Reliability of Sn/Pb and Lead-free (SnAgCu) Solders of Surface Mounted Miniaturized Passive Components for Extreme Temperature (-185°C to +125°C) Space Missions*

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Abstract:

Surface mount electronic package test boards have been assembled using tin/lead (Sn/Pb) and lead-free (Pb-free or SnAgCu or SAC305) solders. The soldered surface mount packages include ball grid arrays (BGA), flat packs, various sizes of passive chip components, etc. They have been optically inspected after assembly and subsequently subjected to extreme temperature thermal cycling to assess their reliability for future deep space, long-term, extreme temperature environmental missions. In this study, the employed temperature range (-185°C to +125°C) covers military specifications (-55°C to +100°C), extreme cold Martian (-120°C to +115°C), asteroid Nereus (-180°C to +25°C) and JUNO (-150°C to +120°C) environments. The boards were inspected at room temperature and at various intervals as a function of extreme temperature thermal cycling and bake duration. Electrical resistance measurements made at room temperature are reported and the tests to date have shown some change in resistance as a function of extreme temperature thermal cycling and some showed increase in resistance. However, the change in interconnect resistance becomes more noticeable with increasing number of thermal cycles. Further research work will be carried out to understand the reliability of packages under extreme temperature applications (-185°C to +125°C) via continuously monitoring the daisy chain resistance for BGA, Flat-packs, lead less chip packages, etc. This paper will describe the experimental reliability results of *miniaturized* passive components (01005, 0201, 0402, 0603, 0805, and 1206) assembled using surface mounting processes with tin-lead and lead-free solder alloys under extreme temperature environments.

Key Words: Reliability, extreme temperatures, baking, thermal cycling, Mars environments, Jupiter environments, intermittent failures, passive components, passive chip resistors, lead-free, tin-lead solders.

Introduction:

Tin63/Lead37 (Sn/Pb or Sn63/Pb37) solders are being used in electronic packaging industry and aerospace applications. There may be an urgent need for the replacement of Sn/Pb solders with alternate materials such as lead-free solder due to environmental and health reasons or concerns. Sn/Pb solder materials have unique properties such as reliability, known physical and chemical properties, and also the cost to use these materials in several applications due to established technical infrastructure in commercial manufacturing industries. Due to the rapid advancement of computer and other technologies many electronic products are normally disposed in landfill. These discarded products include lead from solder material which will contaminate the underground water and subsequently damage the health of human beings. The usable life of the consumer electronic products these days is very short which will *in-turn* have a significant impact on our living environment. The most important applications for miniaturized passive and other components/parts are package-on-package, high density printed circuit assemblies, mobile phones, radio-frequency modules, micro drives, hand-held memory products, portable application-mobile phones, and digital cameras.

Titan (-180^oC, for a proposed Titan *in-situ* mission), Europa (-160^oC, for a proposed Europa surface and subsurface mission), asteroids (-185^oC, MUSES-CN project), comets (-140^oC, for a proposed comet nucleus sample return), Earth's moon (recorded temperature on the moon: -233^oC to +123^oC, moon mineralogy and mapper, M3), and Mars [MER (-120^oC to +85^oC), MSL (-143^oC to +85^oC)] require operations of thermally uncontrolled hardware under extremely cold temperatures and hot temperatures with a large diurnal temperature change/swing from day to night. Planetary protection requires the hardware to be baked at +125^oC for 72 h to kill microorganisms to avoid any biological contamination, especially for sample return missions. NASA standards thermal cycling temperature range varies from -55^oC to +100^oC per NHB-5300.4 (3A-1) (NASA Handbook: Requirements for soldered electrical connections, Dec 1976). Therefore, the present Sn/Pb and SnAgCu package reliability research study has encompassed the temperature range of -185^oC to +125^oC to cover various potential future NASA deep space missions.

Hardware used in space exploration missions could experience temperature extremes of -230^oC to +200^oC. Evaluation of lead-free electronics currently being conducted focuses on a standard set of temperature ranges, -20^oC to +80^oC, -55^oC to +125^oC, -40^oC to +125^oC and -40^oC to +150^oC, none of which approaches the expected operating temperatures of space exploration issues. Testing of lead-free electronics used in space exploration hardware will need to be conducted in a simulated deep space environment in order to truly understand the reliability of lead-free electronic packaging technologies.

Pan et al., have described the *state-of-the-art* technology on lead-free solder-joint reliability in electronics applications [1]. There are no specific regulations banning lead in electronic packaging industry in the USA. The European Union and Japanese electronics industry have taken significant steps particularly to ban lead in the consumer electronics industry. Solder-joint reliability *in general* depends not only on the composition of the solder-joint alloy materials, but also on the metallization of printed circuit board (PCB) and the metallization or finish of component. Physical properties of the Pb-free alloy materials have significant effect on the reliability of the materials for a given application such as Aerospace, Department of Defense (DoD), etc. Solder-joint failures occur due to thermal stress, which are due to coefficient of thermal expansion (CTE) mismatch of the combination of materials. Solder-joint failures are caused by the crack initiation and expand to fracture due to physical effects. Reliability of a solder joint is defined as the probability that the solder joint can perform a required function under given conditions for a given time interval. So the reliability is application specific and the reliability of a solder joint depends on the component (including size, packaging type, component surface finish, and metallization), the PCB surface finish, the solder paste, solder joint geometry, and test conditions. Component size and packaging types, and test conditions determine the loading condition on the solder joint. Intermetallic layers formed at the interfaces between the solder and the component metallization, between the solder and the PCB metallization will affect the mechanical performance of the joint.

The use of lead-free electronics is changing based on the component lead finishes offered by the component manufacturers. This impacts all electronic equipment manufacturers whether or not they need to produce lead-free products. Two considerations when choosing an alternative lead finish are its impact on manufacturing quality and product reliability. Component finishes with acceptable manufacturing quality may have intrinsic solderability with lead based and lead-free solders, a reproducible method for its application, and a reproducible method for soldering quality over an economically viable shelf-life or reliability.

All the component finishes are not available for every electronic package type. Most package styles only have one or two lead-free finishes available. The resistors and capacitors is 100% tin due to its low cost. SnAgCu is by far the choice for ball grid array (BGA) and chip scale packages (CSP) components. Quad flat packages (QFP) and small outline packages are plated tin, tin-bismuth, etc. Reliability of solder connections depend on the integrity of the solder-joint and component finish. The component finish interacts with the solder alloy in a metallurgical reaction to generate a reliable solder-joint which is indicated by solderability. The main function of printed circuit board (PCB) finishes is to enhance the solderability of the substrate or underlying layer so that reliable solder-joints will achieve at the board level assembly. Another important function of the PCB finishes is that it should be wire bondable. Electroless Nickel Immersion Gold (ENIG) is a popular lead-free PCB finish because of its good solderability performance with a lead-free solders and ability to withstand multiple soldering processes.

Among many developed lead-free solders, tin-silver-copper (SnAgCu or SAC) appears the best choice as an alternate to Sn/Pb solder for several applications. There are several technical differences between SnPb and lead-free solders. The reflow temperature of eutectic SnPb solder is lower than SnAgCu or SAC305. The wetting properties, voiding in the solders and appearance of the solders are different for Sn/Pb and lead-free solders. Lead-free solders appear dull and have a poor wetting characteristics and can be improved using inert gas environment. There are more voids in the lead-free solders when compared with Sn/Pb solders. These physical properties may have an effect on the reliability of the lead-free solders.

A study on five board finishes (hot air solder leveled (HASL), NiAu, immersion Ag, immersion Sn, Organic Solderability Preservatives (OSP)) on 2512 chip resistors using the SnAg4.0Cu0.5 (SAC405) solder found that immersion Ag performed about the same as ENIG and immersion Sn. The components were temperature cycled from -55^{o}C to +125^{o}C. Comparison of immersion Ag and ENIG in temperature cycling (0^{o}C to +100^{o}C) of 2512 chip resistors using SAC405 found that the immersion Ag boards had a higher mean life (5803 thermal cycles) than ENIG (5100 cycles) [2] . However, this study used interval break for every 250 thermal cycles and the resistance was checked at room temperature, which may results in longer times to indication of failure.

Sn/Ag/Cu alloy is likely to be the replacement of Sn/Pb solder although it has not been established yet in the literature. Tonapi [3] stated in their review that the absence of critical data on the reliability of lead-free solder joint assemblies has become of increasing concern. Suhling et al., [4] compared thermal cycling reliability of lead-free solder joints of chip resistors 2512 where the board finish was ENIG and the chip resistor finish was pure Sn. Two temperature cycles profiles (-40^{o}C to +125^{o}C and -40^{o}C to +150^{o}C) were used and 6,000 thermal cycles were completed. They found that the reliability of SnAg3.8Cu0.7 and SnPb37 solder alloys was similar at the temperature range from -40^{o}C to +125^{o}C but SnPb37 out performs SnAg3.8Cu0.7 at the temperature range from -40^{o}C to +150^{o}C. Apparently, lead based alloys out performs in reliability at higher strains per Pan et al., [2]. Woodrow [5] found SnPb outperforms SnAgCu in a reliability study of 1206 chip resistors with SnCu0.7 finish. Ochiao et al., [5] have assessed the reliability of solder joints assembled with led-free solder (SnAgCu) that are more harder to deform and are resistant to hardening than conventional tin-lead solder. Therefore, Sn/Ag/Cu solder alloy has a longer fatigue life over standard SnPb solder. Solder materials employed in electronics assemblies are used for many NASA, commercial and DoD applications. Therefore, any change in the soldering materials will have significant impact/implications for space applications. Lead-free soldering materials technology is fast becoming the norm for many commercial applications. Before long, there will be a technology switch to lead-free solder technology for high reliability electronics for NASA applications. The reliability of most lead-free solders is not well known for high reliability applications. [7, 8, and 9]

Despite the many studies on Pb-free alloys there is no worldwide consensus on the solder material of choice. The main reason is that the materials behavior in particular reliability is still insufficiently understood especially fatigue resulting from the applications of cyclical stresses. Solder-joint fatigue is attributed primarily to stresses brought about by temperature swings and mismatches between the coefficients of thermal expansion of the mounted packages solder joints and the PCB. Prior to the actual fatigue, solder-joint first undergo deformation from the cyclical stresses as the temperature alternatives between it's high and low temperatures. Improper design of the solder joint aggravates the effects of this cyclical deformation, which can occur in large steps especially in cases of low cycle fatigue.

Based on the existing published data, to the best of author's knowledge there is no published systematic experimental data available to assess the reliability of Tin-Lead and Lead-free packages in extremely cold and hot temperatures such as -185^{o}C to +125^{o}C and also reliability vs., bake duration. This paper provides preliminary experimental reliability results of lead-free solder alloys and compare with tin/lead alloys under extreme temperatures for deep space applications.

Experimental description:

Board material that has been chosen in this study is IS410 (Isola). IS410 is high-performance FR-4 epoxy laminate designed to support the PCB industry's requirements for higher levels of reliability and the trend to lead-free solder. The glass transition (T_g) temperature of IS410 is +180^{o}C which has superior performance through multiple thermal excursions. This supports small feature size PCB designs for passive and other components to improve the long-term circuit reliability. CTE of this material in z-axis: 65 ppm/^{o}C (pre-T_g) and 250 ppm/^{o}C (post-T_g). CTE of this material in x and y-axis: 11 ppm/^{o}C (pre-T_g) and 13 ppm/^{o}C (post-T_g). Thermal conductivity of this material is around 0.4 to 0.6 W/mK. The maximum operating temperature is +150^{o}C. The board finish that has been employed is Electroless Nickel Immersion Gold (ENIG). Electroless Nickel Immersion Gold has been growing as one of the best finishing methods for PCBs. ENIG is a costlier finish, but offers the best characteristics for PCBs. The electroless nickel is an auto-catalytic process depositing nickel on the palladium catalyzed copper surface. The nickel is then processed with the gold, or the gold applies it-self to the nickel plated areas to protect the nickel until the soldering process. The gold thickness needs to meet tolerances to ensure that the nickel maintains its solderability. Thickness of the board is 0.062" or 62mil. The number of layers of the board is 2. [10]

Figures 1 and 2 shows the schematics of the top and bottom view of the assembled PCBs. Figures 3 and 4 are the temperature profiles that were used to reflow Sn/Pb and SnAgCu solder materials. Figures 5 and 6 are the optical photographs of the boards that were assembled using Sn/Pb and SnAgCu solders and tested in this study to assess the reliability. Tables 1 and 2 show the list of components used to build Sn/Pb based and SnAgCu based test boards. The component finishes (tin finish) have also been shown in the Table 1 for lead-free solder materials. Table 3 shows the various body sizes of the miniaturized passive components such as 01005, 0201, 0402, 0603, 0805, and 1206 which were used to build the test boards and assessed their solder-joint reliability under extreme temperature thermal cycling and bake duration.

Results and Discussion:

Sn/Pb and Lead-free (SnAgCu) solder based boards have been built and subjected to high temperature bake for days to weeks to simulate the planetary protection of the hardware. Solder joints that are subjected to permanent mechanical loading degrade over time and eventually fail. This process will accentuate if the boards are subjected high temperature bake. There were several daisy chained components on Sn/Pb and Lead-free solder boards. Resistance of the daisy chained components on the both types of boards has been measured at room temperature at various time intervals and also at various thermal cycle intervals/breaks. The boards were subjected to +125^{o}C bake in gaseous nitrogen for days to weeks. The total bake time used on these test boards was 2076 hrs (~13 weeks or ~3 months).

Table 4 and Table 5 show the resistance values of the daisy chains of the various types of packages. Initial resistance of the daisy-chains was not measured unfortunately to compare the values due to the effect of baking. Some of the packages in tables 4 and 5 have been highlighted with red that there were some problems from the beginning. The boards were inspected prior to the baking test. QFP 256-2 daisy-chain 1 and PBGA388-2 daisy-chain B or 2 in Sn/Pb PCB test board have shown an open-circuit from the time they were measured. QFP 100-1 daisy-chain 1 and QFP100-2 daisy-chain 2 in lead-free PCB test board have shown an open-circuit from the time they were measured. No other packages either in Sn/Pb or SnAgCu have shown open-circuit or change in resistance have been observed. We do not know whether there are failures at cold or hot temperatures since the resistance monitored only at the room temperature. This is a preliminary study to assess the Sn/Pb and SnAgPb solders on the PCB boards test.

The total number of thermal cycles performed on this Sn/Pb and SnAgCu test boards was 650 cycles. Tables 6 and 7 show the resistance values of the daisy-chains of the various types of packages. Initial resistance of the daisy-chains was not measured unfortunately to compare the values due to the effect of thermal cycling. Some of the packages in tables 6 and 7 have been highlighted with red that there were some problems from the beginning of the test. The boards were inspected prior to the thermal cycling test. PBGA388-2 daisy-chain 2 in Sn/Pb PCB test board has shown an open-circuit from the time they were measured. QFP 100-1 daisy-chain 1 and QFP100-2 daisy-chain 2 in lead-free PCB test board have shown an open-circuit from the time they were measured.

There are five to six packages in Sn/Pb board have shown the higher resistance for the daisy-chains measured. The first failure of QFP256-2 daisy-chain 1 was at 408 thermal cycle break. The failure would have occurred between 297 and 408 thermal cycles. This can be identified in future reliability studies by monitoring the daisy-chains continuously. There are several failures in QFP-256-1 daisy-chain 1, QFP256-2 daisy-chain 1, CVBGA 97-1 daisy-chain 1, BGA256-1 daisy-chain 1 observed during the next chamber break at 521 cycles. The failures would have occurred between 408 and 521 thermal cycles. There are several failures in QFP208-1 daisy-chain 1, in addition to QFP-256-1 daisy-chain 1, QFP256-2 daisy-chain 1, CVBGA 97-1 daisy-chain 1, and

BGA256-1 daisy-chain 1 observed during the next chamber break at 650 cycles. The failures would have occurred between 521 and 650 thermal cycles. Preliminary studies show that several packages which are susceptible to failure beyond 300 extreme temperature thermal cycles. There may be failures below 300 thermal cycles since the resistance was not monitored during thermal cycling and this will be addressed in the future reliability study. The summary of the results have been provided in the Table 6.

There are three packages in Sn/Ag/Cu board have shown the higher resistance for the daisy-chains measured. The first failures of CVBGA97-1 daisy-chain 1, PBGA388-1 daisy-chain 3 or C., MLF68-1 were at 650 thermal cycle break. The failure would have occurred between 521 and 650 thermal cycles. This can be identified in future reliability studies by monitoring the daisy chains continuously. Preliminary studies show that there are some packages which are susceptible to failure beyond 521 extreme temperature thermal cycles. There may be failures below 521 thermal cycles since the resistance was not monitored during thermal cycling and this will be addressed in the future reliability study. The summary of the results have been provided in the Table 7.

Tables 8 and 9 provide the test data for Sn/Pb and SnAgCu solders used in the PCB subjected to extreme temperature thermal cycling that are required for Martian environments. The temperature covered in this test are -130°C to 45°C (Mars winter environments) and -105 °C to 70°C (Mars summer environments). No solder joint failures were observed in either Sn/Pb or SnAgCu boards even after 740 thermal cycles. Further tests will be conducted to assess the reliability for increasing number of thermal cycles.

Figure 7 shows the optical photographs of the miniaturized passive components solder joints after 1356 hours of bake at 125°C. There is subtle change in the microstructure of the solder joints. Figure 8 show the optical photographs of the passive components soldered with Sn/Pb material after 650 extreme temperature thermal cycles. There was a change in microstructure of the solder or increased grainy nature of the solder.

It is also observed that the IS-410 have shown several cracks in the board. This cracking may have an effect on the surface mounted electronic components and their reliability. 1206 passive component solder have started showing signs of damage. Figures 9, 10, and 11 show the optical photographs of the lead-free solder joints that were taken after 408 and 521 thermal cycles. Lead-free solder have shown more damage in the passive component solder-joints after extreme temperature thermal cycling. 1206 passive component has shown cracking in the lead-free solder joint. There were also several cracks in the board material after 650 thermal cycles.

Conclusions:

Surface mount packages and miniaturized passive components have been tested for extreme temperature deep space thermal cycling and baking at high temperature conditions. Two types of boards based on Sn/Pb and SnAgCu (SAC305) solders have been designed and fabricated. Baking has shown the metallographic or grainy structure of the both the solder materials. Sn/Pb solder have started showing damage to the surface mount packages SnAgPb have started shown cracks in the solder joints as a result of thermal cycling for 408 and 521 thermal cycles. IS410 boards have shown significant cracking as a result of extreme temperature thermal cycling. Lead-free solders have shown their vulnerability over Sn/Pb solders with passive components. Whereas other surface components with Sn/Pb solders have shown more damage over the similar components SnAgCu solder. Further studies are needed to understand Sn/Pb and SnAgCu and other potential alloys

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Figure 1: Bottom view of the test board (Source: Practical components)

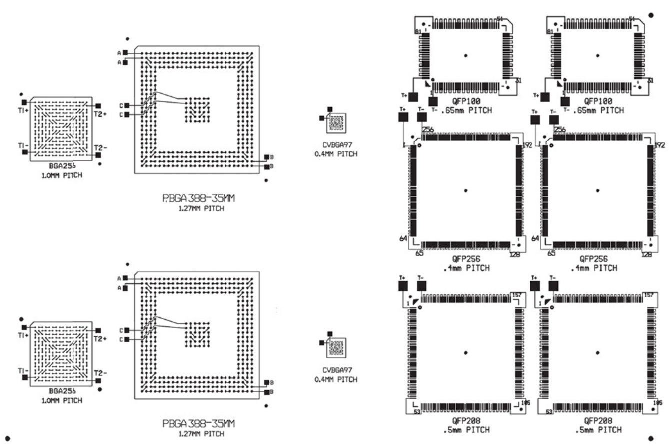

Figure 2: Top view of the test board (Source: Practical components)

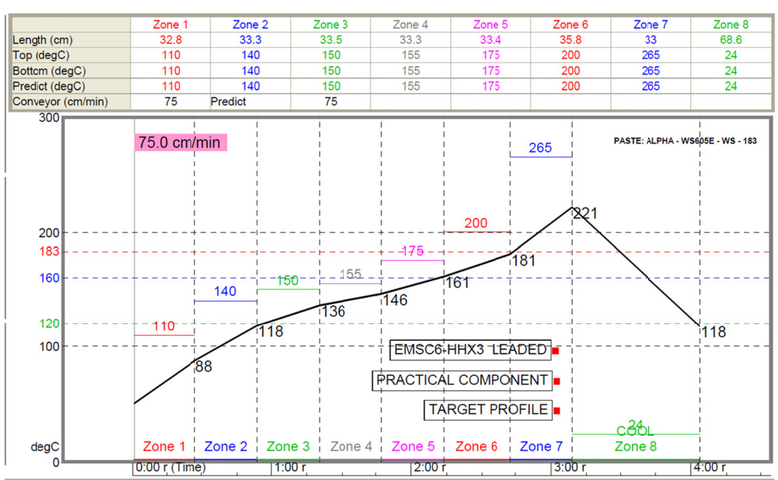

Figure 3: Solder reflow profile for the Sn/Pb alloy used to build the boards.

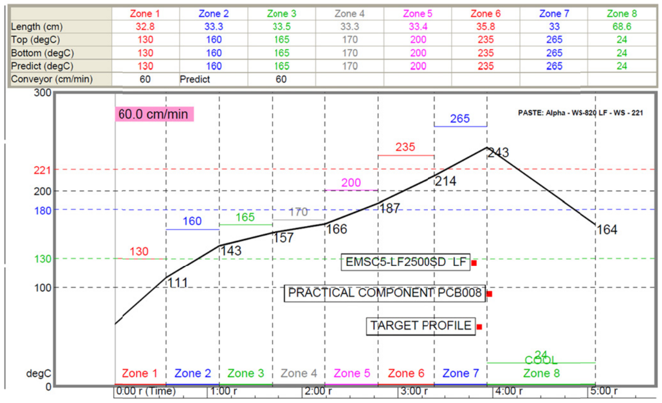

Figure 4: Solder reflow profile for the SnAgCu alloy used to build the boards.

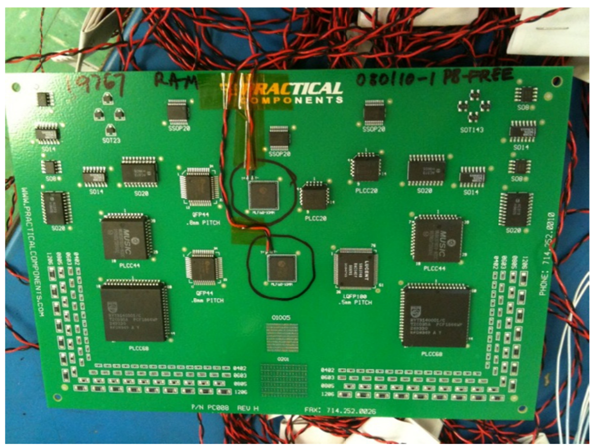

Figure 5: Optical photograph of bottom view of the test board (5.5" x 8")

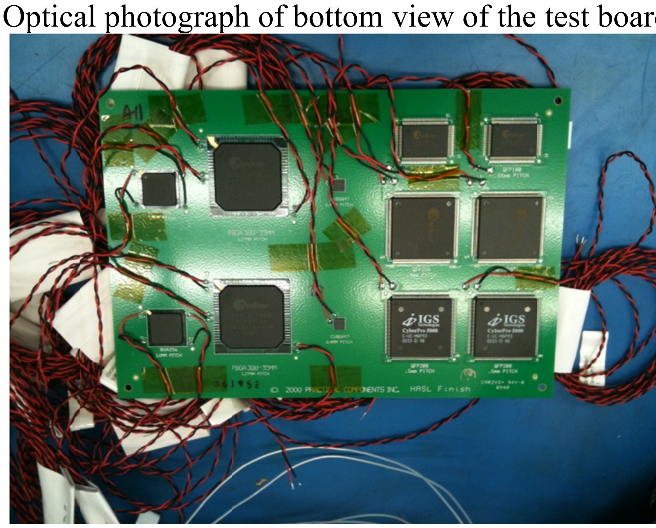

Figure 6: Optical photograph of top view of the test board (5.5" x 8")

Part Description	Quantity Per Board
MLF68-10mm-.5mm-DC-Sn	2
PBGA256-1.0mm-17mm-DC-LF	2
CVBGA97-.4mm-5mm-DC-LF	2
PBGA388-1.27mm-35mm-DC-LF	2
QFP44-10mm-.8mm-3.9mm-Sn	2
QFP100-14x20mm-.65mm-3.9mm-DC-Sn	2
QFP208-28mm-.5mm-2.6mm-DC-Sn	2
QFP256-28mm-.4mm-2.6mm-DC-Sn	2
LQFP100-14mm-.5mm-2.0mm-Sn	1
PLCC20-Sn	2
PLCC44-Sn	2
PLCC68-Sn	2
SO8-3.8mm-Sn	4
SO14-3.8mm-Sn	4
SO20-7.6mm-Sn	4
SSOP20-5.3mm	3
01005SMR-Sn	200
SOT23-TR-Sn	4
SOT143-TR-Sn	4
0201SMR-Sn	180
0402SMR-Sn	52
0603SMR-Sn	42
0805SMR-Sn	36
1206SMR-Sn	32

Table 1: Lead-Free components list

Part Description	Quantity Per Board
MLF68-10mm-.5mm-DC	2
PBGA256-1.0mm-17mm-DC	2
CVBGA97.4mm-5mm-DC	2
PBGA388-1.27mm-35mm-DC	2
QFP44-10mm-.8mm-3.9mm	2
QFP100-14x20mm-.65mm-3.9mm-DC	2
QFP208-28mm-.5mm-2.6mm-DC	2
QFP256-28mm-.4mm-2.6mm-DC	2
LQFP100-14mm-.5mm-2.0mm	1
PLCC20	2
PLCC44	2
PLCC68	2
SO8-3.8mm	4
SO14-3.8mm	4
SO20-7.6mm	4
SSOP20-5.3mm	3
01005SMR	200
SOT23-TR	4
SOT143-TR	4
0201SMR	180
0402SMR	52
0603SMR	42
0805SMR	36
1206SMR	32

Table 2: Tin-Lead components list

Body size of the Resistor	Length, mm	Length, micrometers	Width, mm	Width, micrometers
01005	0.4	400	0.2	200
0201	0.6	600	0.3	300
0402	1	1000	0.5	500
0603	1.7	1700	0.8	800
0805	2	2000	1.25	1250
1206	3.2	3200	1.6	1600

Table 3: Body sizes of the surface mount resistors.

Duration of Burn-In/Annealing of Tin-Lead PCB Board at 125°C

Burn-in duration	QFP208-1	QFP208-2	QFP256-1	QFP256-2	CV BGA 97-1	CV BGA 97-2	PBGA 388-1			PBGA 388-2			BGA 256-1		BGA 256-2		QFP 100-1	QFP100-2	MLF 68-1	MLF 68-2
	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1
Units	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms
0.0 hrs.																				
690.4 hrs.	7.68	7.69	10.47	OC	0.94	0.94	0.53	0.53	0.68	0.53	OC	0.71	0.67	0.73	0.74	0.74	2.67	2.68	Not Measured	Not Measured
842.0 hrs.	7.80	7.76	10.64	OC	0.97	0.98	0.56	0.56	0.72	0.51	OC	0.74	0.86	0.77	0.77	0.77	2.72	2.72	Not Measured	Not Measured
1080.0 hrs.	7.70	7.68	10.48	OC	0.95	0.96	0.56	0.56	0.76	0.56	OC	0.72	0.77	0.75	0.76	0.76	2.68	2.69	Not Measured	Not Measured
1356.0 hrs	7.69	7.69	10.48	OC	0.92	0.93	0.51	0.51	0.67	0.52	0.52	0.67	0.69	0.70	0.71	0.71	2.66	2.68	1.75	1.75
2076.0 hrs	7.66	7.66	10.44	OC	0.95	0.95	0.54	0.54	0.70	0.55	OC	0.71	0.84	0.74	0.76	0.75	2.66	2.67	1.75	1.75

Table 4: Baking of Tin-Lead board at 125°C vs., Duration

Duration of Burn-In/Annealing of Lead-Free PCB Board at 125°C																				
Burn-in duration	QFP208-1	QFP208-2	QFP256-1	QFP256-2	CV BGA 97-1	CV BGA 97-2	PBGA 388-1			PBGA 388-2			BGA 256-1		BGA 256-2		QFP 100-1	QFP100-2	MLF 68-1	MLF 68-2
	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1
Units	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms
0.0 hrs.																				
690.4 hrs.	527.00	526.70	10.91	10.72	1.00	0.97	0.57	0.56	0.76	0.56	0.56	0.75	0.79	0.81	0.80	0.81	OC	OC	Not Measured	Not Measured
842.0 hrs.	554.00	550.60	11.13	10.94	1.00	0.96	0.58	0.54	0.75	0.56	0.55	0.73	0.78	0.79	0.80	0.80	OC	OC	Not Measured	Not Measured
1080.0 hrs.	521.00	520.90	10.85	10.67	0.94	0.97	0.54	0.53	0.73	0.53	0.53	0.72	0.74	0.76	0.76	0.76	OC	OC	Not Measured	Not Measured
1356.0 hrs	531.00	531.20	10.92	OC	0.92	0.95	0.50	0.50	0.71	0.52	0.53	0.72	0.71	0.73	0.74	0.75	OC	OC	1.80	1.78
2076.0 hs	515.30	517.70	10.81	10.66	0.94	0.97	0.53	0.53	0.72	0.54	0.54	0.73	0.76	0.77	0.77	0.78	OC	OC	1.78	1.79

Table 5: Baking of Lead-Free board at 125°C vs. Duration

Tin-Lead PCB Board																				
No. of Thermal Cycles	QFP208-1	QFP208-2	QFP256-1	QFP256-2	CV BGA 97-1	CV BGA 97-2	PBGA 388-1			PBGA 388-2			BGA 256-1		BGA 256-2		QFP 100-1	QFP 100-2	MLF 68-1	MLF 68-2
	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1
Units	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms
0 Cycles																				
172 Cycles	7.99	8.06	10.93	11.25	1.02	0.99	0.57	2.63	0.75	0.57	2.26	0.75	0.80	0.80	0.80	0.80	2.83	2.87	Not measured	Not measured
237 Cycles	7.98	8.06	10.92		0.99	0.99	0.57	2.60	0.75	0.55	1.14	0.75	0.80	0.80	0.80	0.80	2.82	2.86	Not measured	Not measured
297 Cycles	8.03	8.10	10.99	11.31	1.01	1.01	0.57	0.88	0.75	0.57	0.88	0.75	0.79	0.78	0.81	0.80	2.84	2.89	Not measured	Not measured
408 Cycles	7.99	8.08	10.96	106.71	1.01	1.01	0.55	0.88	0.72	0.56	1.90	0.73	0.79	0.79	0.78	0.79	2.84	2.89	Not measured	Not measured
521 Cycles	7.94	8.02	1.87	OC	1.62	1.05	0.58	1.62 (OC)	0.77	0.57	5.28	0.74	0.79	2.56	0.80	0.80	2.84	2.88	1.75	1.77
650 Cycles	7.88	2.20	10.81	OC	8.4 (OC)	1.06	0.54	OC	0.71	0.54	OC	0.71	0.77	0.77	0.77	0.90	2.77	2.81	1.73	1.74

Table 6: Tin-Lead Test board results vs. thermal cycling

Lead Free PCB Board																				
No. of Thermal Cycles	QFP208-1	QFP208-2	QFP256-1	QFP256-2	CV BGA 97-1	CV BGA 97-2	PBGA 388-1			PBGA 388-2			BGA 256-1		BGA 256-2		QFP 100-1	QFP100-2	MLF 68-1	MLF 68-2
	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1
Units	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms
0 Cycles	516.00	520.00	10.23	10.45	1.00	0.98	0.57	0.56	0.75	0.57	0.57	0.75	0.80	0.80	0.79	0.80	OC	OC	Not Measured	Not Measured
172 Cycles	525.00	528.00	10.68	10.66	0.98	0.98	0.57	0.57	0.74	0.57	0.57	0.71	0.80	0.80	0.80	0.80	OC	OC	Not Measured	Not Measured
237 Cycles	519.00	519.00	1061.00	10.60	0.96	0.96	0.55	0.55	0.71	0.55	0.55	0.71	0.80	0.80	0.80	0.80	OC	OC	Not Measured	Not Measured
297 Cycles	537.50	535.20	10.70	10.67	0.95	0.95	0.53	0.53	0.70	0.54	0.54	0.71	0.71	0.78	0.78	0.78	OC	OC	Not Measured	Not Measured
408 Cycles	536.80	536.80	10.72	10.70	1.02	0.99	0.56	0.56	0.72	0.56	0.56	0.73	0.79	0.81	0.79	0.80	OC	OC	Not Measured	Not Measured
521 Cycles	540.60	539.00	10.74	10.71	1.02	1.04	0.54	0.54	0.70	0.54	0.54	0.71	0.73	0.75	0.75	0.76	OC	OC	1.72	1.76
650 Cycles	523.20	523.70	10.58	10.56	3 to 6 (OC)	1.18	0.53	0.53	3.61	0.52	0.52	0.71	0.76	0.76	0.76	0.76	OC	OC	OC	1.72

Table 7: Lead-Free Test board results vs. thermal cycling

Tin-Lead PCB Board (-130C to 45C and -105 to 70C)																				
No. of Thermal Cycles	QFP208-1	QFP208-2	QFP256-1	QFP256-2	CV BGA 97-1	CV BGA 97-2	PBGA 388-1			PBGA 388-2			BGA 256-1		BGA 256-2		QFP 100-1	QFP 100-2	MLF 68-1	MLF 68-2
	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1
Units	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms
0 Cycles	7.25	OC	10.07	OC	0.52	0.52	0.13	0.13	0.28	0.12	0.12	0.27	0.36	0.36	0.34	0.34	2.26	2.26	1.36	1.34
184 Cycles	7.25	OC	10.08	OC	0.55	0.55	0.14	0.14	0.29	0.14	0.14	0.29	0.36	0.36	0.36	0.36	2.27	2.28	1.35	1.35
740 Cycles	7.28	OC	10.12	OC	0.56	0.56	0.15	0.15	0.30	0.16	0.15	0.30	0.37	0.37	0.37	0.36	2.28	2.29	1.37	1.36

Table 8: Tin-Lead Test board results vs. thermal cycling
(-130°C to 45 °C and -105 °C to 70 °C)

Lead Free PCB Board (-130C to 45C and -105 to 70C)																				
No. of Thermal Cycles	QFP208-1	QFP208-2	QFP256-1	QFP256-2	CV BGA 97-1	CV BGA 97-2	PBGA 388-1			PBGA 388-2			BGA 256-1		BGA 256-2		QFP 100-1	QFP 100-2	MLF 68-1	MLF 68-2
	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-3	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-2	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1
Units	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms	Ohms
0 Cycles	510.60	514.60	9.78	10.01	0.53	0.55	0.13	0.13	0.31	0.13	0.13	0.31	0.37	0.36	0.37	0.37	OC	OC	1.40	1.40
184 Cycles	520.00	517.00	9.82	10.03	0.53	0.55	0.13	0.12	0.31	0.13	0.13	0.31	0.35	0.35	0.36	0.36	OC	OC	1.39	1.39
740 Cycles	513.90	514.40	9.83	10.04	0.58	0.59	0.17	0.15	0.35	0.17	0.16	0.35	0.40	0.40	0.40	0.40	OC	OC	1.40	1.40

Table 9: Lead-free test board results vs. thermal cycling (-130 ^{o}C to 45 ^{o}C and -105 ^{o}C to 70 ^{o}C)

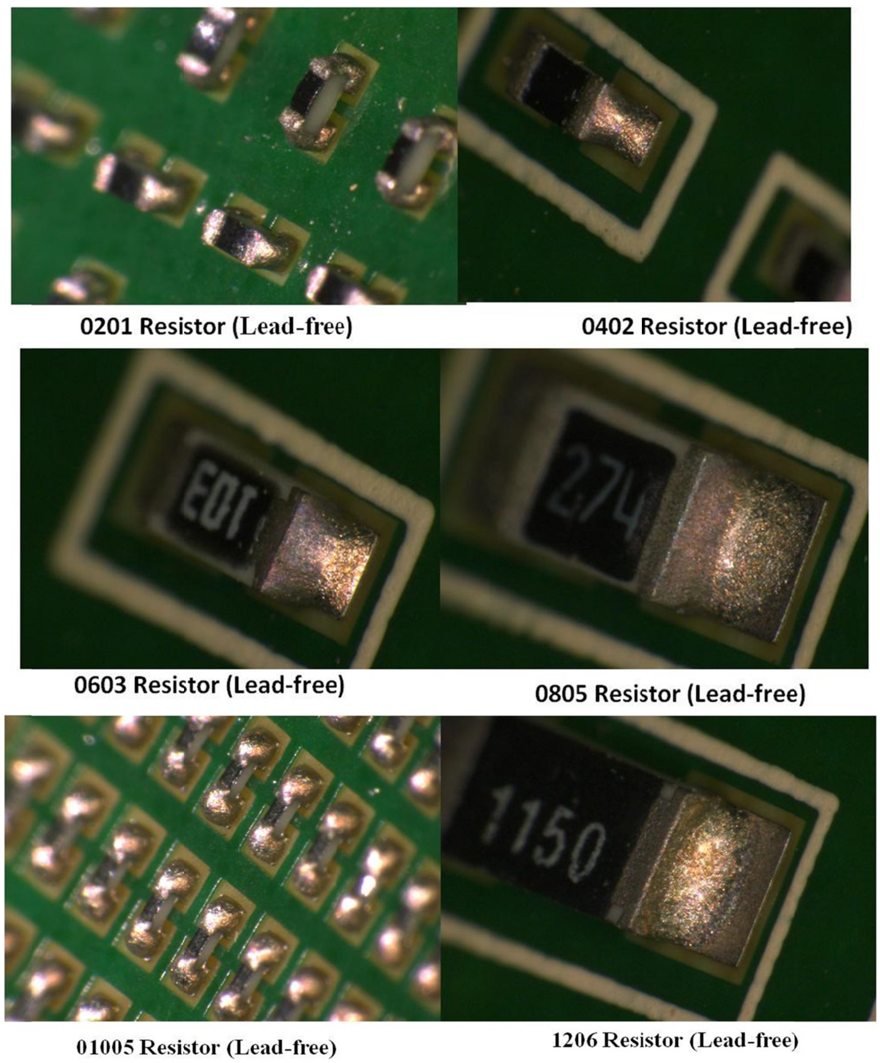

Figure 7: Optical photographs of solder joints of various body size resistor chips after 1356 hours baking.

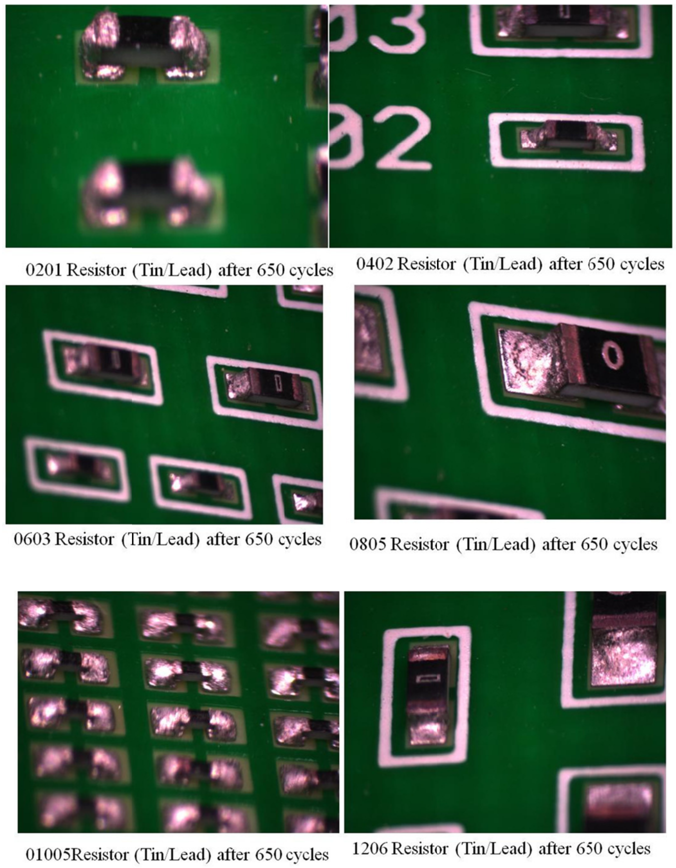

Figure 8: Optical photographs of Sn/Pb solder joints of the Various body sizes of the passive components after 650 Thermal Cycles

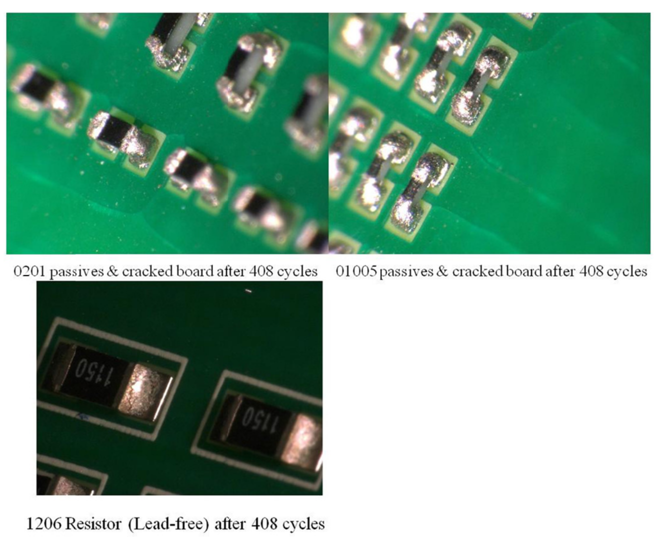

Figure 9: Optical photographs of lead-free solder joints of the various types of packages after 408 Thermal Cycles

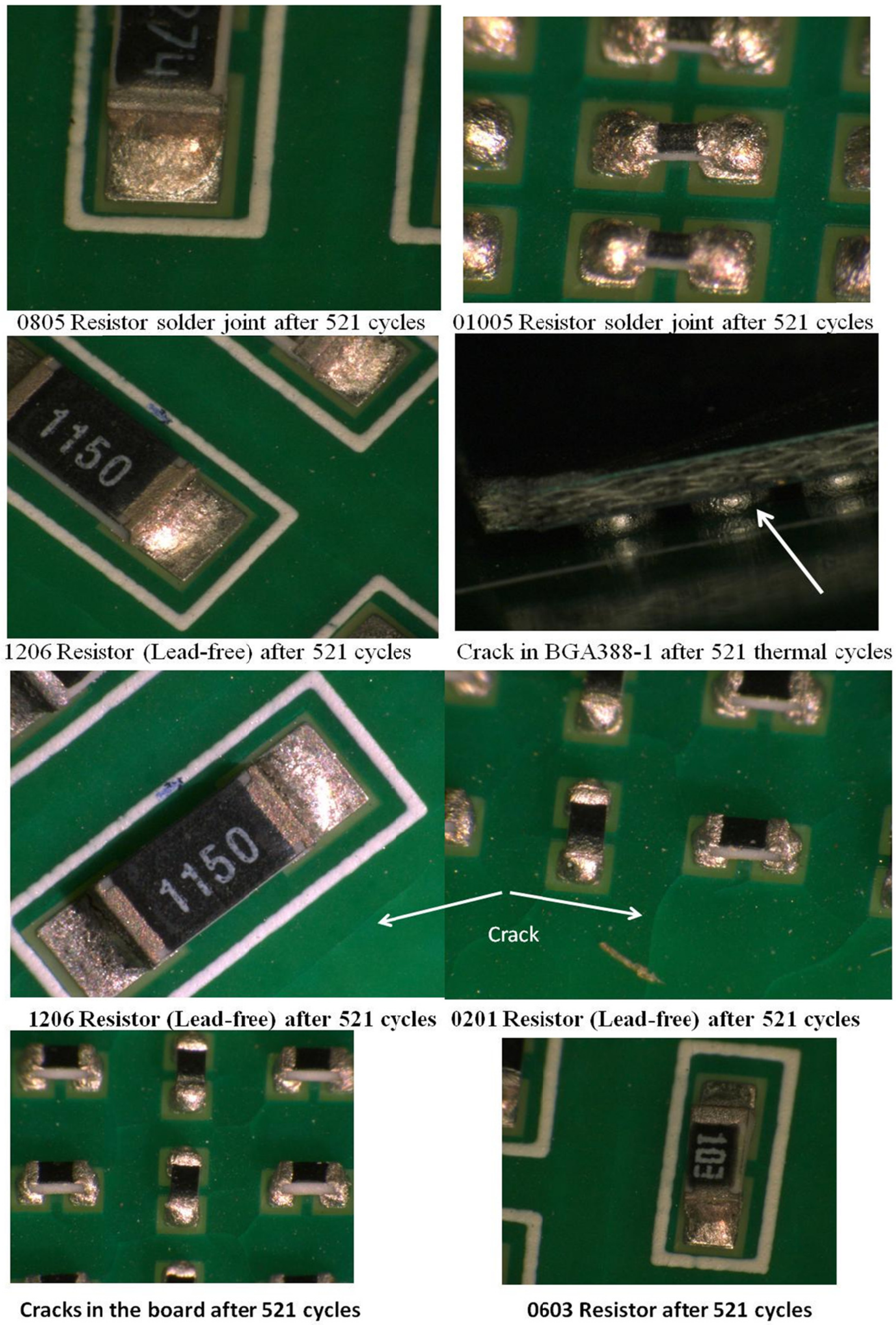

Figure 10: Optical photographs of lead-free solder joints of the various types of packages after 521 Thermal Cycles

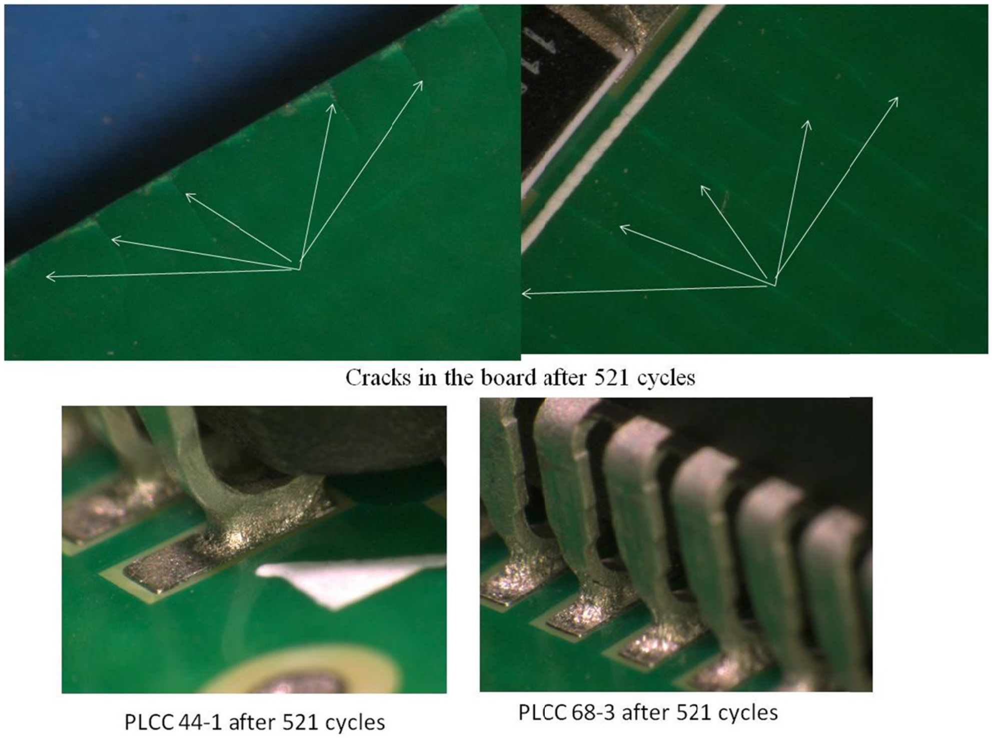

Figure 11: Optical photographs of lead-free solder joints of the various types of packages after 521 Extreme Temperature Thermal Cycling