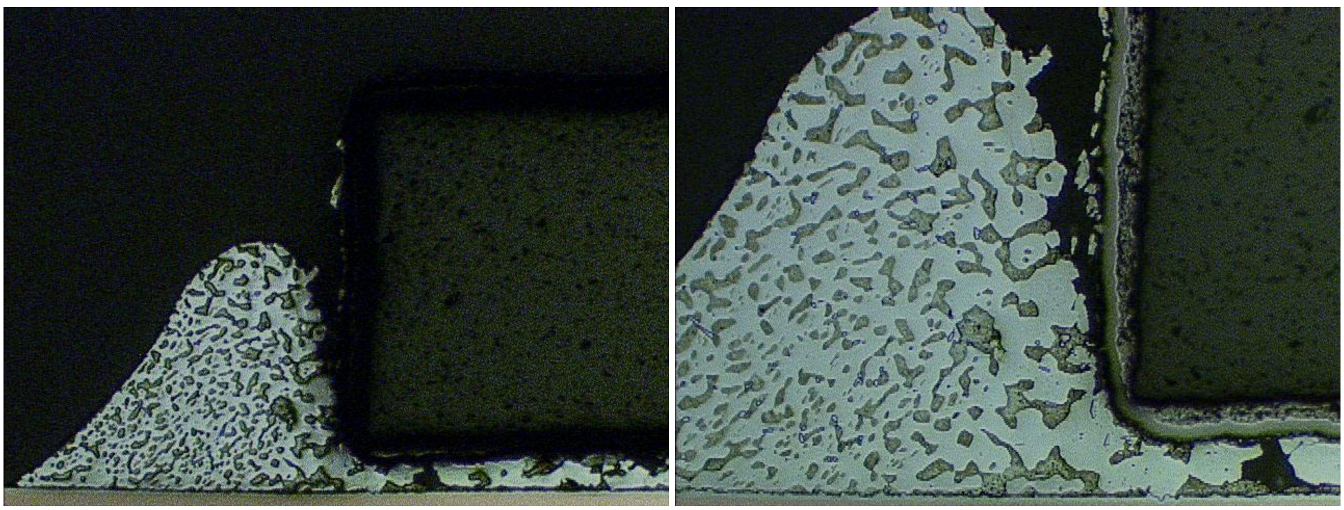

Figure 25 Metallographic View, SMT resistor, SnPb Test Vehicle 194, 2143 Total Thermal Cycles

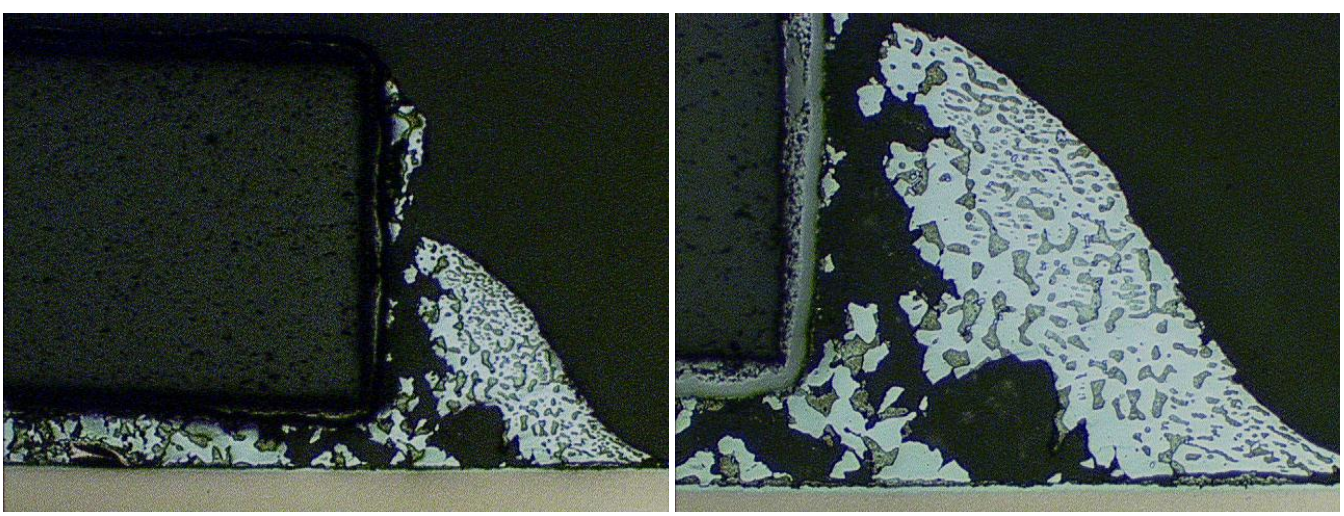

Figure 26 Metallographic View, SMT resistor, SnPb Test Vehicle 194, 2143 Total Thermal Cycles

Failure Analysis – SMT Capacitors Components

Optical and metallographic microscopy documentation was completed on a selected set of SMT capacitor components. The absence of an internal daisy chain resistance circuit increased the difficulty of determining the failure rate and history of a thermal cycled component. At intervals, during the thermal cycle testing, a portion of the SMT capacitor components were removed for metallographic cross-sectional analysis at specific cycle intervals. The authors conducted metallographic cross-sectional analysis for the SMT capacitor components for the 2203 and 3342 thermal cycle intervals. Examination of the 2203 thermal cycle interval solder joints revealed the initiation of solder joint cracks and solder joints undergoing solder joint stresses resulting in solder joint microstructural changes. Examination of the 3442 thermal cycle interval solder joints revealed solder joint cracks causing solder joint opens. Figure 27 thru Figure 43 illustrate the SMT capacitor observations.

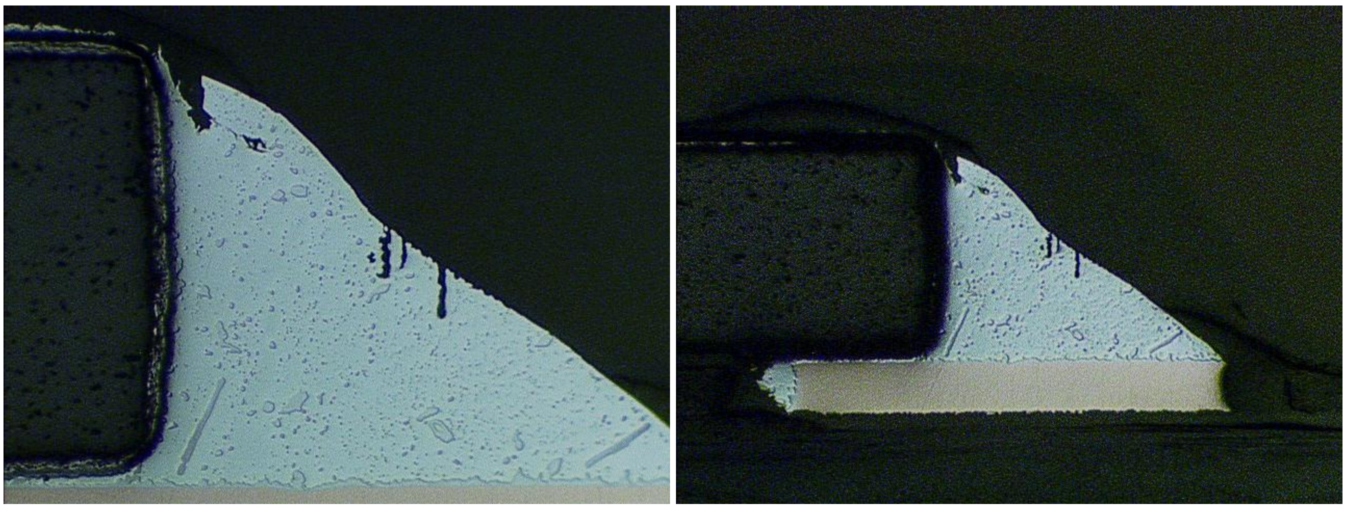

Figure 27 Metallographic View, SMT 0603 Capacitor, SAC Test Vehicle 88, 2203 Total Thermal Cycles

Note Shrinkage Voids in Solder Joint Not Acting As Crack Initiation Locations

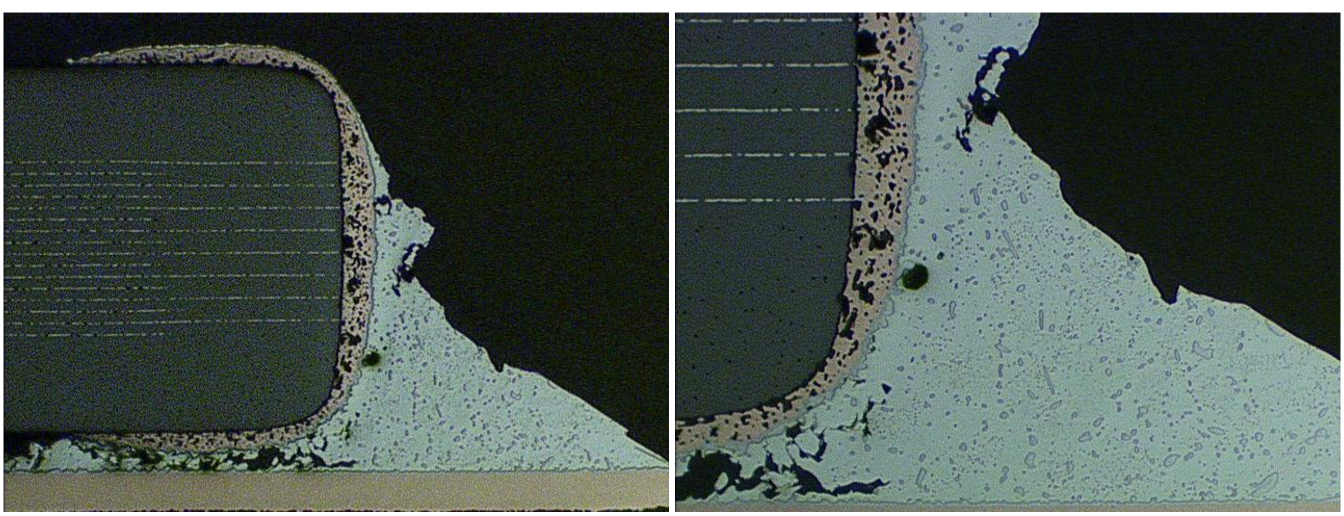

Figure 28 Metallographic View, SMT 0805 Capacitor, SAC Test Vehicle 88, 2203 Total Thermal Cycles

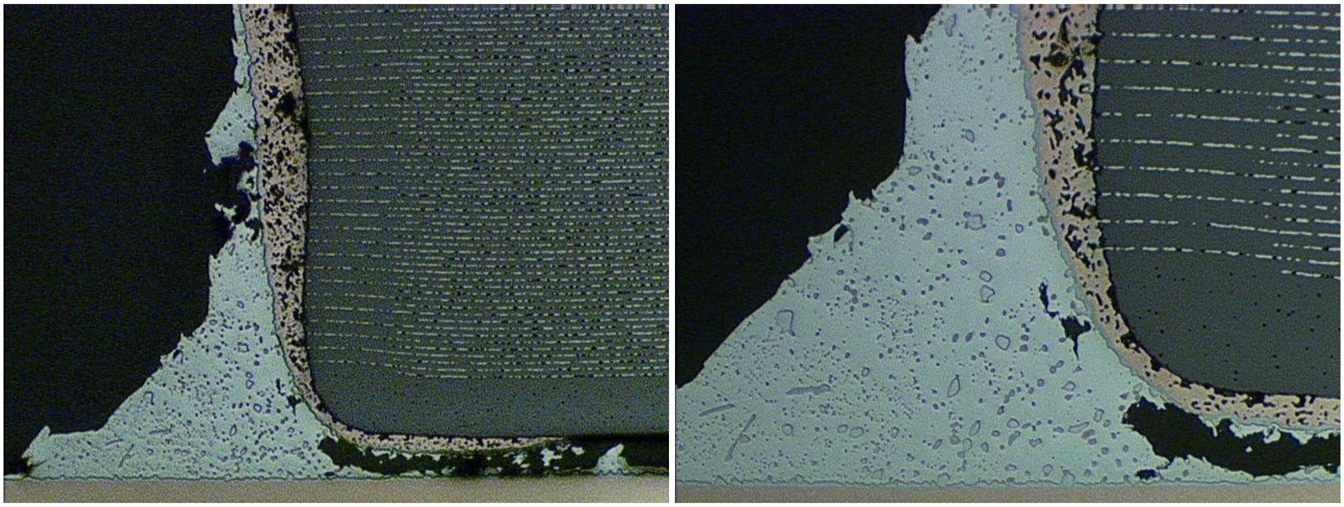

Figure 29 Metallographic View, SMT 1206 Capacitor, SAC Test Vehicle 88, 2203 Total Thermal Cycles

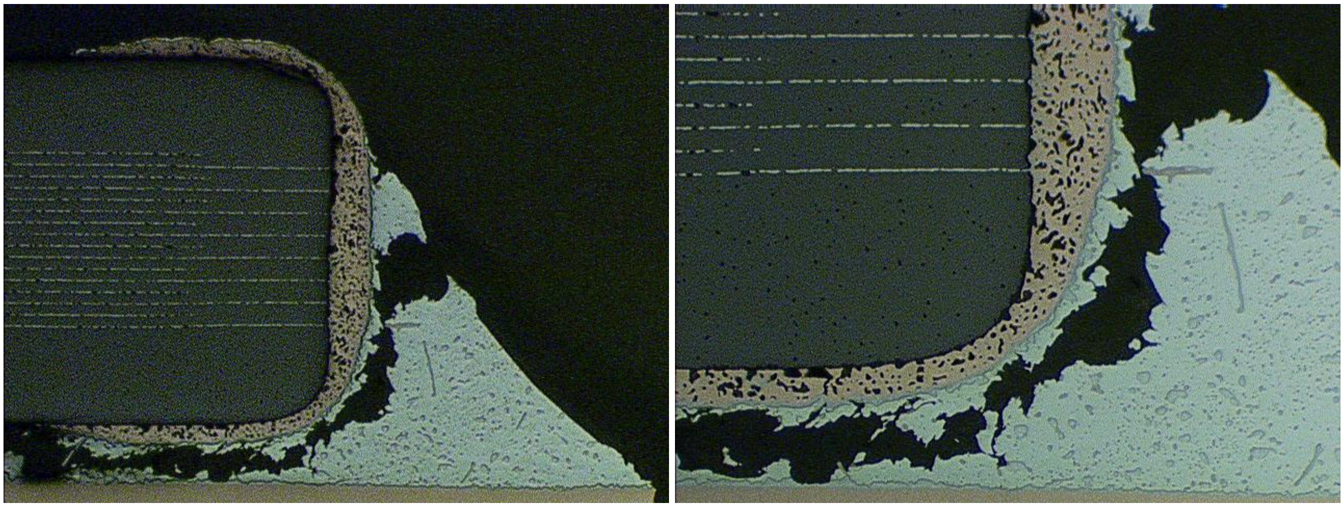

Figure 30 Metallographic View, SMT 0805 Capacitor, SAC Test Vehicle 88, 3342 Total Thermal Cycles

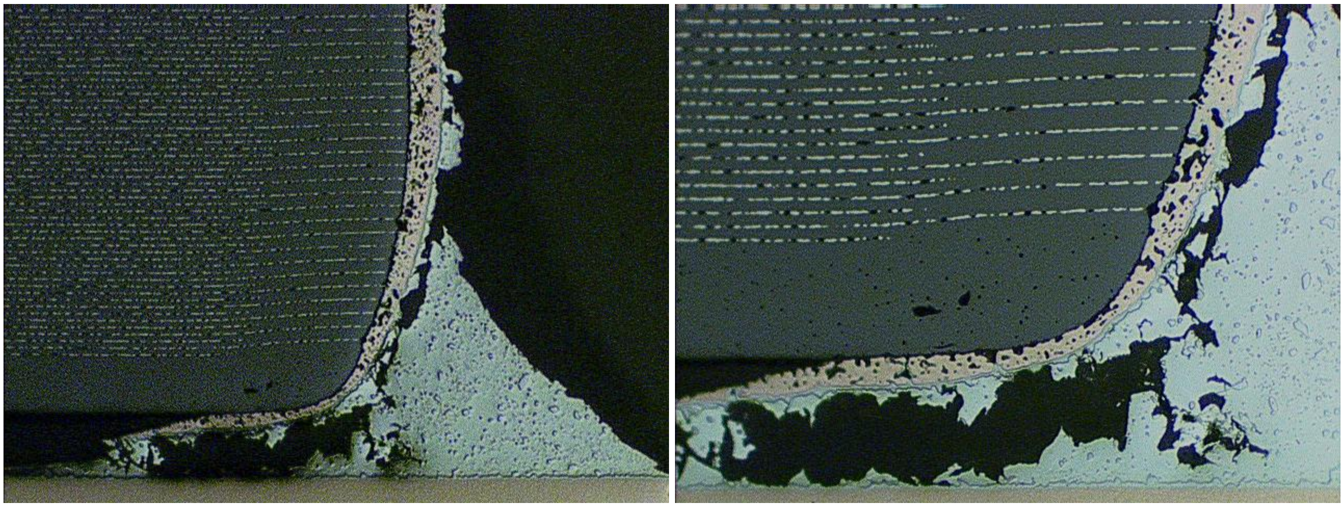

Figure 31 Metallographic View, SMT 1206 Capacitor, SAC Test Vehicle 88, 3342 Total Thermal Cycles

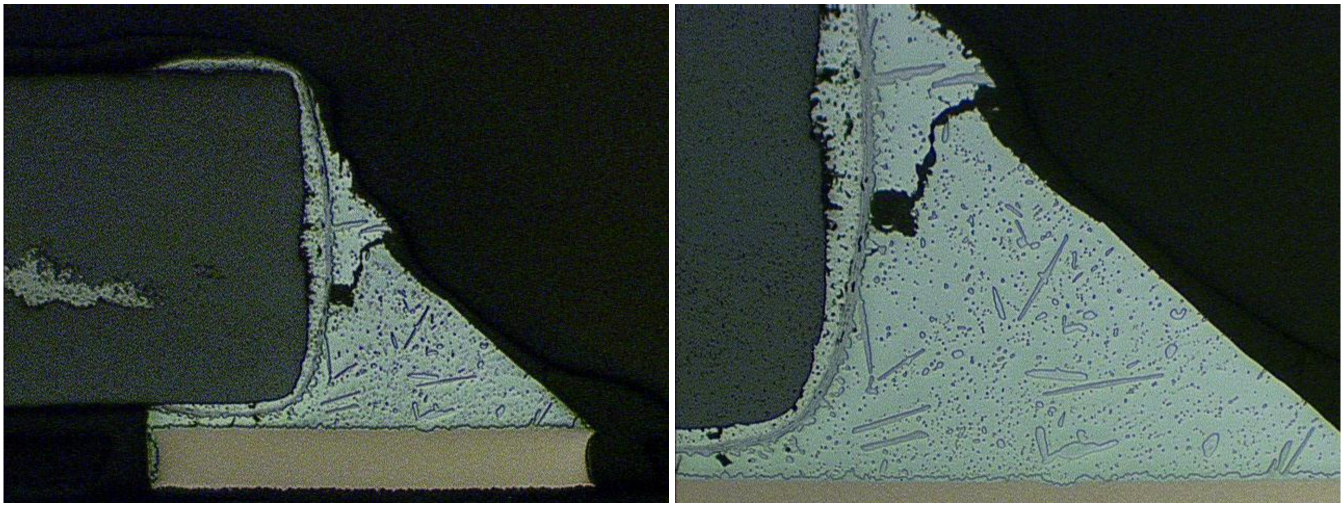

Figure 32 Metallographic View, SMT 0603 Capacitor, SACB Test Vehicle 128, 2203 Total Thermal Cycles

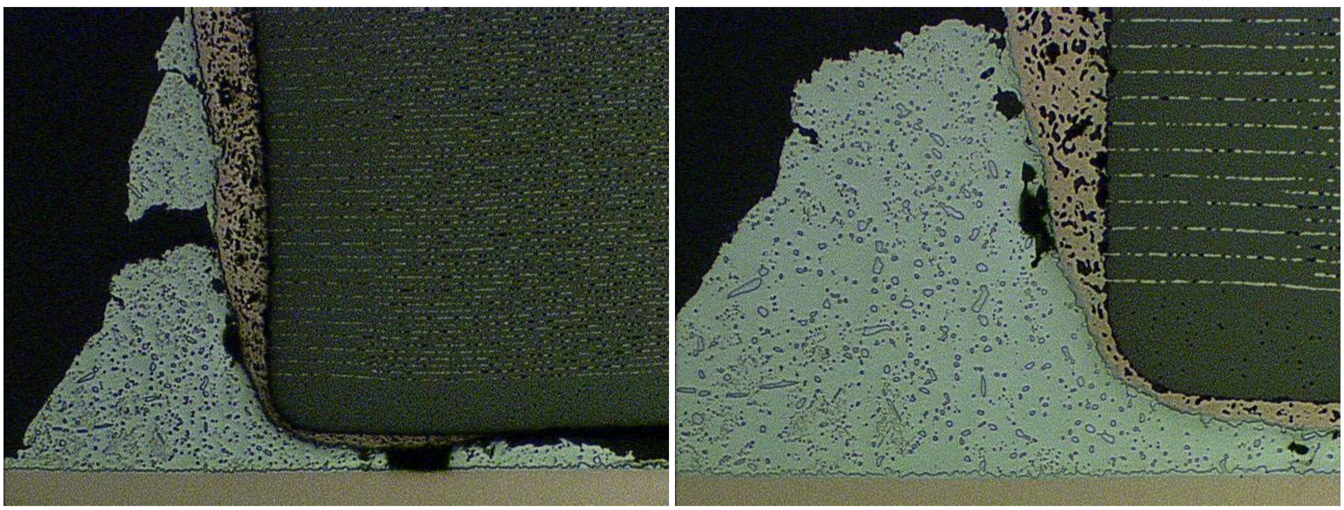

Figure 33 Metallographic View, SMT 0805 Capacitor, SACB Test Vehicle 128, 2203 Total Thermal Cycles

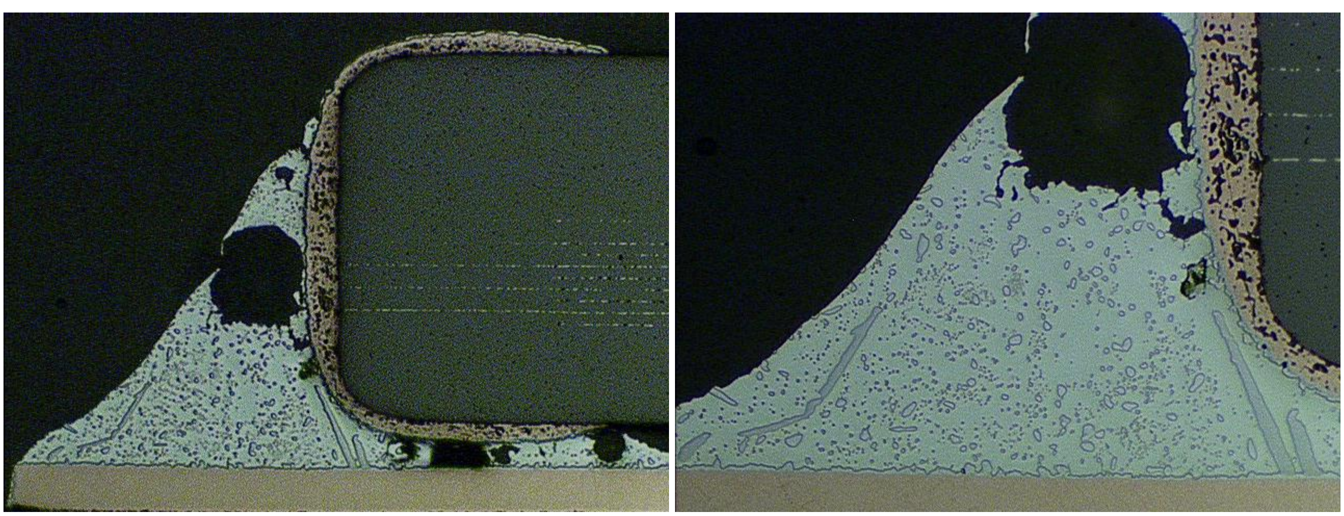

Figure 34 Metallographic View, SMT 1206 Capacitor, SACB Test Vehicle 128, 2203 Total Thermal Cycles

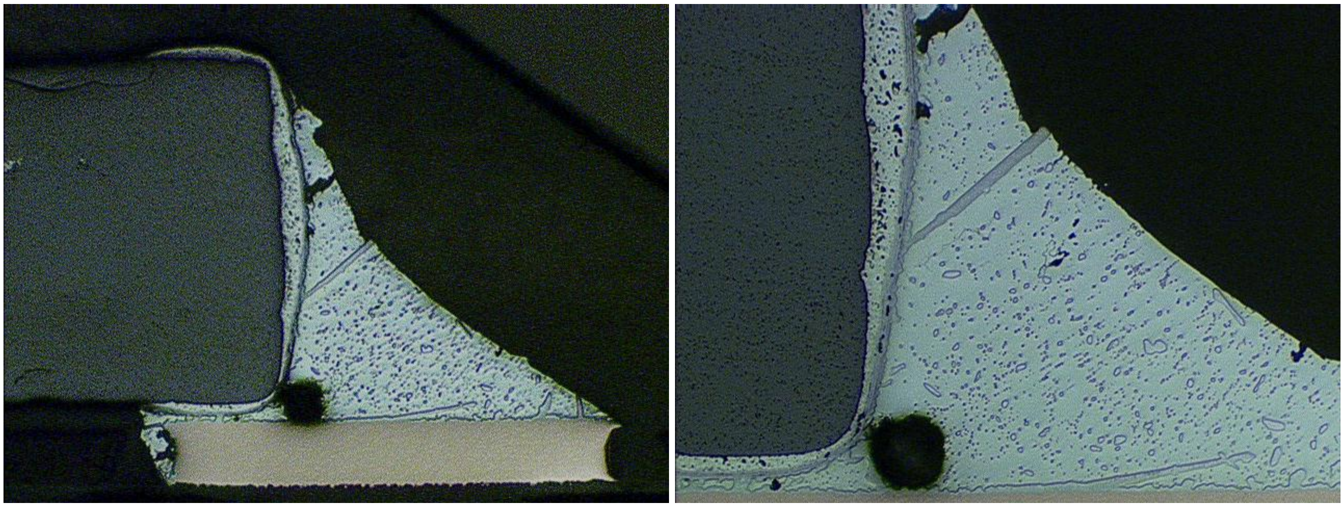

Figure 35 Metallographic View, SMT 0603 Capacitor, SACB Test Vehicle 128, 3442 Total Thermal Cycles

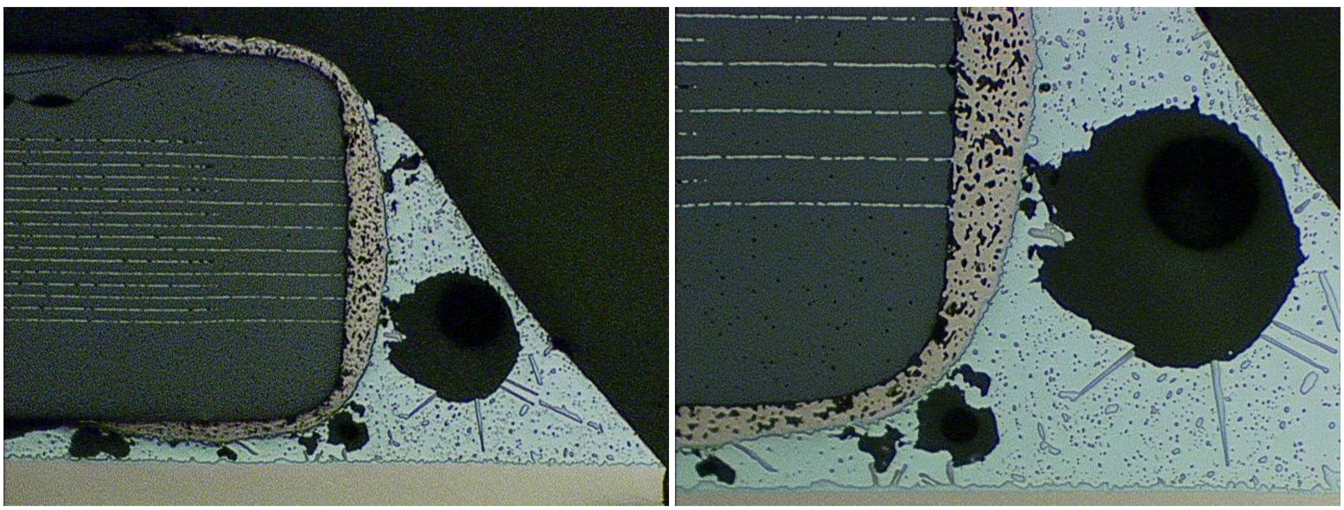

Figure 36 Metallographic View, SMT 0805 Capacitor, SACB Test Vehicle 128, 3442 Total Thermal Cycles

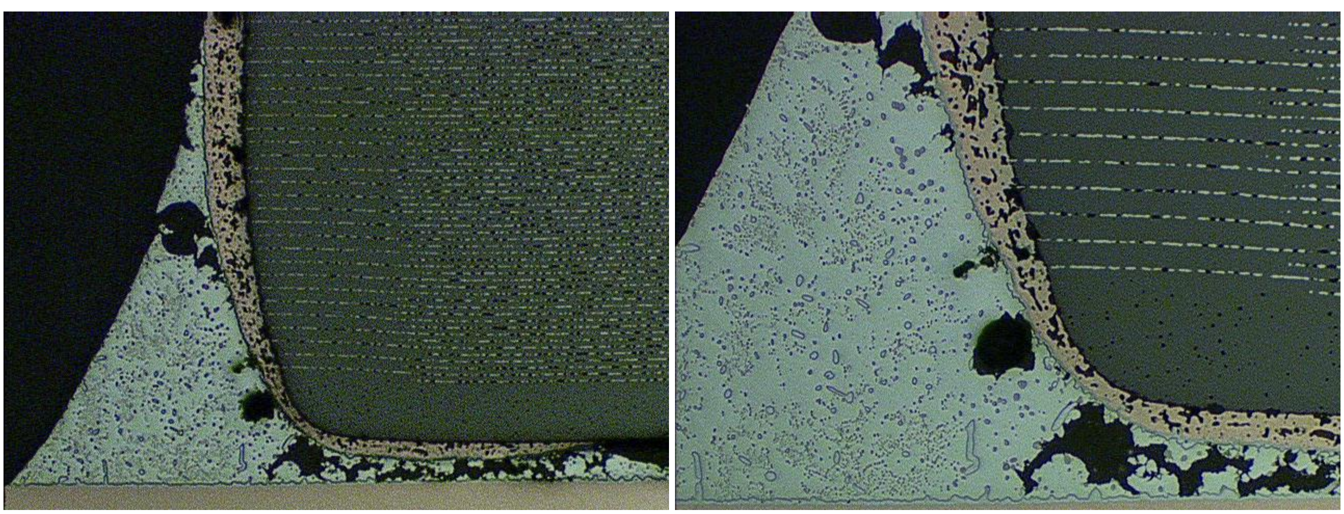

Figure 37 Metallographic View, SMT 1206 Capacitor, SACB Test Vehicle 128, 3442 Total Thermal Cycles

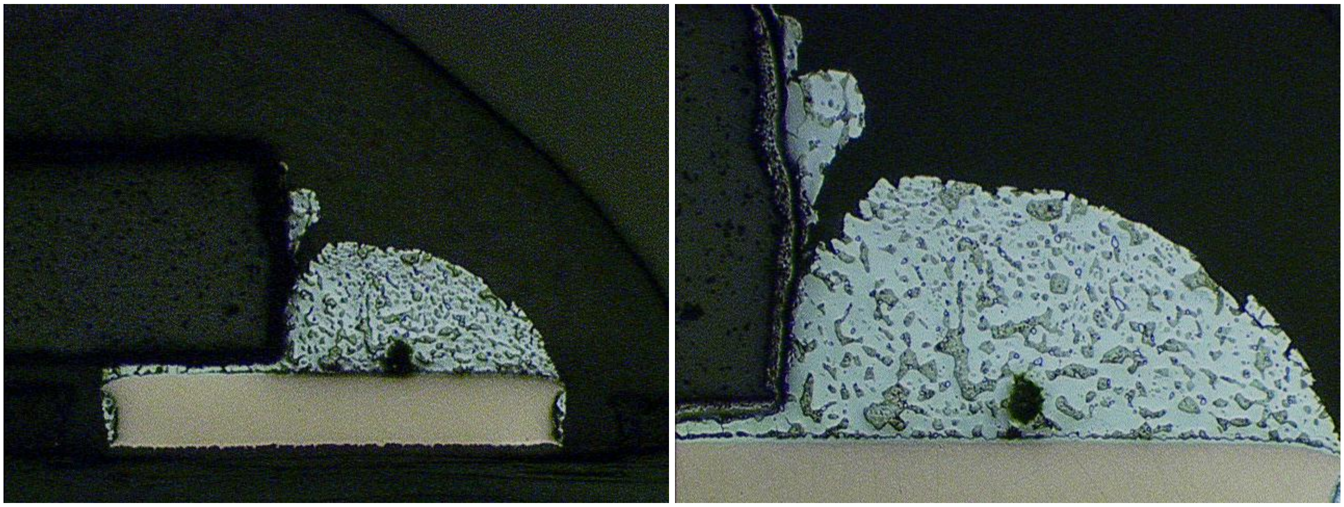

Figure 38 Metallographic View, SMT 0603 Capacitor, SnPb Test Vehicle 16, 2203 Total Thermal Cycles

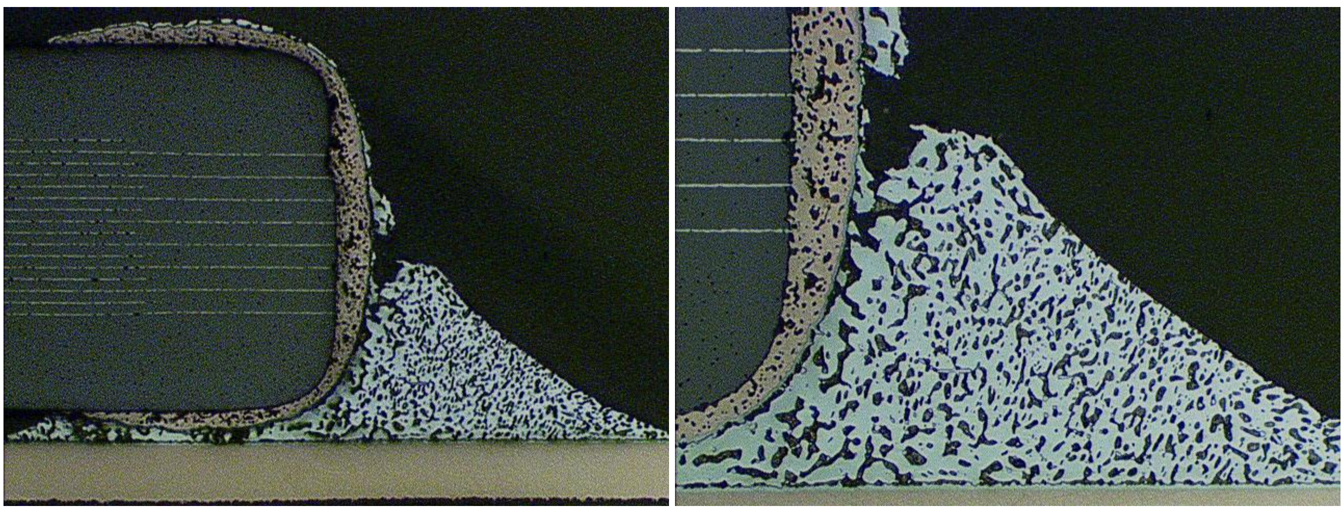

Figure 39 Metallographic View, SMT 0805 Capacitor, SnPb Test Vehicle 16, 2203 Total Thermal Cycles

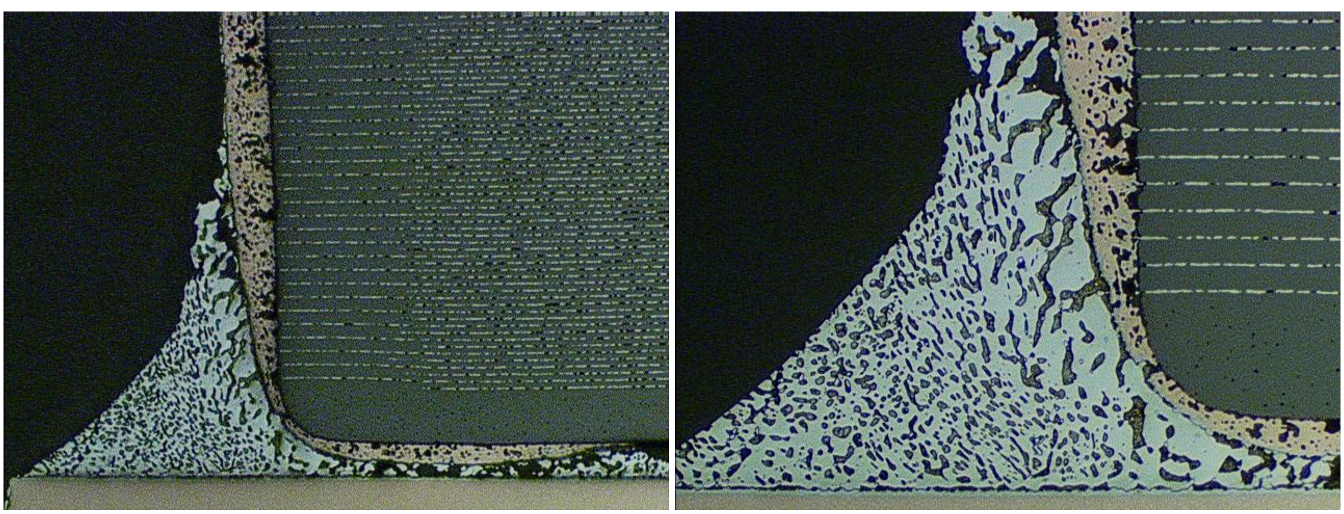

Figure 40 Metallographic View, SMT 1206 Capacitor, SnPb Test Vehicle 16, 2203 Total Thermal Cycles

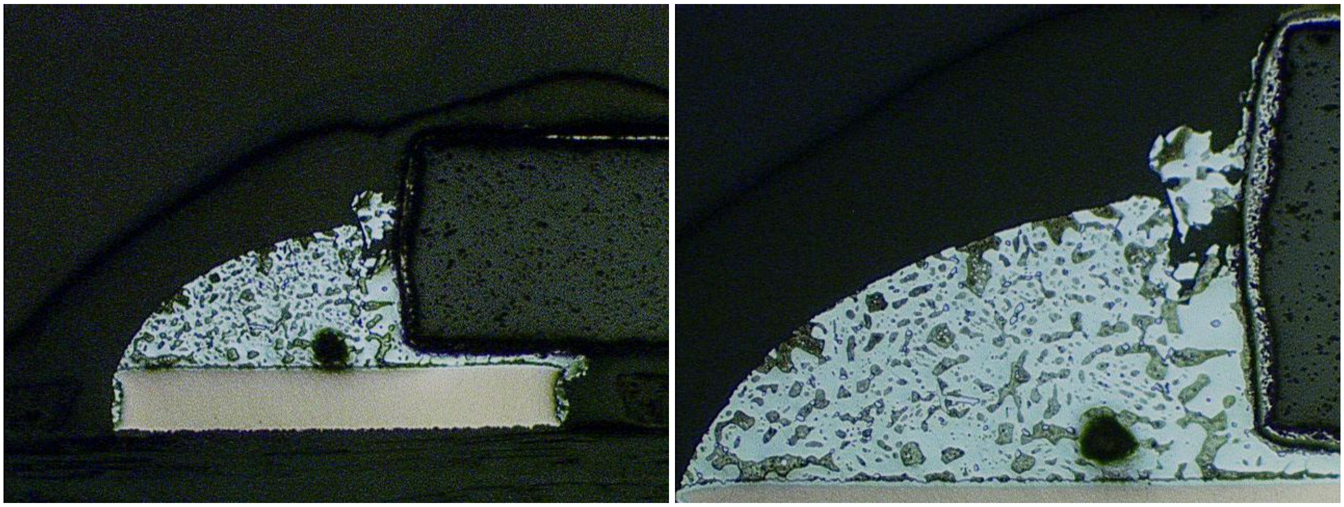

Figure 41 Metallographic View, SMT 0603 Capacitor, SnPb Test Vehicle 15, 3442 Total Thermal Cycles

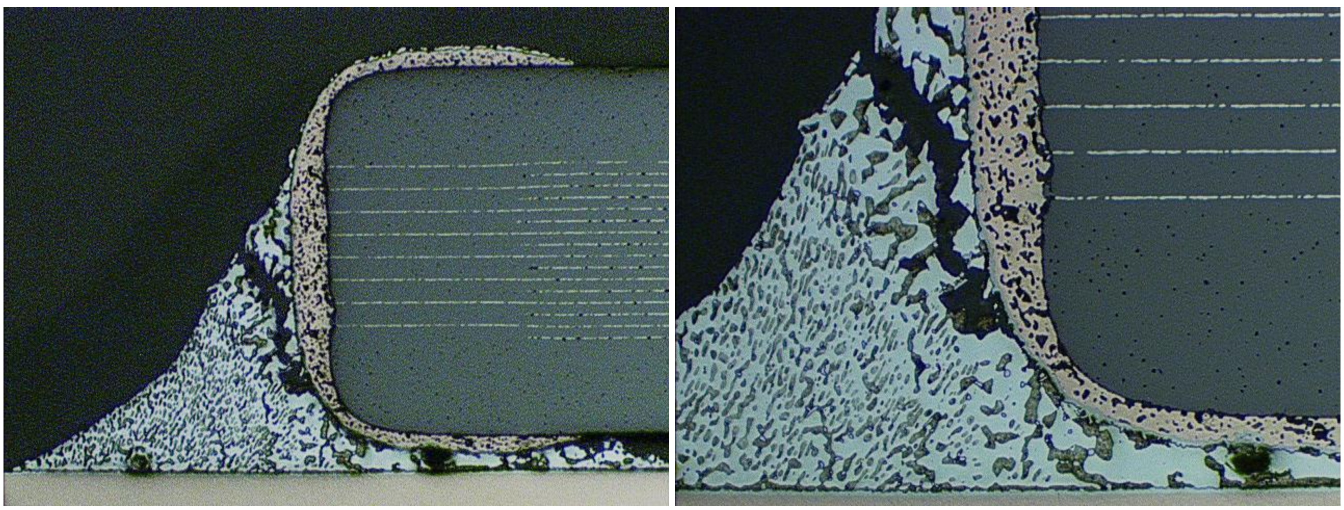

Figure 42 Metallographic View, SMT 0805 Capacitor, SnPb Test Vehicle 15, 3442 Total Thermal Cycles

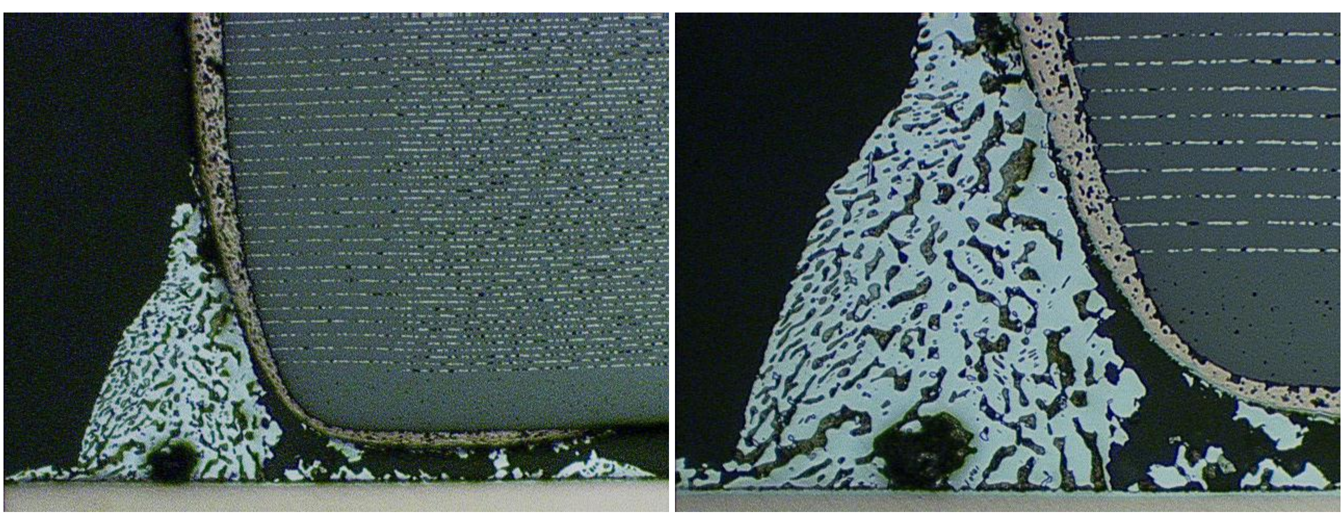

Figure 43 Metallographic View, SMT 1206 Capacitor, SnPb Test Vehicle 15, 3442 Total Thermal Cycles

Conclusions

The investigation conclusions were:

- Hybrid components: statistically the Pbfree solder alloys had equal to or better thermal cycle performance then the SnPb solder alloy baseline. In practical terms, the Pbfree and SnPb solder alloys had equal performance due to the few solder joint failures recorded and the high solder joint fatigue life demonstrated.

- CSP components: the SnPb solder alloy had better overall solder joint integrity performance than either the SAC or SACB solder alloys. The SAC and SACB solder alloys had equivalent solder joint integrity performance. The solder joint thermal cycle integrity of the SAC and SACB solder alloys would not be acceptable for some high performance use environments.

- SMT resistors: the SACB solder alloy had the best thermal cycle performance, followed by the SAC solder alloy with the SnPb solder alloy with the lowest performance. In practical terms, the thermal cycle performance of all three solder alloys was acceptable for high performance electronics with very high N63 values and only two failures below the 2000 thermal cycle milestone. A review of the test results reveals a reduction in thermal cycle performance when comparing the SnPb Manufactured test vehicles and the SnPb Reworked test vehicles due to a difference in Tg values.

- SMT capacitors: statistical analysis was not conducted on the SMT capacitor components due to their lack of daisy chain circuits for event detection monitoring, which prevented the collection of cumulative failure data. Metallographic cross-sectional analysis revealed the SMT capacitors began failing between 2203 thermal cycles and 3342 thermal cycles.

Recommendation

The investigation recommendation was:

- The feasibility of using Pbfree solder alloys in place of SnPb solder alloys for new product designs was demonstrated under thermal cycle test conditions. Additional investigation and characterization of Pbfree solder alloys will be required as a segment of a Pbfree solder alloy implementation plan. The application/introduction of Pbfree soldering processes for legacy product designs is not recommended without extensive materials characterization and product design review.

Acknowledgements

The authors would like to thank the Joint Council on Aging Aircraft (JCAA)/ Joint Group on Pollution Prevention (JG-PP) Pbfree Solder program and Rockwell Collins Inc. for project funding, Ken Blazek for metallographic cross-sectioning efforts, Dwayne Koch for SEM analysis, and Kurt Kessel of NASA for his scathing critique of the manuscript.

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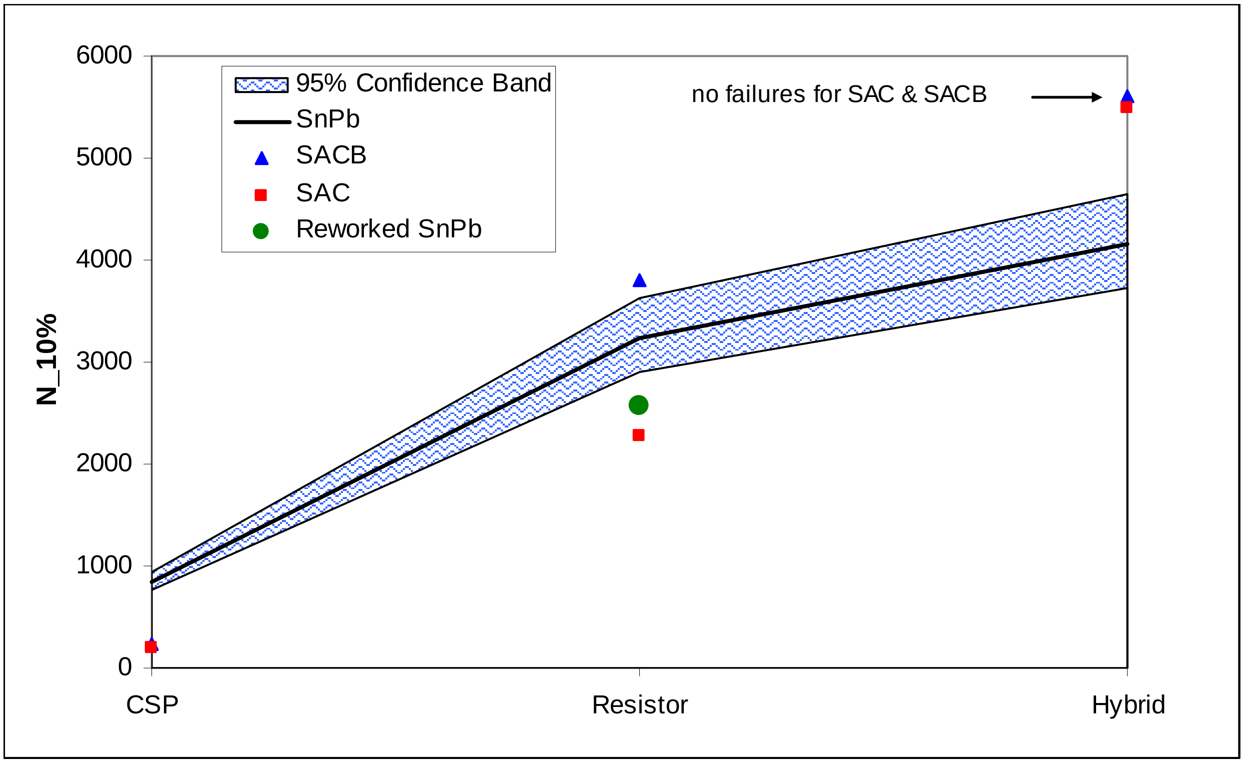
Appendices

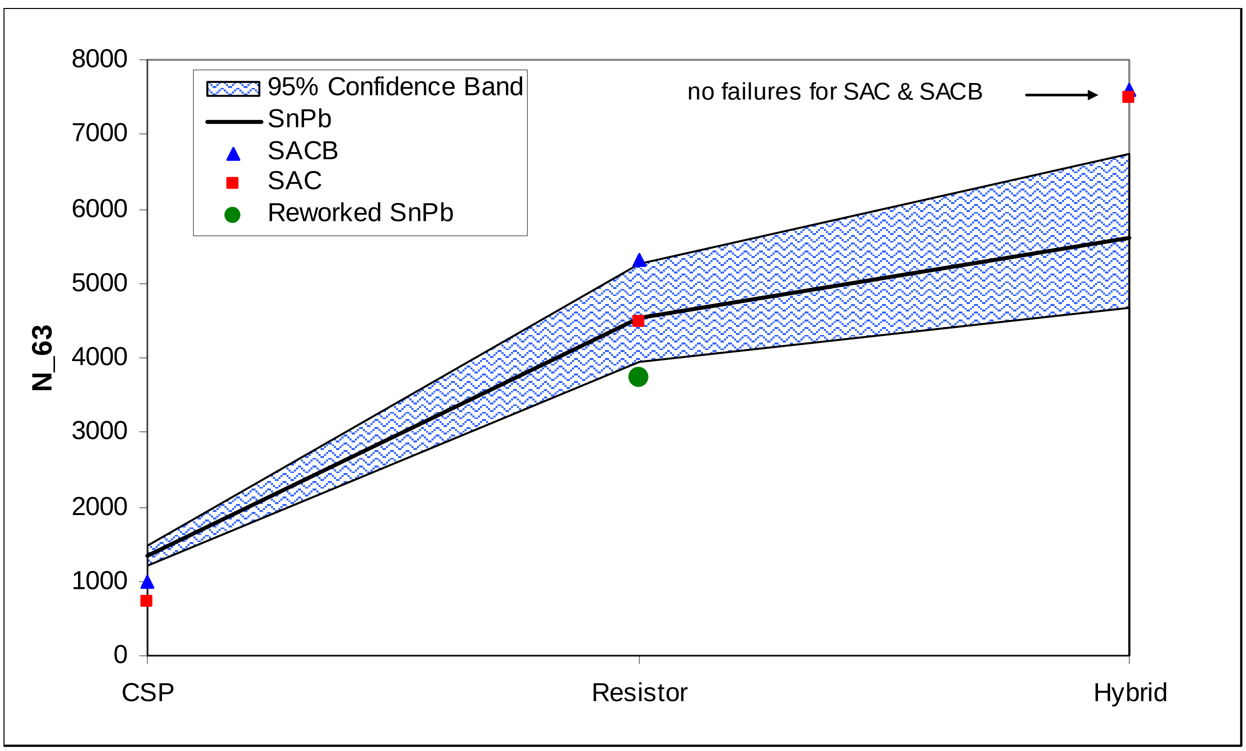
List of Figures in the Appendices

List of Figures in the Appendices

Appendix A Solder Comparison: Average Values to Control Spread



App Fig 1 Pbfree Compared to Tin-Lead Controls: 10% Failure Level in RCI Thermal Cycling



App Fig 2 Pbfree Compared to Tin-Lead Controls: 63% Failure Level in RCI Thermal Cycling

Appendix B Performance Tables for CSPs, Hybrids, and Resistors

App Table 1 N1/N10/N63 Solder Performance for -55C to +125 C Thermal Cycle Testing

Solder Performance				
Component	**Solder/Finish**	**1st Failure**	**N10**	**N63**
CSP	SnPb/SnPb	549	836	1336
	SAC/SAC	89	190	730
	SACB/SACB	81	224	1003
Hybrid	SnPb/SnPb	3676	4157	5610
	SAC/SAC	NF	NF	NF
	SACB/SACB	NF	NF	NF
SMT Resistors	SnPb/Sn (Tg – 170°C)	2702	3228	4943
	SnPb/Sn (Tg – 140°C)	2138	2494	3734
	SAC/Sn	1702	2263	5199
	SACB/Sn	3343	3851	6775
SMT Capacitors	SnPb/ Sn	NA	NA	NA
	SAC/ Sn	NA	NA	NA
	SACB/ Sn	NA	NA	NA

*NF = Not Enough Failures for the Generation of Weibull N10 and N63Values

*NA = Not Applicable due to absence of event detection data prevented collection of cumulative failure distribution data

App Table 2 Solder Performance Comparison for -55C to +125 C Thermal Cycle Testing

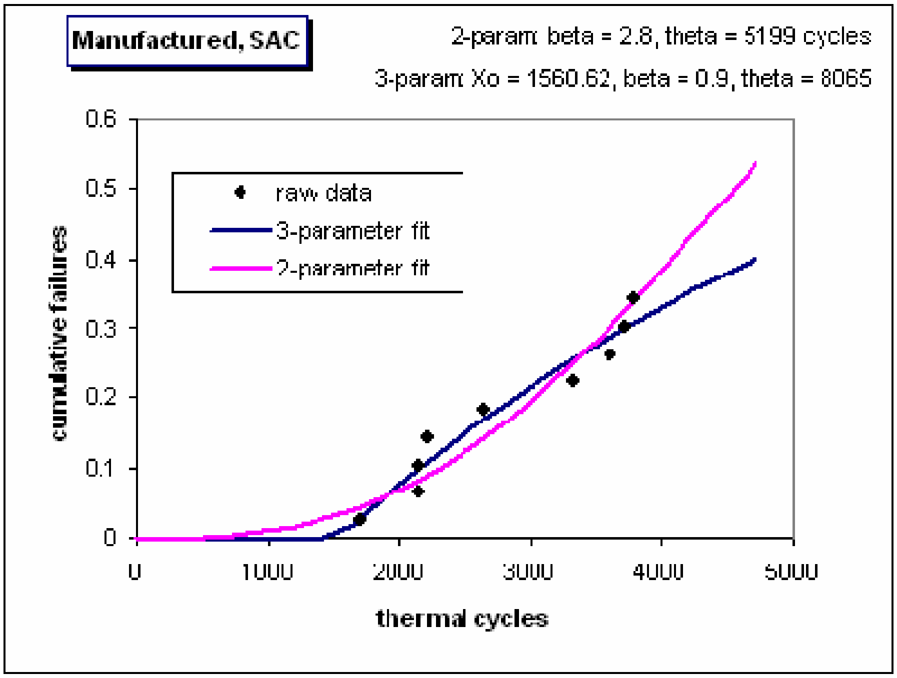
Relative Solder Performance				
Component	**Solder/Component Finish**	**1st Failure**	**N10**	**N63**
CSP	SnPb/SnPb	0	0	0
	SAC/SAC	--	--	--
	SACB/SACB	--	--	--
Hybrid	SnPb/SnPb	0	0	0
	SAC/SAC	++	++	++
	SACB/SACB	++	++	++
SMT Resistors	SnPb/Sn (Tg – 170°C)	0	0	0
	SnPb/Sn (Tg – 140°C)	--	--	--
	SAC/ Sn	--	--	+
	SACB/ Sn	++	+	++
SMT Capacitors	SnPb/ Sn	NA	NA	NA
	SAC/ Sn	NA	NA	NA
	SACB/ Sn	NA	NA	NA

Legend:
0 = Same as control or <5% difference
+ = 5 to 20%
++ = >20%
- = -5 to -20%
-- = >-20% (red if much greater than -20%)
NA = Not Available (not enough failures)
NT = Not Tested

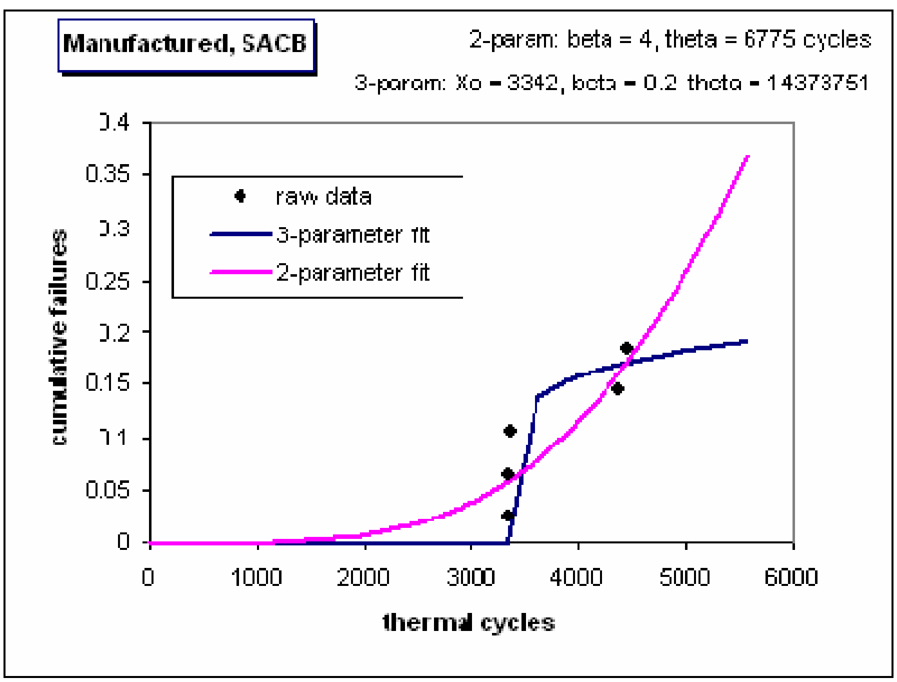
App Table 3 -55C to +125C Thermal Cycle Raw Data

CSP	SnPb/SnPb	549, 806, 890, 974, 1028, 1053, 1091, 1121, 1122, 1168, 1210, 1232, 1244, 1249, 1252, 1336, 1360, 1388, 1397, 1429, 1432, 1433, 1471, 1701, 1743
	SAC/SAC	89, 118, 183, 389, 389, 411, 428, 433, 435, 446, 509, 510, 523, 578, 580, 629, 653, 843, 851, 851, 890, 1021, 1483, 1527, 1574
	SACB / SAC	81, 185, 201, 262, 413, 433, 512, 526, 553, 594, 804, 804, 901, 911, 957, 959, 1000, 1107, 1172, 1272, 1495, 1574, 1733, 1767, 1808
Hybrid	SnPb/SnPb	3676, 4381, 4478, 4664, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
	SAC/SAC	DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
	SACB/SACB	DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
Resistors	SnPb/Sn (Tg – 170°C)	2702, 3079, 3301, 3343, 3593, 3933, 4152, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
	SnPb/Sn (Tg – 140°C)	1871, 2143, 2322, 2400, 2474, 2502, 2586, 2615, 2636, 2638, 2676, 2691, 2746, 2776, 2843, 2855, 2872, 2899, 2930, 2978, 2982, 3044, 3050, 3061, 3061, 3061, 3083, 3085, 3135, 3194, 3196, 3200, 3207, 3245, 3265, 3296, 3298, 3298, 3313, 3334, 3343, 3344, 3346, 3352, 3354, 3354, 3492, 3560, 3574, 3683, 3692, 3784, 3889, 4000, 4036, 4117, 4144, 4192, 4519, 4519, 4530, 4531, 4664, 4691, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
	SAC/Sn	1702, 2138, 2138, 2203, 2644, 3323, 3601, 3717, 3776, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF
	SACB/Sn	3343, 3343, 3345, 4362, 4452, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF, DNF

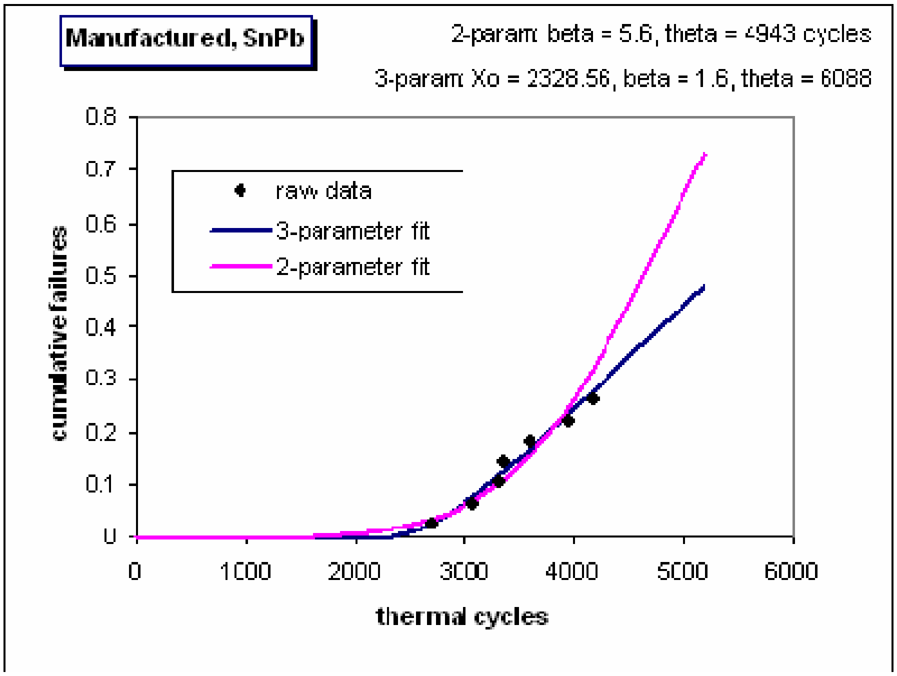
Appendix C Additional Weibull Charts Components/Test Vehicles



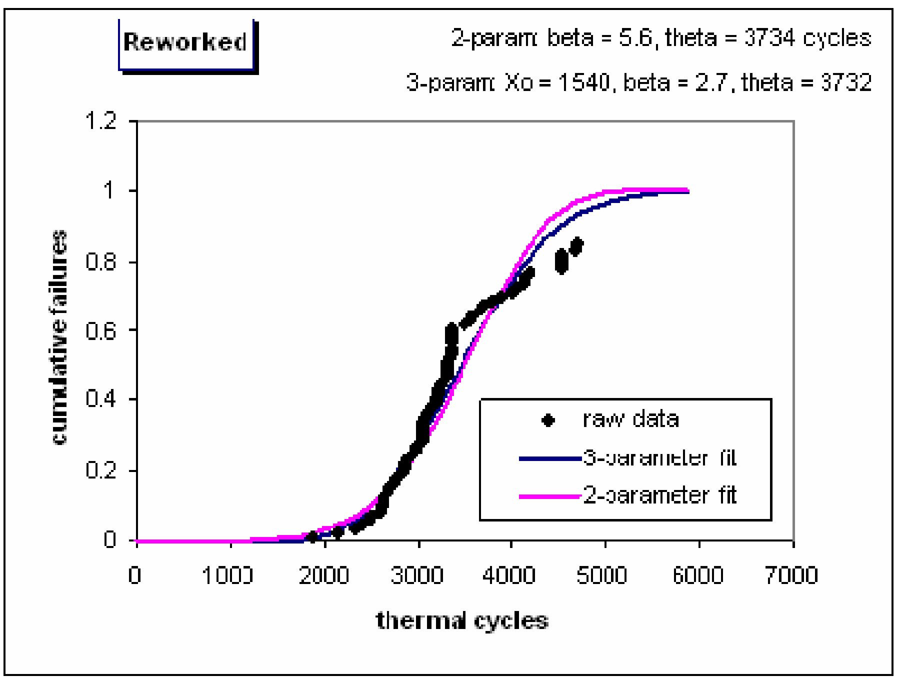
App Fig 3 Resisters SAC for the "Manufactured" test vehicles (170°C Tg)



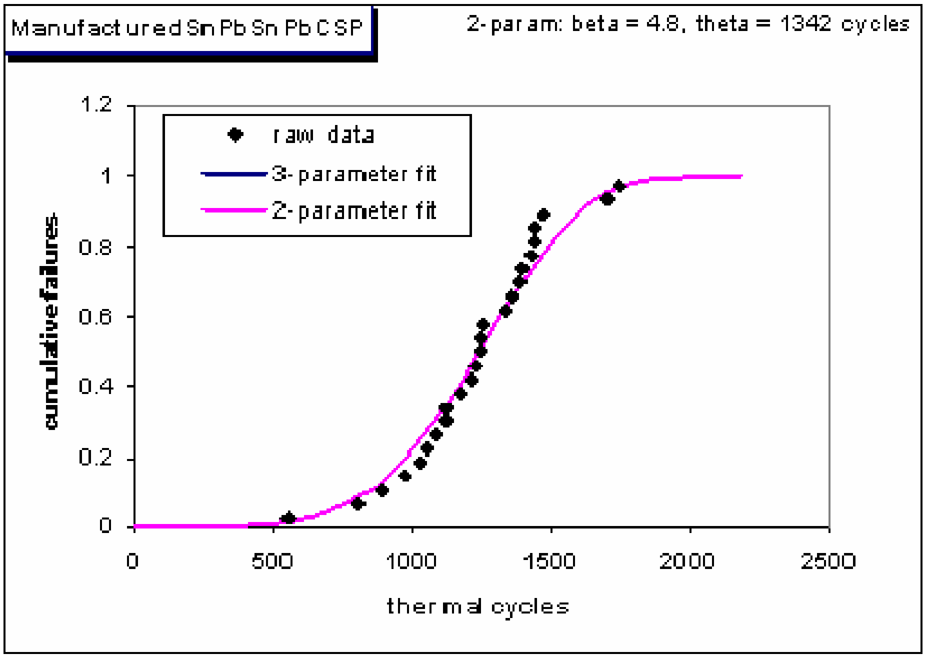
App Fig 4 Resisters SACB for the "Manufactured" test vehicles (170°C Tg)



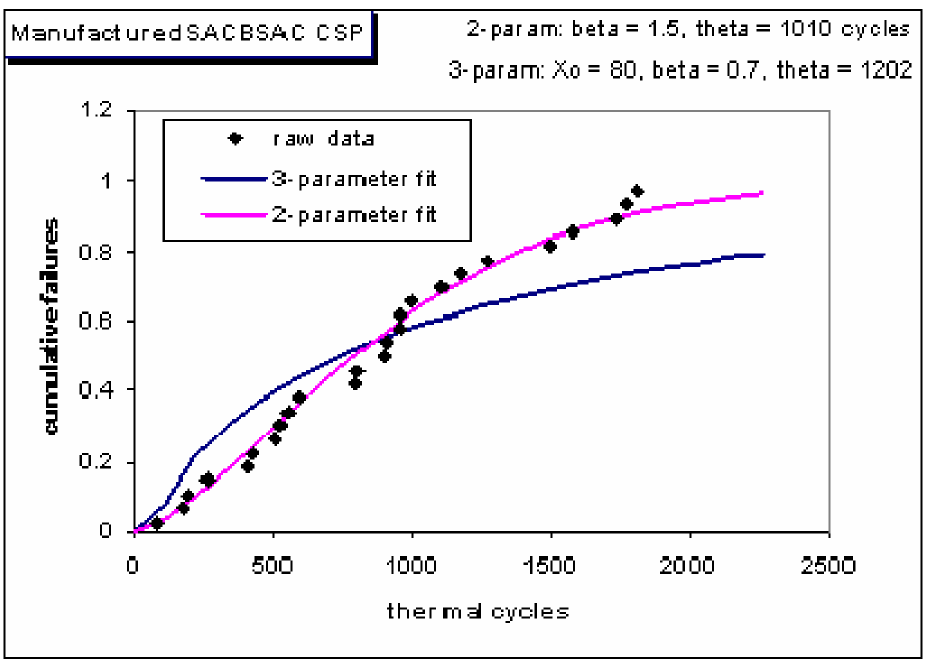
App Fig 5 Resisters SnPb for the "Manufactured" test vehicles (170°C Tg)



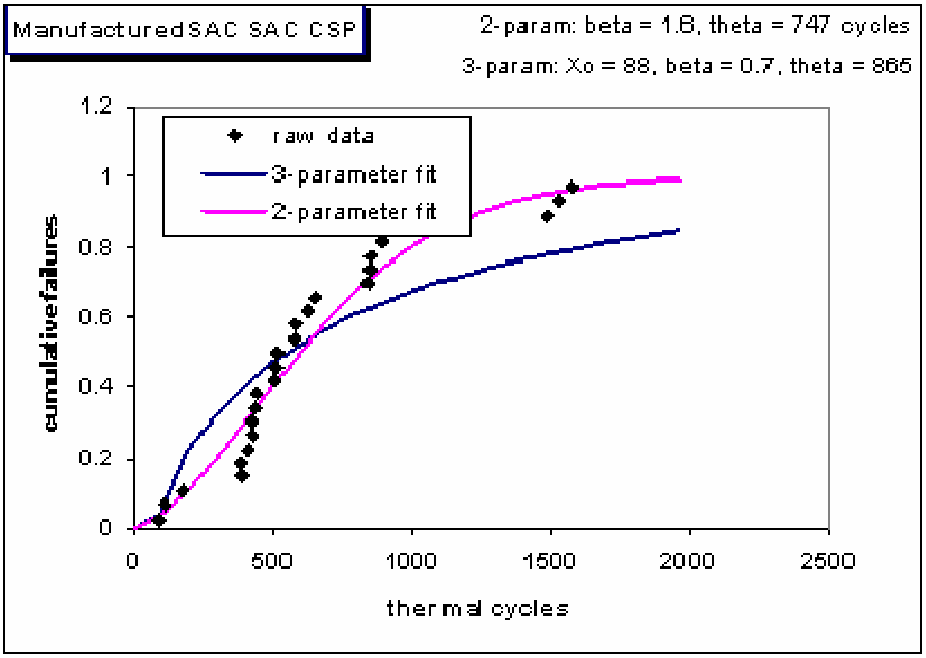
App Fig 6 Resisters SnPb for the "Reworked" test vehicles (140°C Tg)



App Fig 7 CSP SnPb for the "Manufactured" test vehicles (170°C Tg)



App Fig 8 CSP SACB for the "Manufactured" test vehicles (170°C Tg)



App Fig 9 CSP SAC for the "Manufactured" test vehicles (170°C Tg)