Reliability of Solder Materials (Sn-Pb & Pb-Free) For Deep Space Missions *

Rajeshuni Ramesham

Jet Propulsion Laboratory/NASA,

Pasadena, CA 91109

Tel: 818 354 7190

e-mail: Rajeshuni.Ramesham@jpl.nasa.gov

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Outline

- Objective
- Introduction
- Environmental Test Conditions
- Board details
- Results and Discussion
- Conclusions
- Acknowledgements

Objective

The purpose of this study is to assess the experimental reliability results of *miniaturized* passive components (01005, 0201, 0402, 0603, 0805, and 1206) assembled using surface mounting processes with tin-lead (Sn-Pb) and lead-free (Pb-Free) solder alloys under extreme temperature deep space environments.

Introduction and the Study

- Titan (-180°C, for a proposed Titan *in-situ* mission)
- Europa (-160°C, for a proposed Europa surface and subsurface mission)
- Asteroids (-185°C, MUSES-CN project)
- Comets (-140°C, for a proposed comet nucleus sample return)
- Earth's moon (recorded temperature on the moon: -233°C to +123°C, moon mineralogy and mapper, M3)
- Mars Exploration Rover, MER (-120°C to +85°C)
- MSL (-143°C to +85°C)] large diurnal temperature change/swing from day to night.
- Planetary protection requires the hardware to be baked at +125°C 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°C to +100°C for 200 thermal cycles

Therefore, the present Sn/Pb and SnAgCu package reliability research study has encompassed the temperature range of -185°C to +125°C to cover various potential future NASA deep space missions.

Sn/Pb & Pb-Free Solders, Where and Why?

- Tin-Lead solders are being used in electronic/aerospace industry.
- Replacement of Sn/Pb solders with alternate materials such as Pb-free solder due to environmental and health reasons or concerns.
- Sn/Pb solder materials have unique properties, reliability, known physical & chemical properties, and also the cost.
- 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 is very short which will *in-turn* have a significant impact on the environment.
- The most important applications for miniaturized passive and other components are
  - package-on-package
  - mobile phones
  - micro drives
  - portable application-mobile phones
  - Space avionics/electronics

high density printed circuit assemblies
radio-frequency modules
hand-held memory products
digital cameras

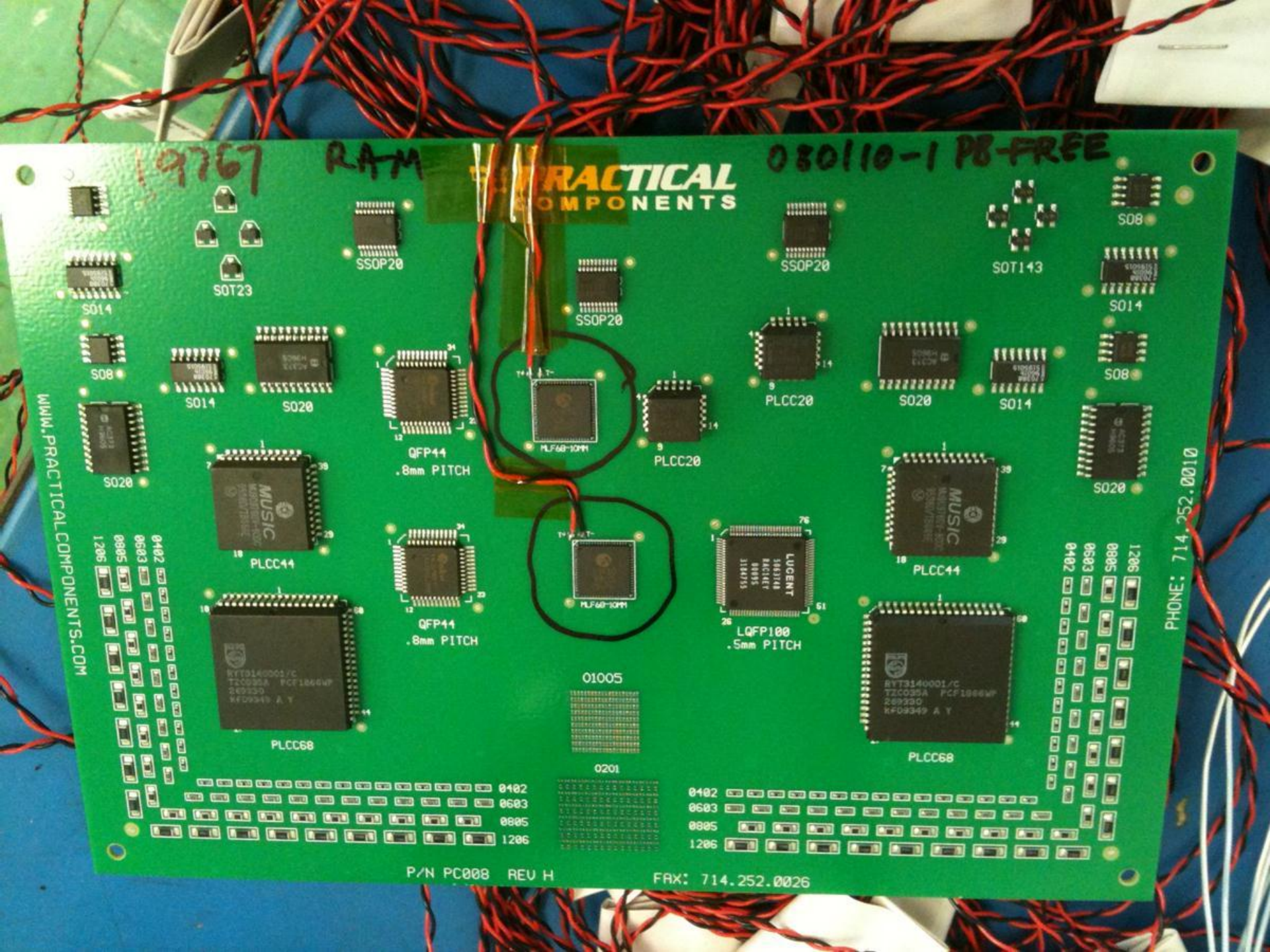
Environmental Test Conditions

Examples of Tests performed

- **Test 1 involves Baking**: +125°C
- **Test 2 involves thermal cycling**: +125°C to -185°C cover deep space missions, multiple NASA missions
- **Test 3 involves thermal cycling: Mars Science Laboratory**
  - Summer season: +40°C to -105°C
  - Winter season: +15°C to -130°C

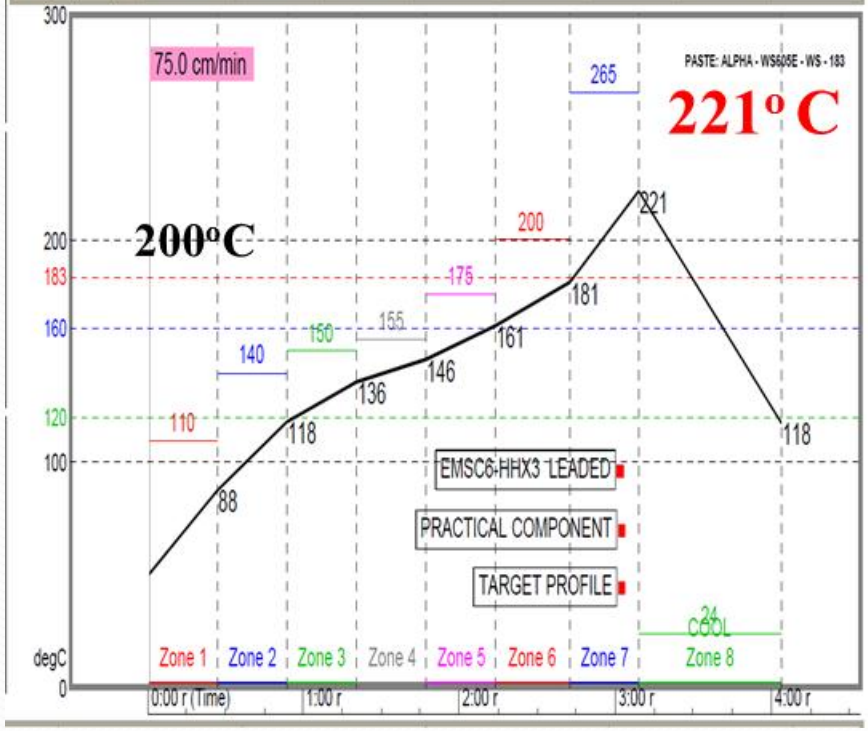
Details of the Test Board

- Board material is IS410 (Isola).
  - IS410 is high-performance FR-4 epoxy laminate designed for higher levels of reliability and the trend to lead-free solder.
  - The glass transition (T_g) temperature of IS410 is +180°C
  - 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°C.
- The board finish that has been employed is Electroless Nickel Immersion Gold (ENIG).
  - ENIG is a costlier finish
- Thickness of the board is 0.062” or 62mil.
- The number of layers of the board is 2.


19767 RAM
080110-1 PB-FREE
PRACTICAL COMPONENTS
SOT23
SSOP20
SSOP20
SSOP20
SOT143
SO8
SO14
SO14
SO8
SO14
SO20
QFP44
.8mm PITCH
MLF60-10MM
PLCC20
PLCC20
SO20
SO14
SO8
SO20
PLCC44
QFP44
.8mm PITCH
MLF60-10MM
LQFP100
.5mm PITCH
PLCC44
PLCC68
PLCC68
01005
0201
0402
0603
0805
1206
WWW.PRACTICALCOMPONENTS.COM
PHONE: 714.252.0010
P/N PC008 REV H
FAX: 714.252.0026

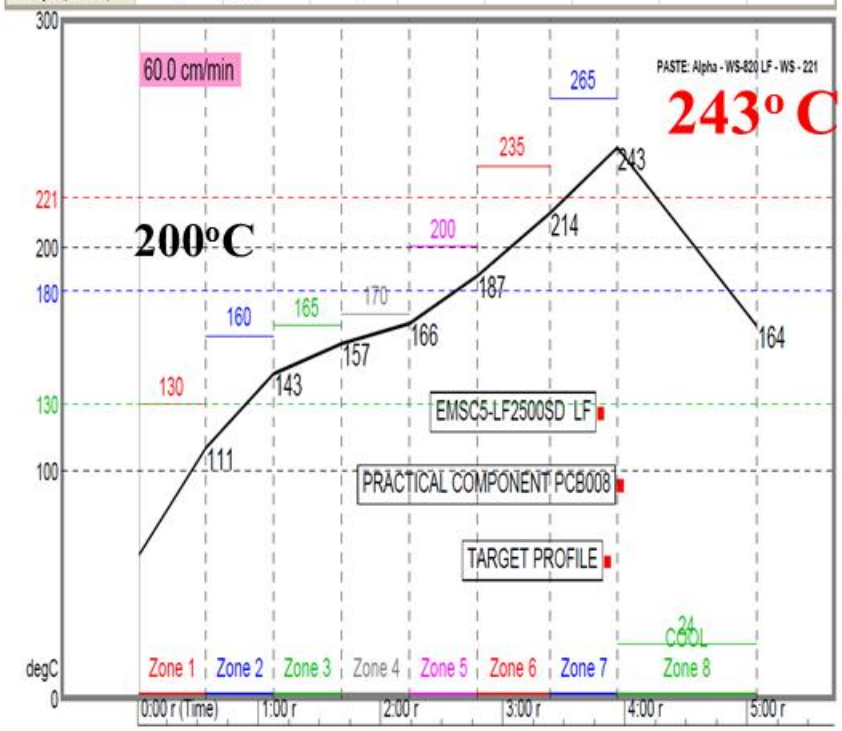
Solder reflow profile for the Sn/Pb alloy used to build the boards

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Length (cm)	32.8	33.3	33.5	33.3	33.4	35.8	33	68.6
Top (degC)	110	140	150	155	175	200	265	24
Bottom (degC)	110	140	150	155	175	200	265	24
Predict (degC)	110	140	150	155	175	200	265	24
Conveyor (cm/min)	75	Predict	75					



Solder reflow profile for the SnAgCu (Pb-free) alloy used to build the boards

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8
Length (cm)	32.8	33.3	33.5	33.3	33.4	35.8	33	68.6
Top (degC)	130	160	165	170	200	235	265	24
Bottom (degC)	130	160	165	170	200	235	265	24
Predict (degC)	130	160	165	170	200	235	265	24
Conveyor (cm/min)	60	Predict	60					



Reflow temperature, C

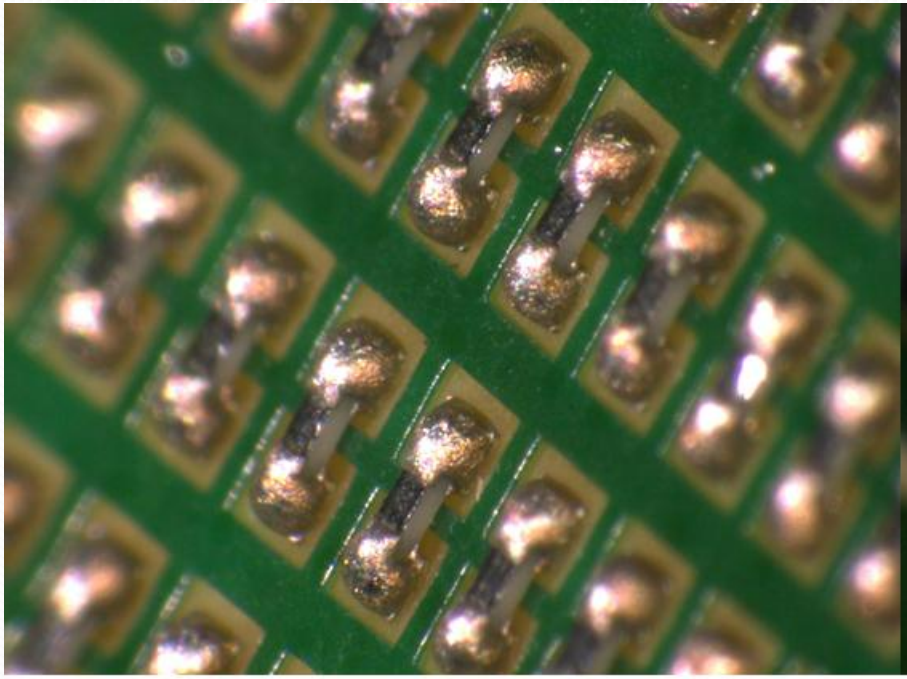
Time, hrs

Time, hrs

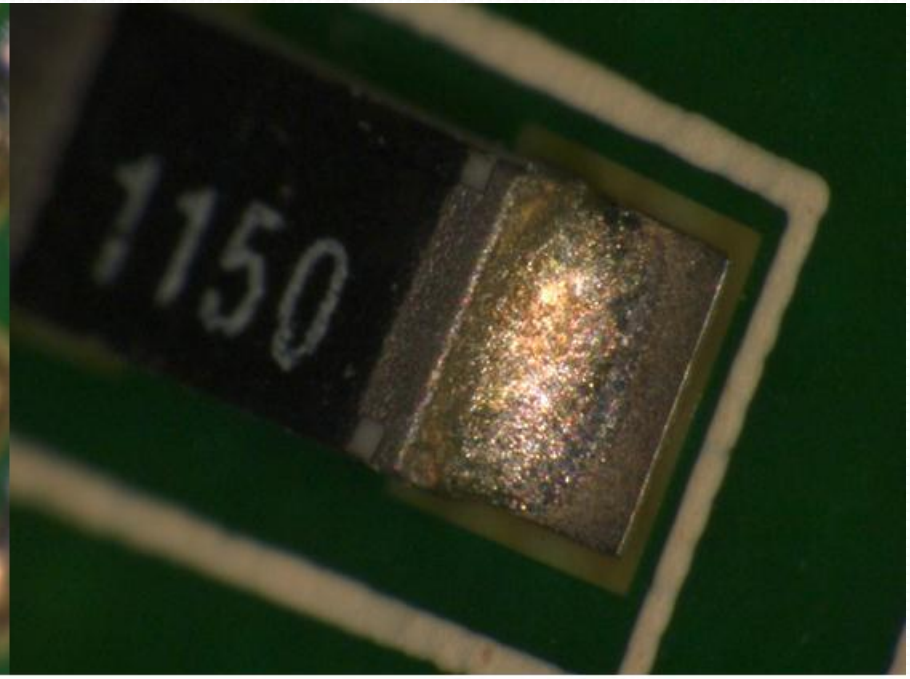
Body sizes of the surface mount resistors

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

Optical images of Pb- free solder joints of various body size resistor chips after 1356 hours baking.

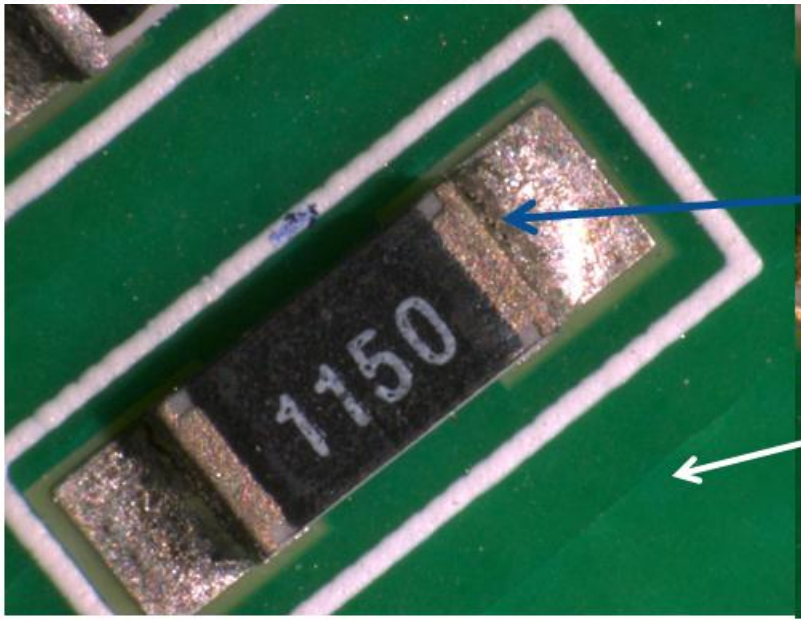


01005 Resistor (Pb-free)

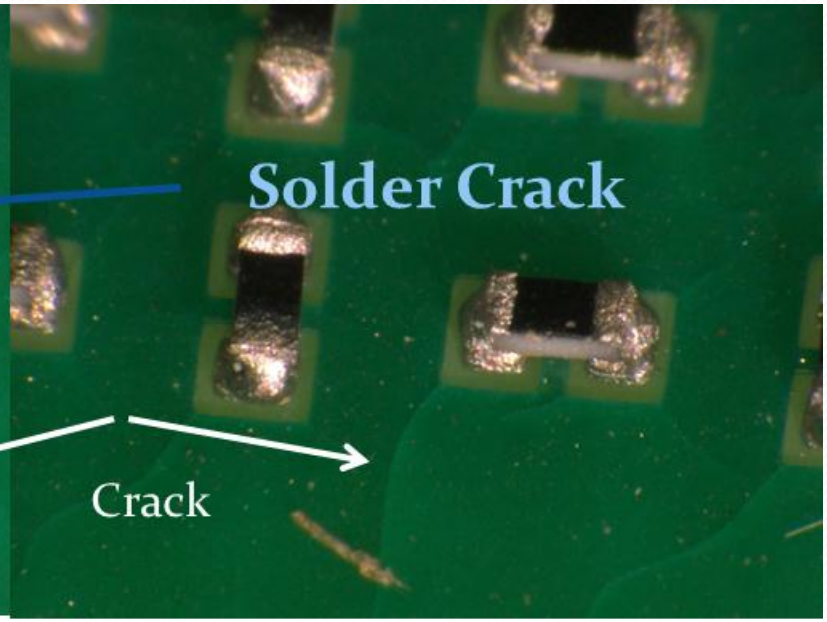


1206 Resistor (Pb-free)

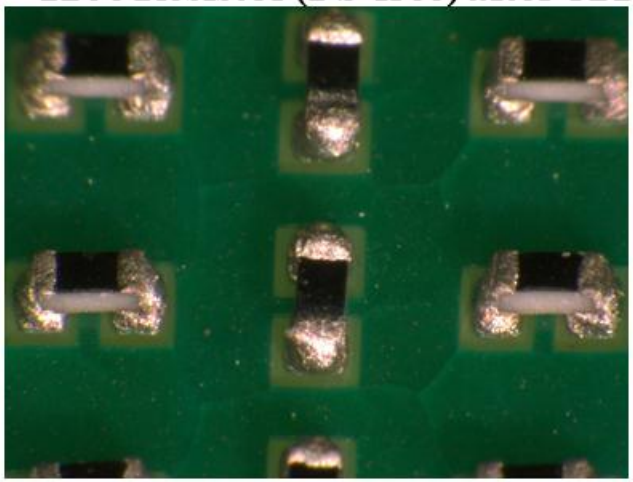
Cracks Observed in the Pb-free Test Boards



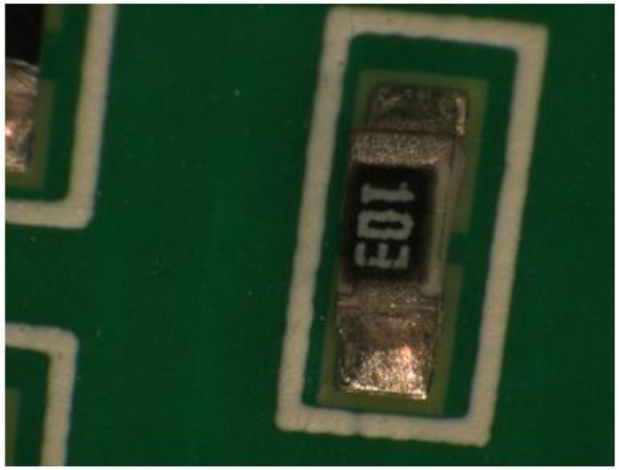
1206 Resistor (Pb-free) after 521 cycles



0201 Resistor (Pb-free) after 521 cycles

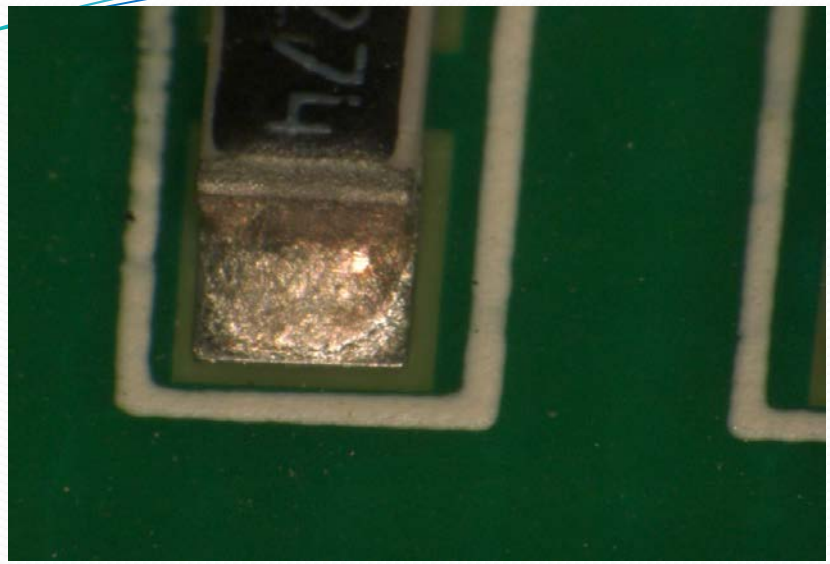


Cracks in the board after 521 cycles

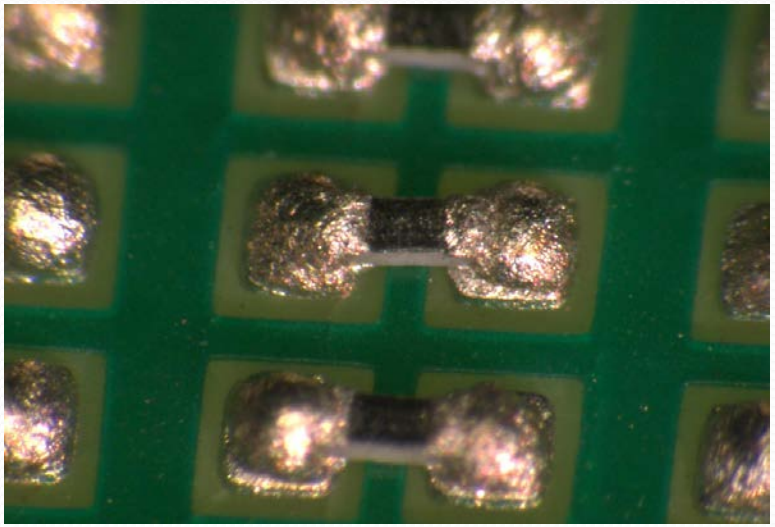


0603 Resistor after 521 cycles

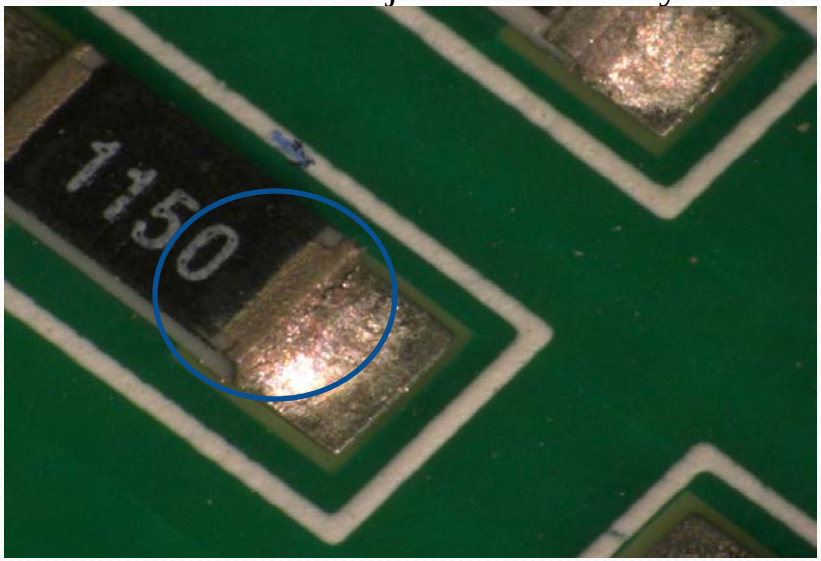
Images of Lead-Free solders of Passives



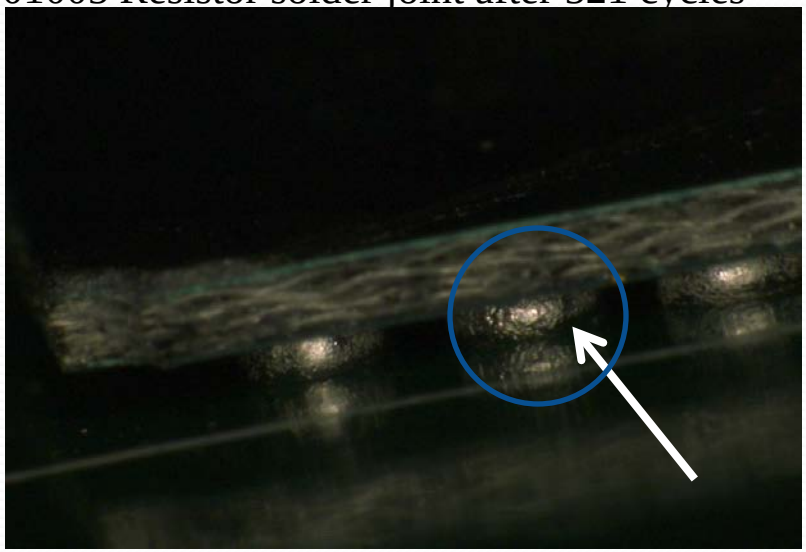
0805 Resistor solder joint after 521 cycles



01005 Resistor solder joint after 521 cycles

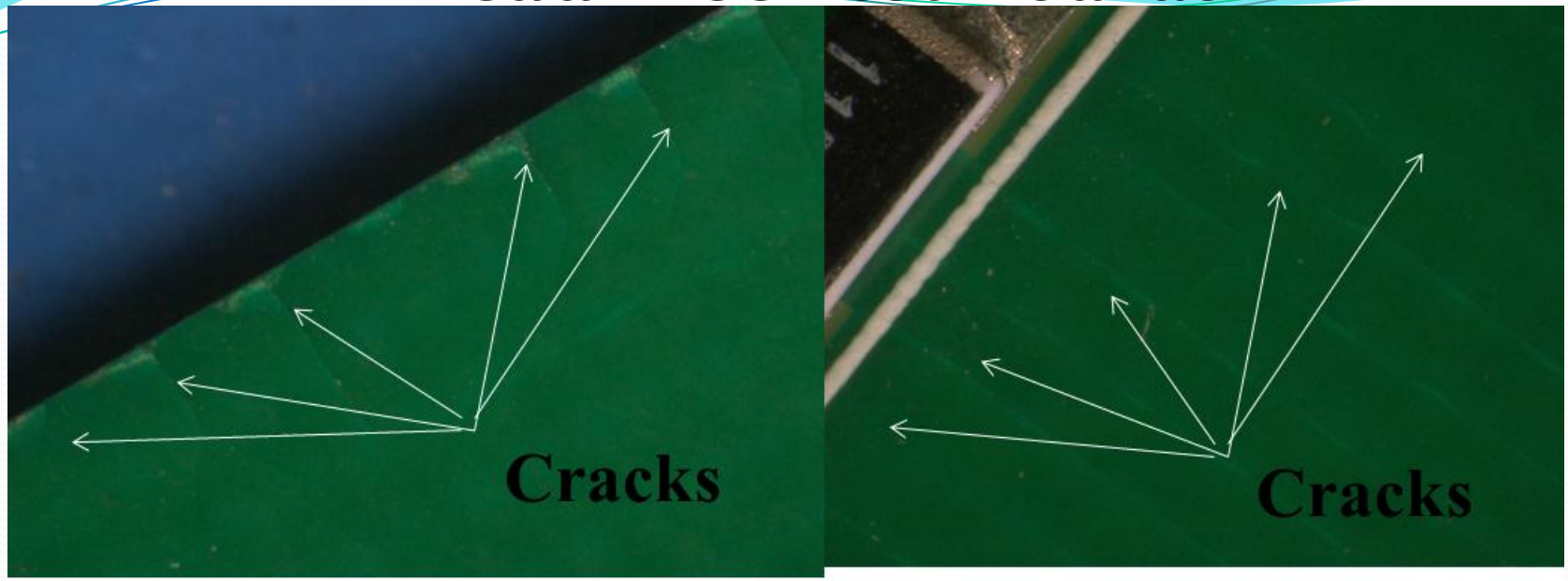


1206 Resistor (Pb-free) after 521 cycles

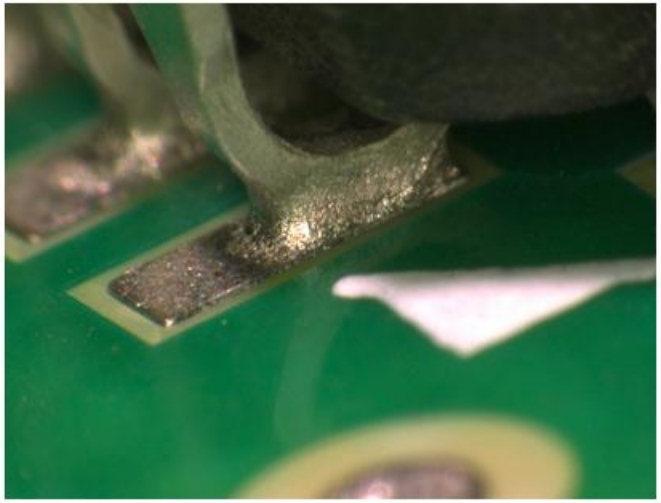


Crack in BGA388-1 after 521 thermal cycles

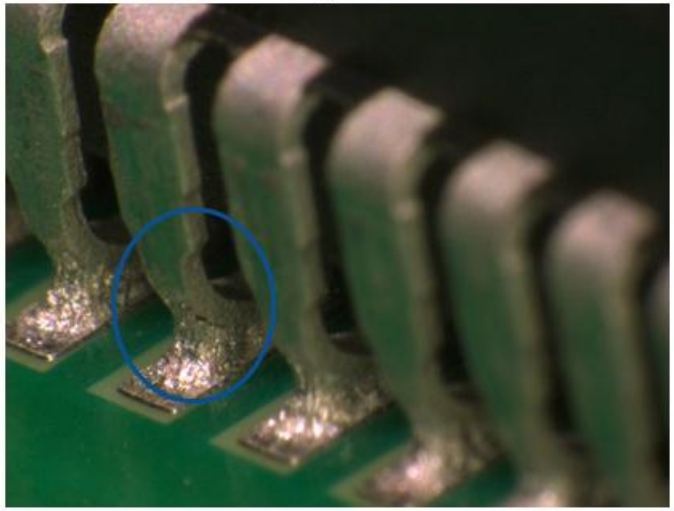
Lead Free Test Boards



Cracks in the board after 521 cycles

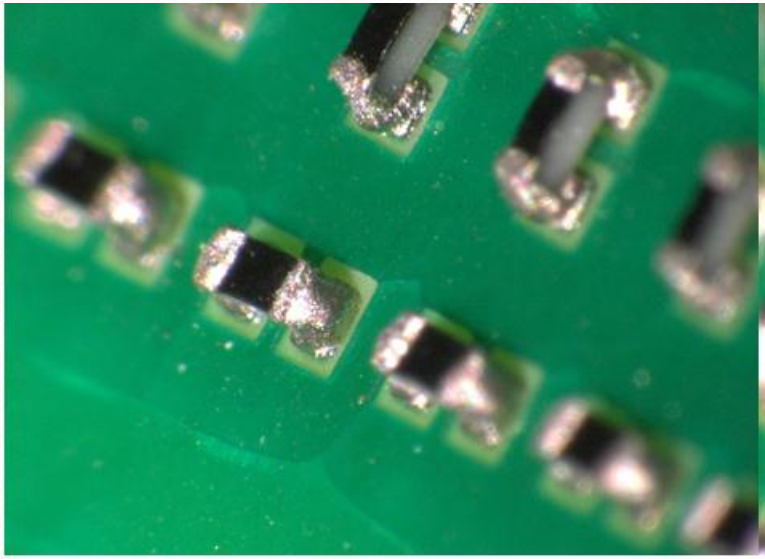


PLCC 441 after 521 cycles

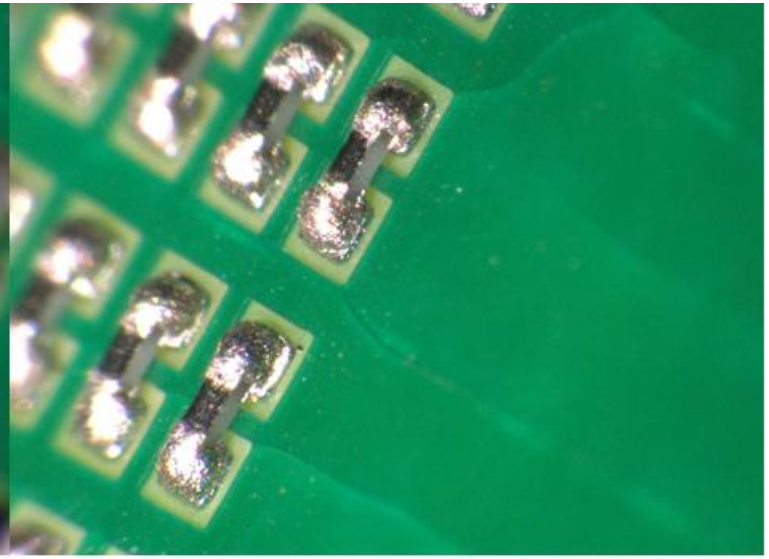


PLCC 68-3 after 521 cycles

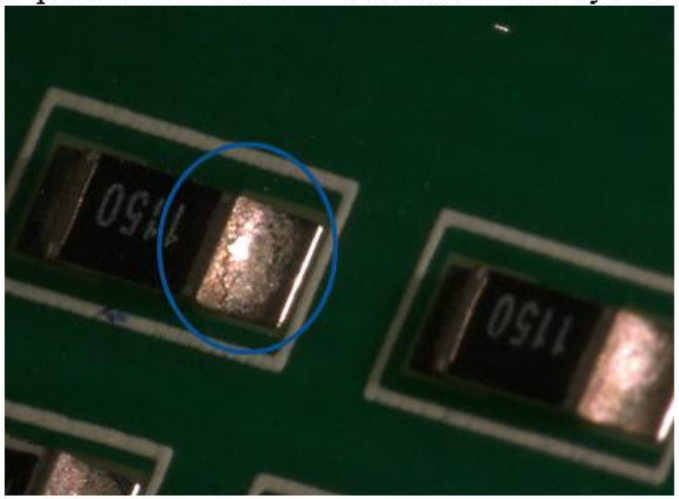
Lead-Free



0201 passives & cracked board after 408 cycles

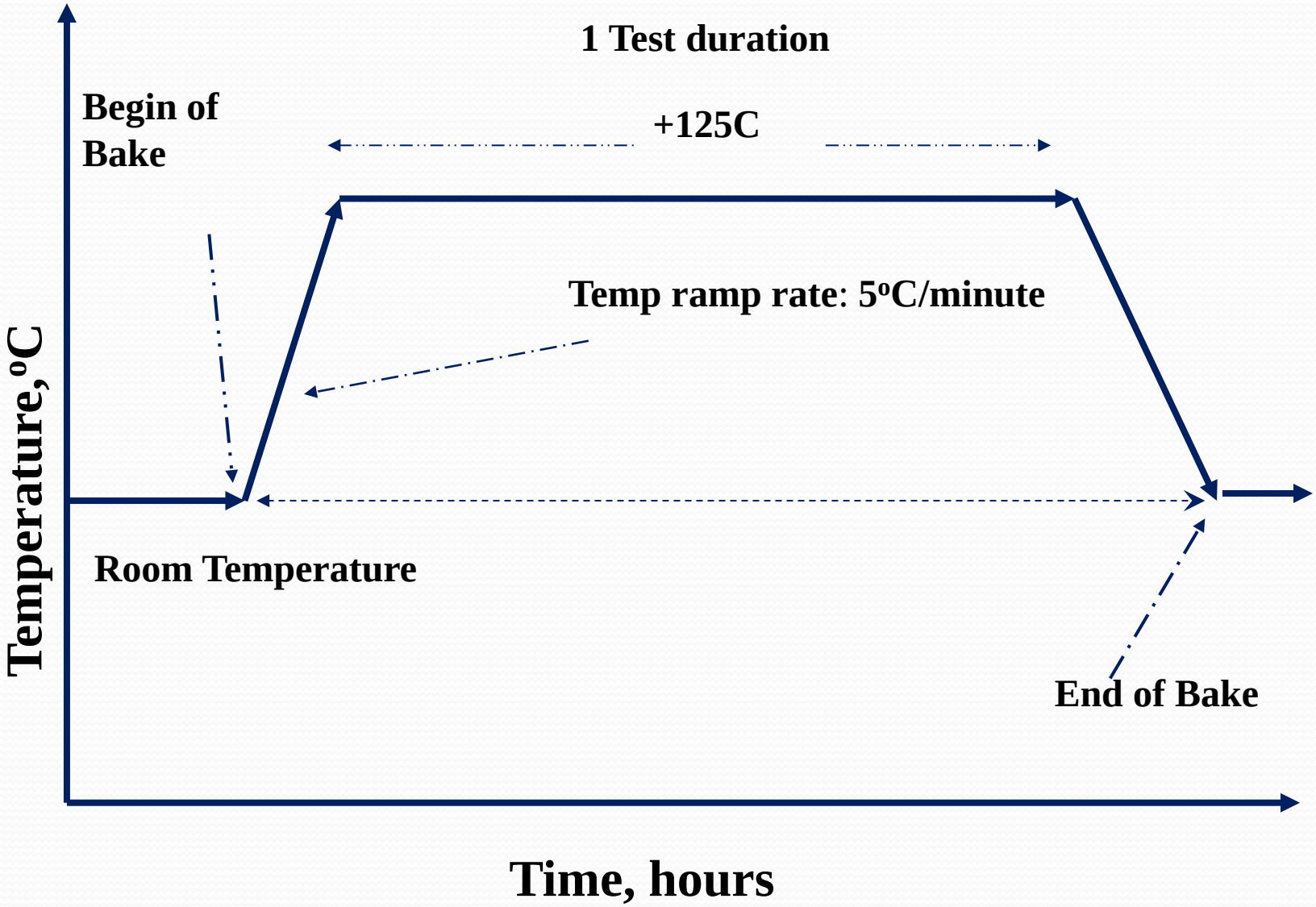


01005 passives & cracked board after 408 cycles



1206 Resistor (Lead-free) after 408 cycles

Bake Temperature Profile



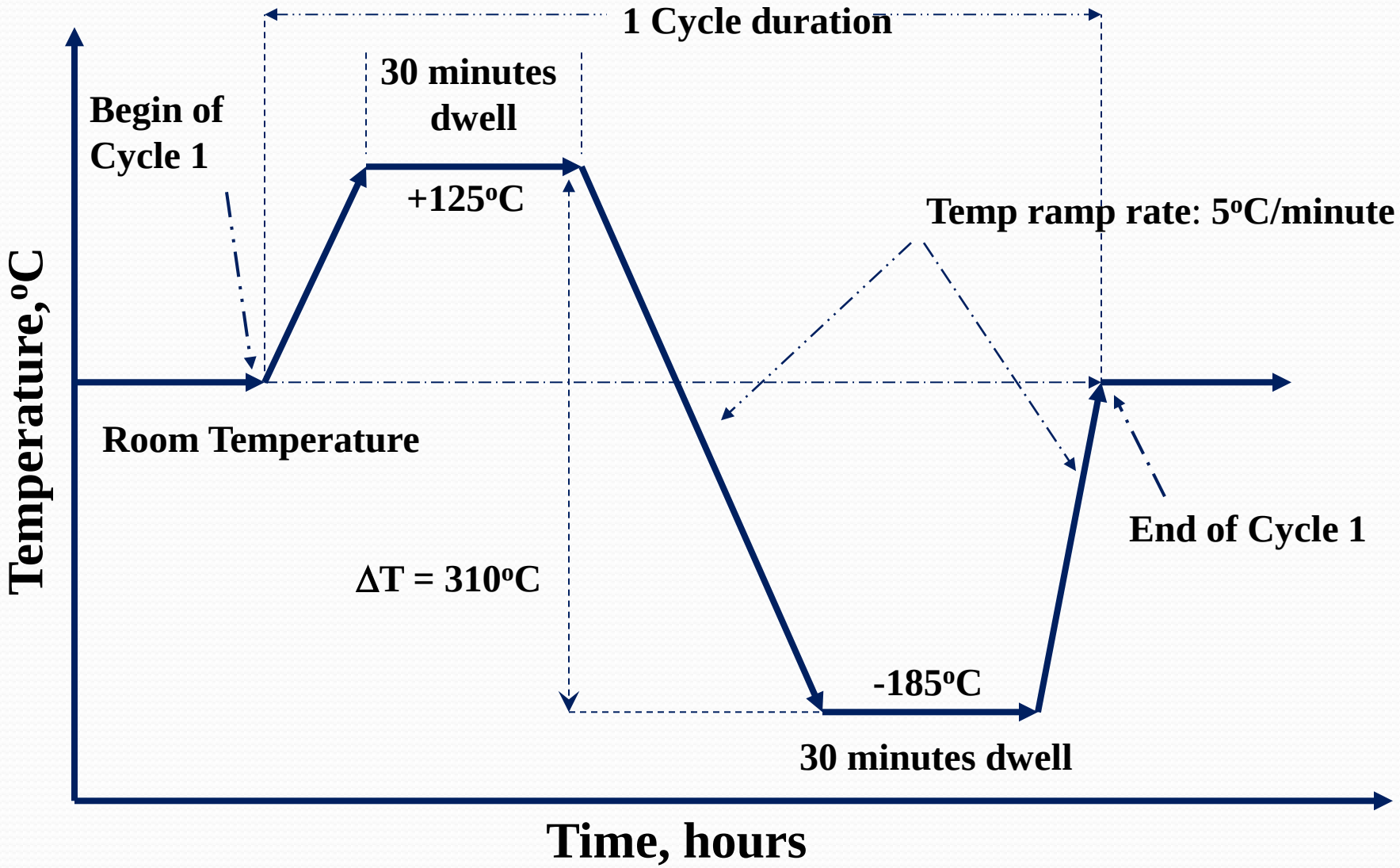
Baking of Tin-Lead board at 125°C vs., Duration

Duration of Annealing/Bake 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

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

Duration of Annealing/baking 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

Thermal Cycling Temperature Profile



Sn-Pb Test board results vs. thermal cycling

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

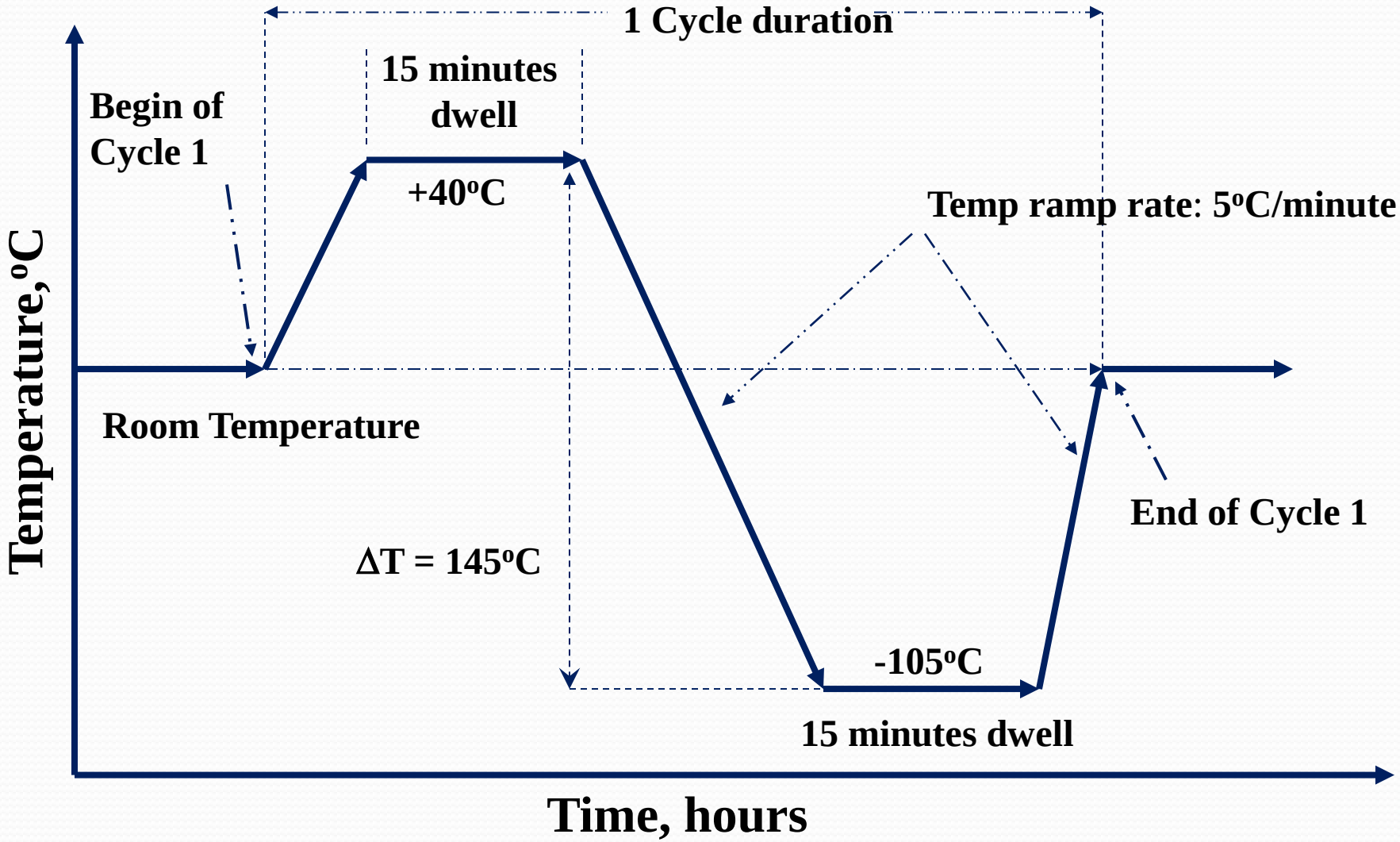
Ram

Pb-Free Test board results vs. thermal cycling

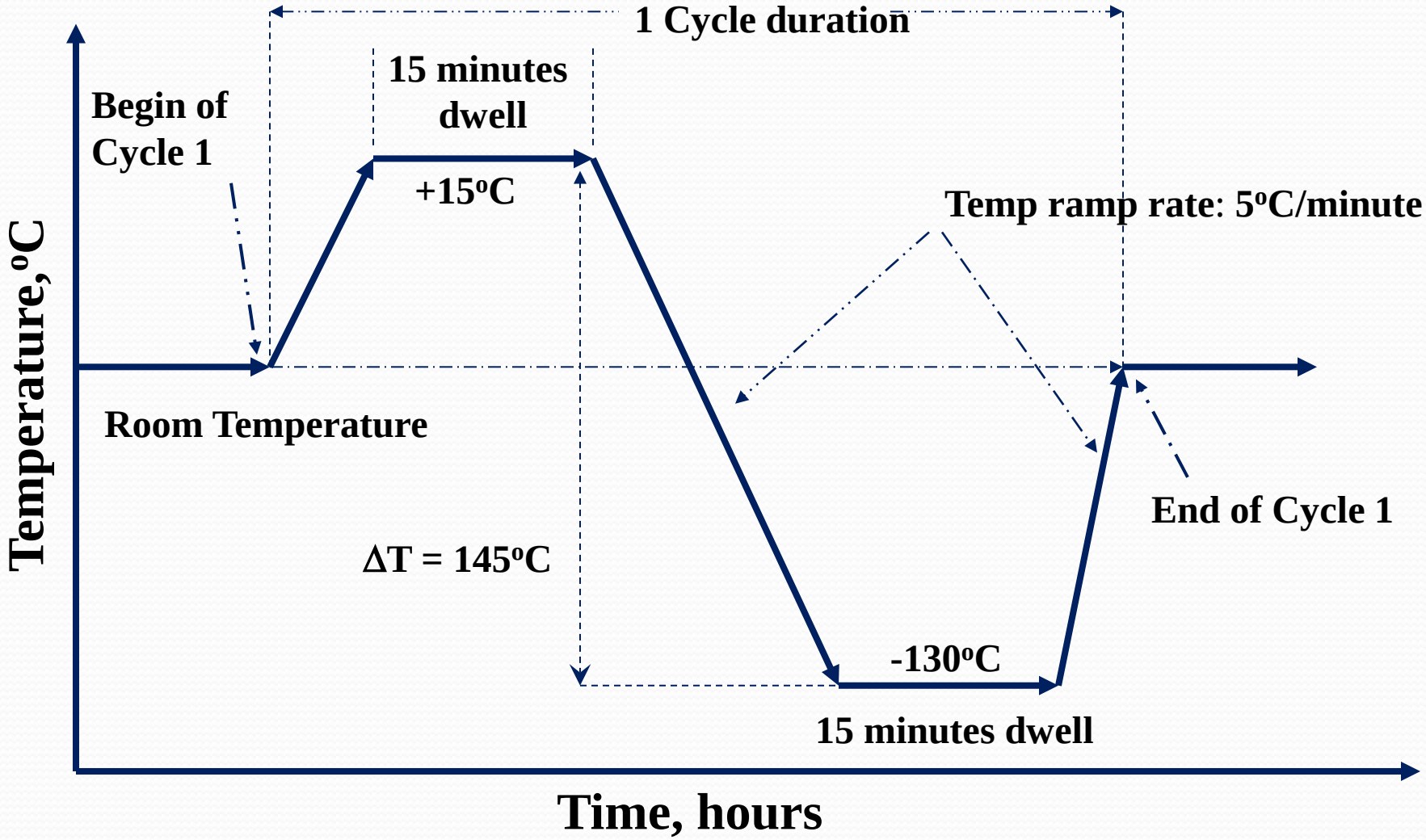
Lead Free PCB Board																				
No. of Thermal Cycles	QFP208-1	QFP208-2	QFP256-1	QFP256-2	CV BGA 97-1	CV BGA 97-2	PBGA 388-1			PBGA 388-2			BGA 256-1		BGA 256-2		QFP 100-1	QFP100-2	MLF 68-1	MLF 68-2
	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	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

Ram

Thermal Cycling Temperature Profile



Thermal Cycling Temperature Profile



Ram

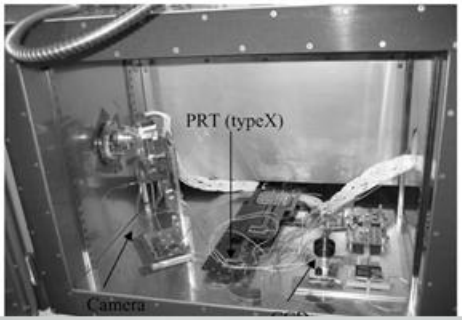
Tin-Lead Test board results vs. thermal cycling (-130ºC to 45 ºC and -105 ºC to 70 ºC)

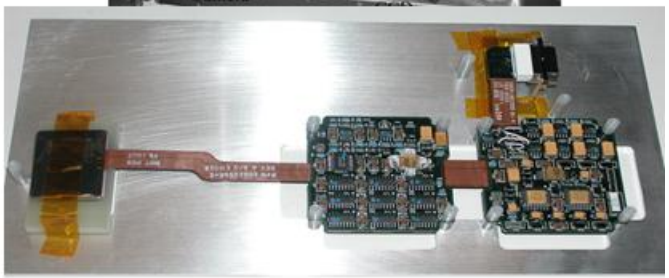
Tin-Lead PCB Board (-130C to 45C and -105 to 70C)																				
No. of Thermal Cycles	QFP208-1	QFP208-2	QFP256-1	QFP256-2	CV BGA 97-1	CV BGA 97-2	PBGA 388-1			PBGA 388-2			BGA 256-1		BGA 256-2		QFP 100-1	QFP 100-2	MLF 68-1	MLF 68-2
	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy Chain-1	Daisy 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

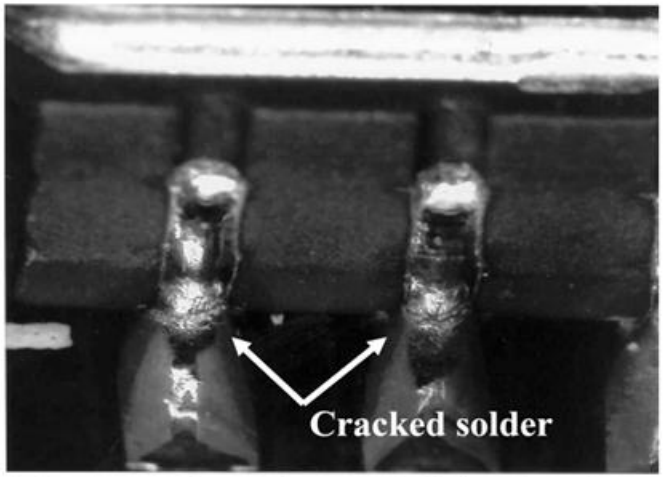
Pb-free test board results vs. thermal cycling (-130 °C to 45 °C and -105 °C to 70 °C)

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	0.16	0.35	0.17	0.16	0.35	0.40	0.40	0.40	0.40	OC	OC	1.40	1.40

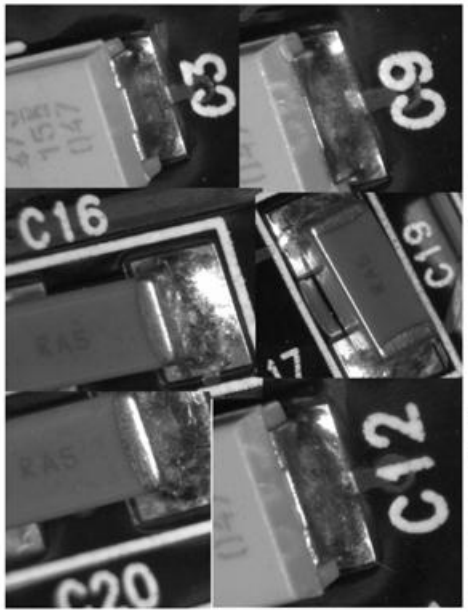
Solder Tin-Pb after 2010 Cycles
1005: -105C to 40C Summer Cycles
1005 Cycles: -130C to 15C Winter cycles



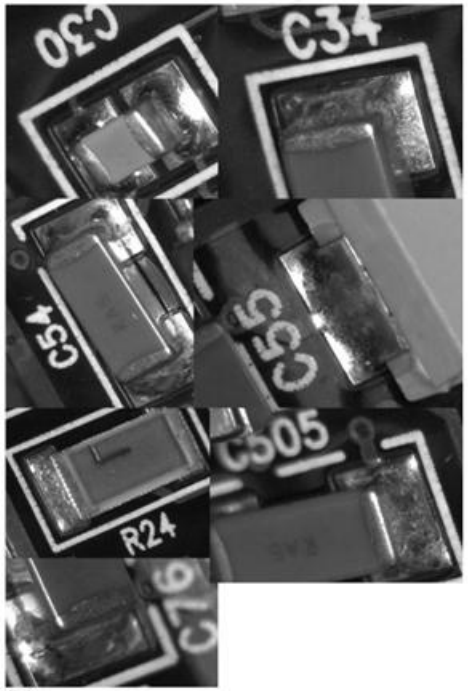




After 170 summer cycles



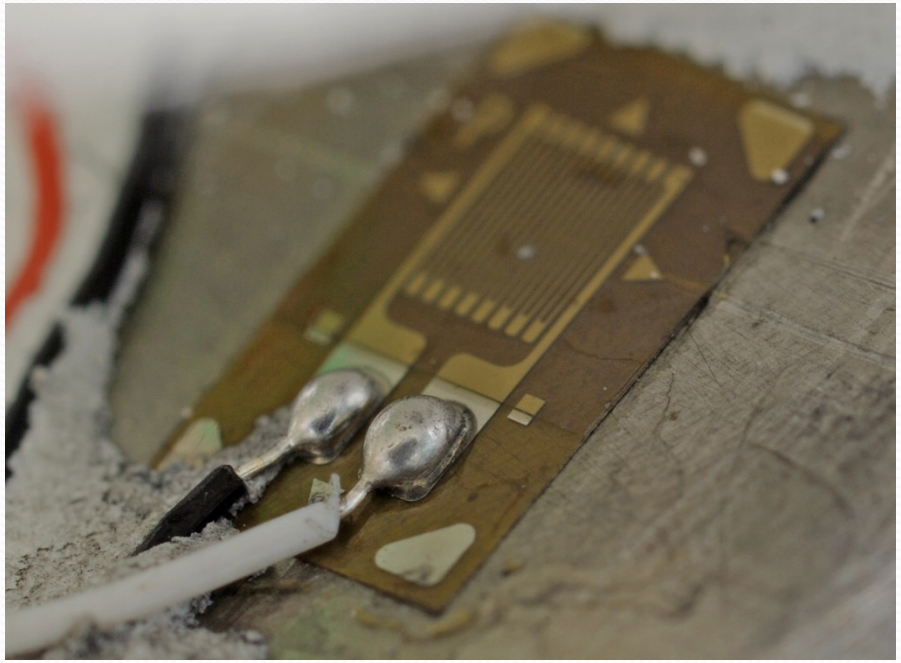
(a)



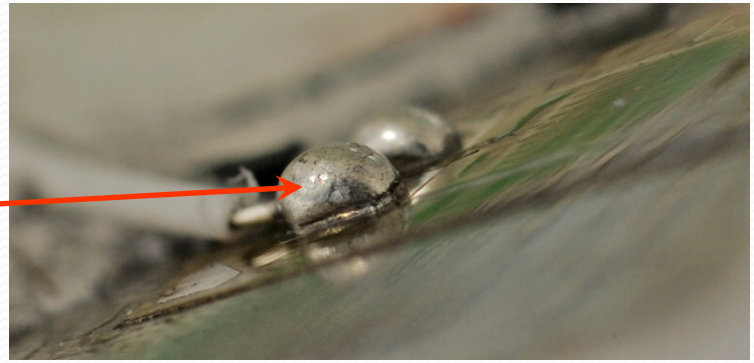
(b)

(c)

Pb-Sn solder Failure due to Workmanship

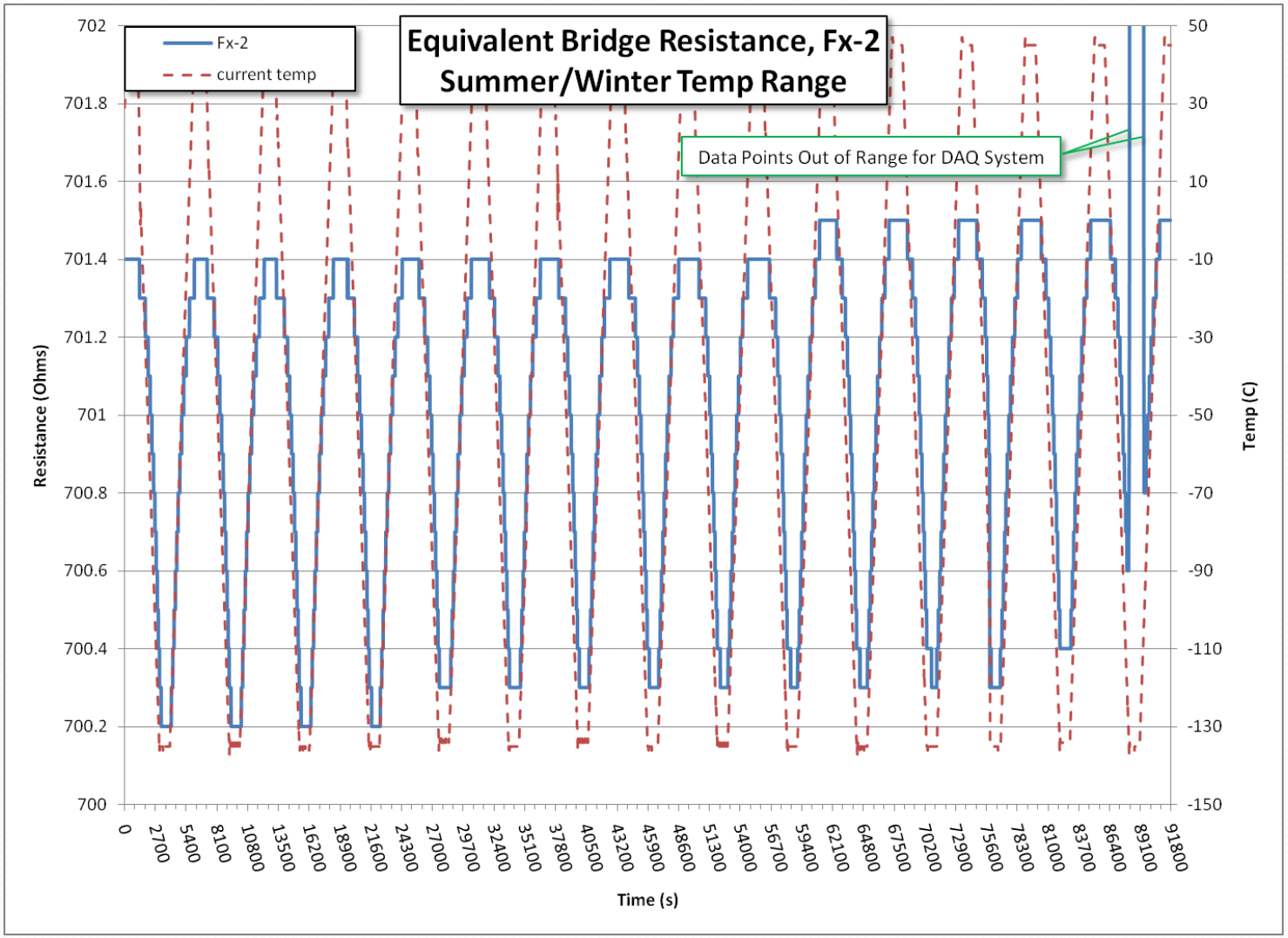


Bad solder joint?



Pb-Sn solder Failure due to Workmanship

Resistance, Ohms

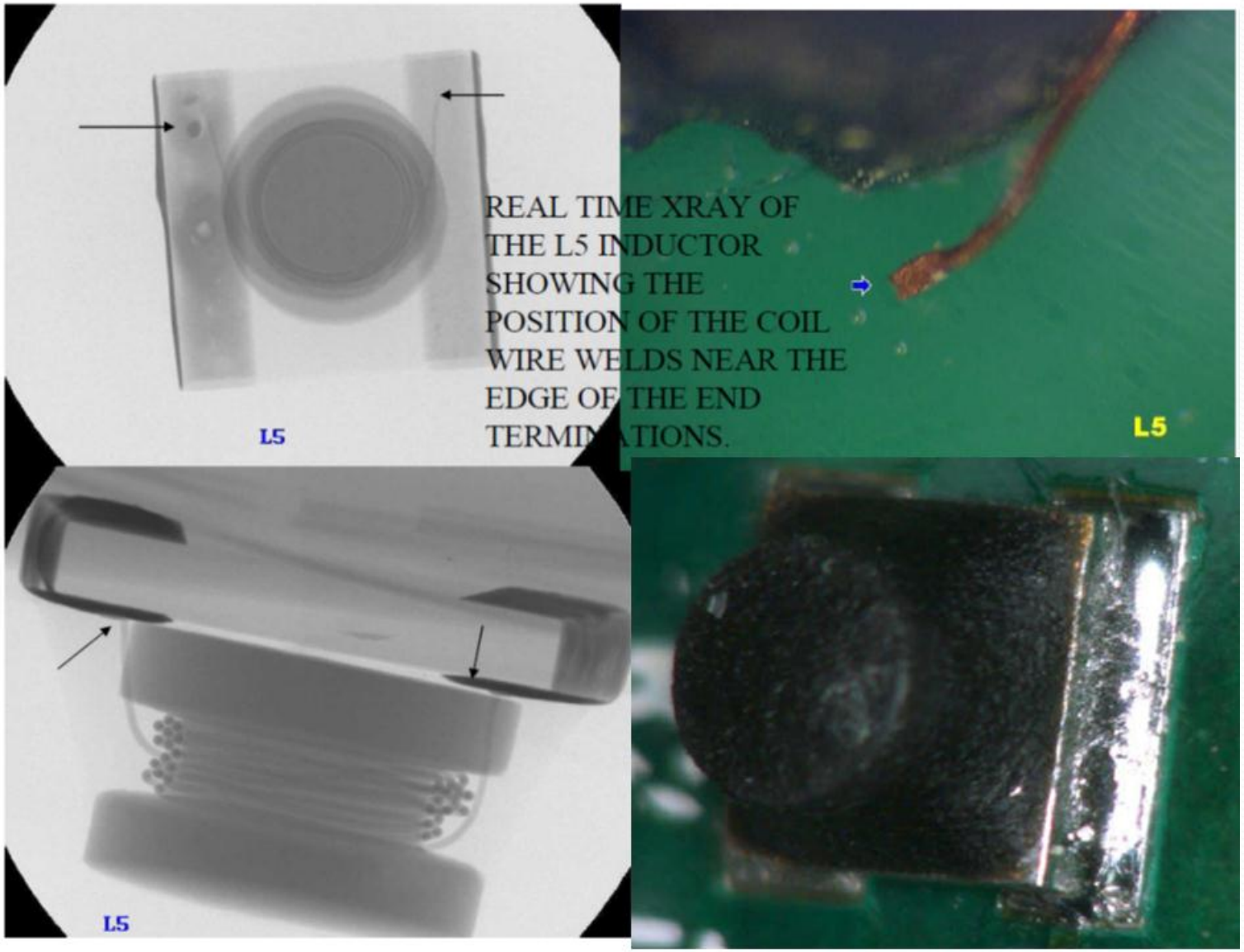


Time, seconds

AIAA

Ram

X-ray image of a failed Component in a Camera Board



Conclusions

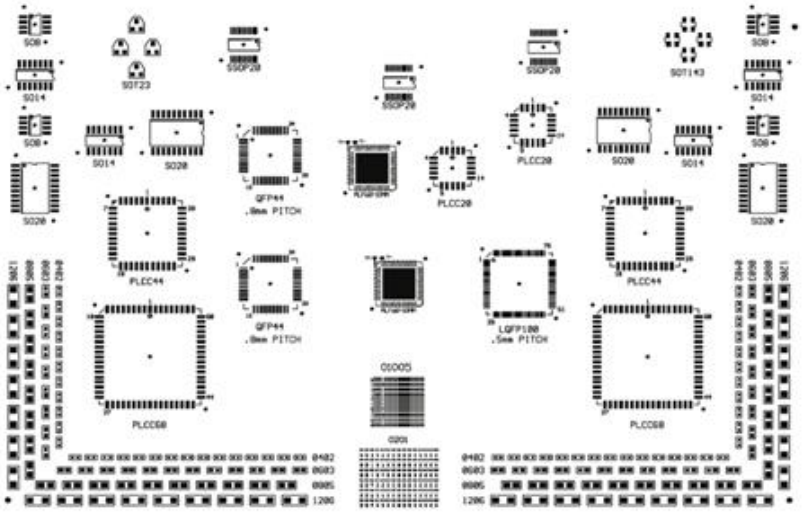
- Surface mount packages and miniaturized passive components have been tested for extreme temperature deep space thermal cycling and baking at high temperature conditions.
- Two types of boards based on Sn/Pb and SnAgCu (SAC305) solders have been designed and fabricated.
- Baking has shown that the metallographic or grainy structure of the both the solder materials.
- 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.

Acknowledgements

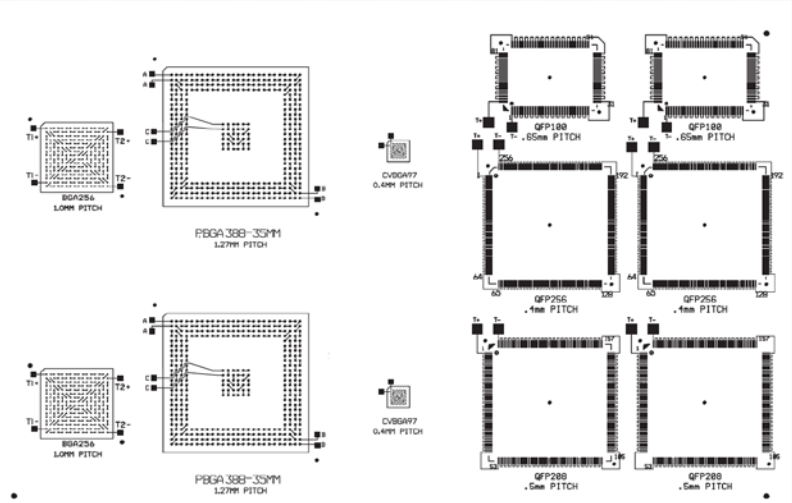
- This work is sponsored by the NASA at JPL/Caltech.
- Thanks are due to Russell Kido of Practical Components for his help during the manufacturing of the boards.
- MSL project is acknowledged for allowing me to support some of the test/anomaly/inspection studies.
- Thanks are due to Dr. Kin Fung Man for his constructive comments/suggestions.

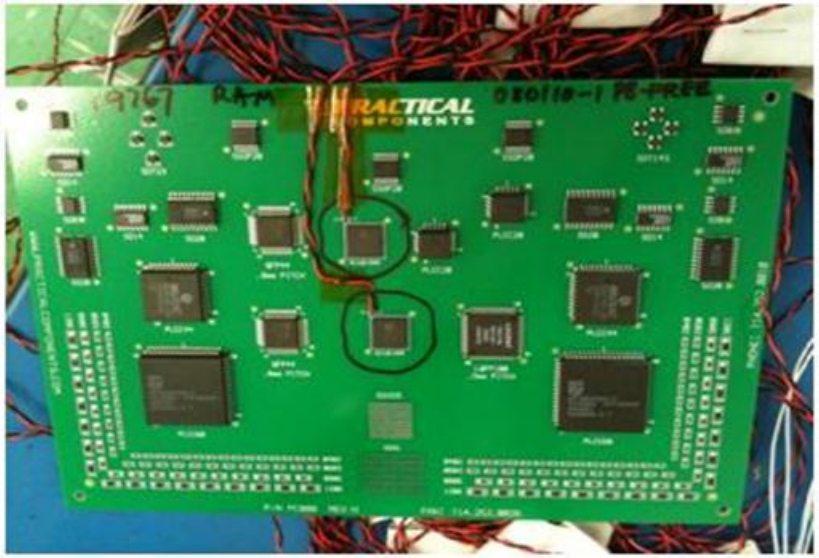
Back-up slides

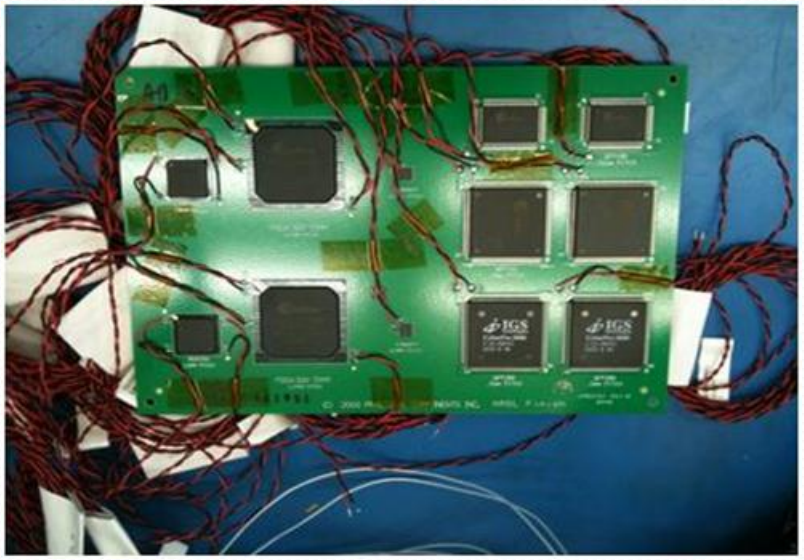
Bottom view of the test board



Top view of the test board







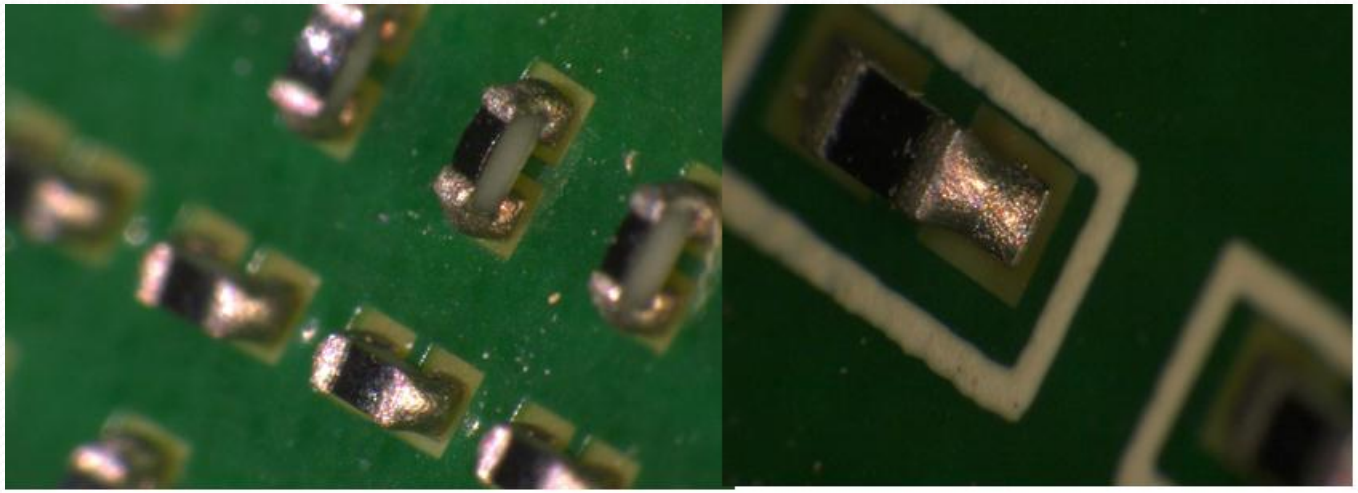
Part Description	Quantity Per Board
MLF68-10mm-.5mm-DC-Sn	2
PBGA256-1.0mm-17mm-DC-LF	2
CVBGA97-.4mm-5mm-DC-LF	2
PBGA388-1.27mm-35mm-DC-LF	2
QFP44-10mm-.8mm-3.9mm-Sn	2
QFP100-14x20mm-.65mm-3.9mm-DC-Sn	2
QFP208-28mm-.5mm-2.6mm-DC-Sn	2
QFP256-28mm-.4mm-2.6mm-DC-Sn	2
LQFP100-14mm-.5mm-2.0mm-Sn	1
PLCC20-Sn	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

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

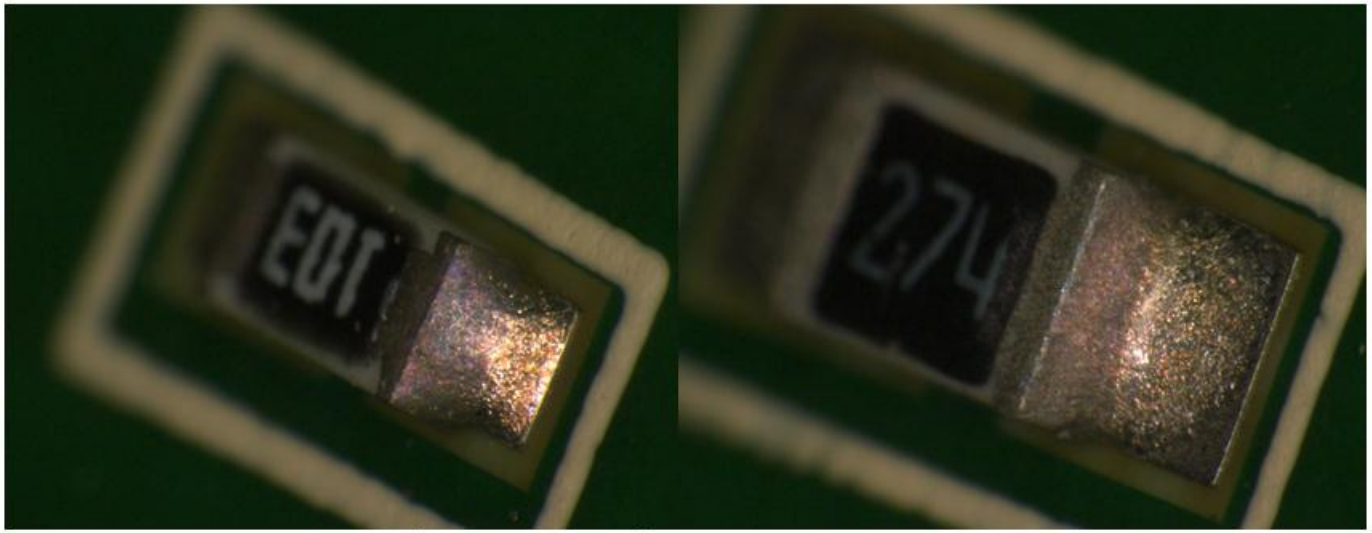
Tin-Lead components list

Optical images of lead free solder joints of various body size resistor chips after 1356 hours baking



0201 Resistor (Lead-free)

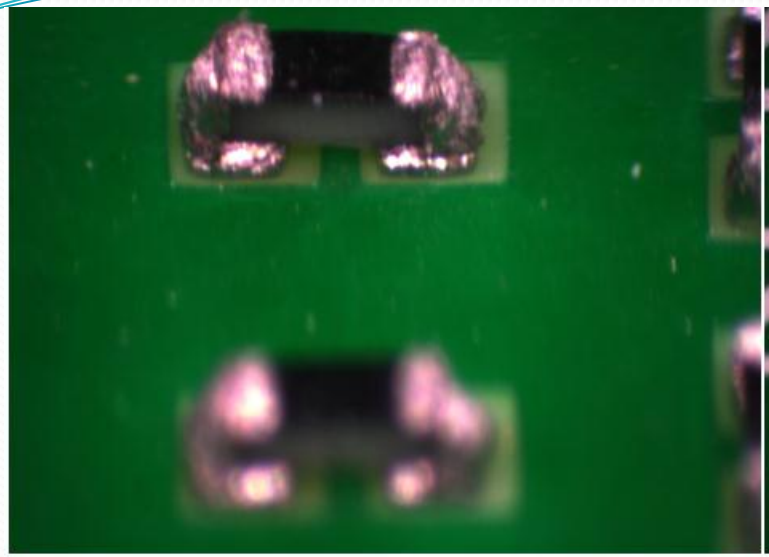
0402 Resistor (Lead-free)



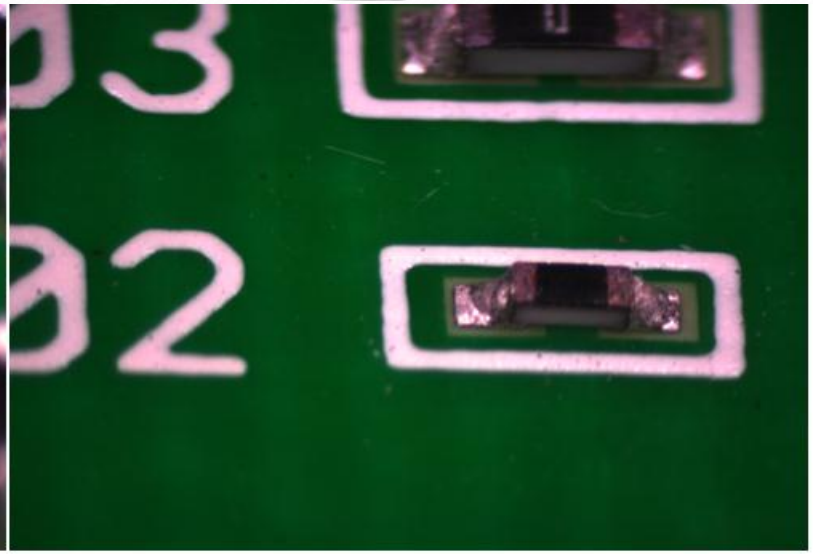
0603 Resistor (Lead-free)

0805 Resistor (Lead-free)

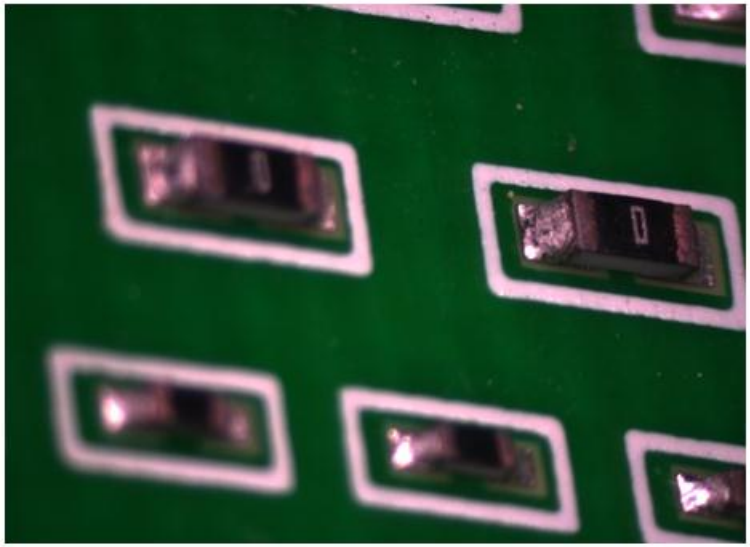
Sn-Pb Solder Alloys



0201 Resistor (Tin/Lead) after 650 cycles



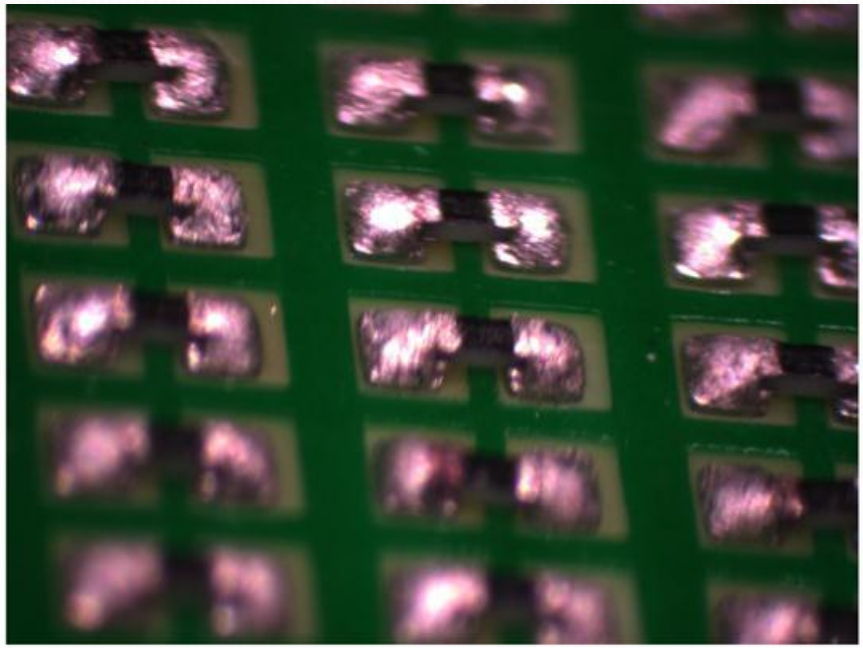
0402 Resistor (Tin/Lead) after 650 cycles



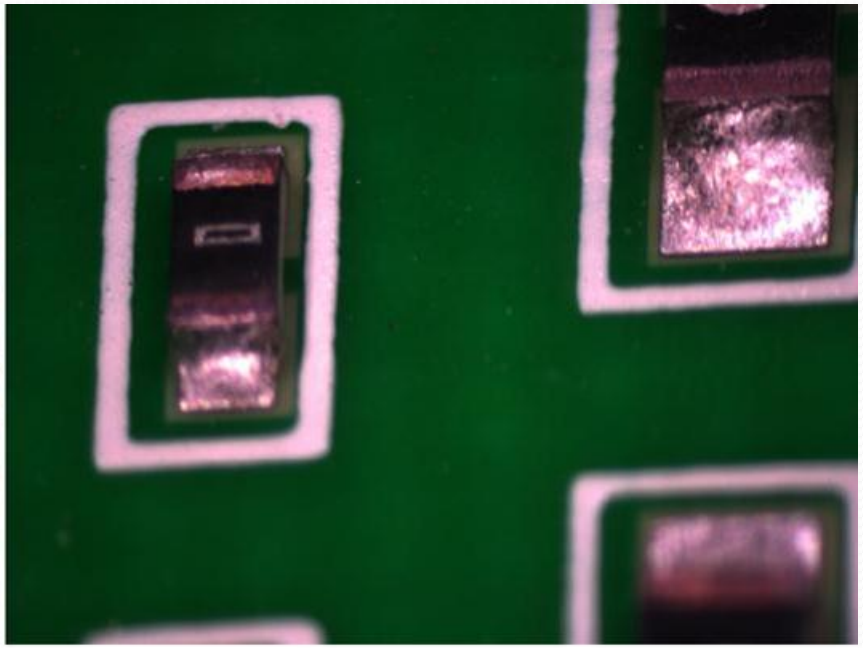
0603 Resistor (Tin/Lead) after 650 cycles

0805 Resistor (Tin/Lead) after 650 cycles

Sn-Pb Solder Alloys



01005Resistor (Tin/Lead) after 650 cycles



1206 Resistor (Tin/Lead) after 650 cycles