

**NPL REPORT
DEPC MPR 030**

**Measuring the Reliability of
Electronics Assemblies
During the Transition Period
to Lead-Free Soldering**

**M WICKHAM, L ZOU,
M DUSEK AND C HUNT**

NOT RESTRICTED

AUGUST 2005

Measuring the Reliability of Electronics Assemblies During the Transition Period of Lead-Free Soldering

Martin Wickham, Ling Zou, Milos Dusek
and Christopher Hunt

Engineering and Process Control Division

ABSTRACT

A wide-ranging study of Pb-contamination of lead-free solder joints has been undertaken. Over 200,000 solder joints on assemblies incorporating the main types of surface mount and through components, have been manufactured with SnPb and LF terminated components using SnPb, LF and mixed alloy systems. The work has included manufacture of joints with specifically controlled levels of Pb-contamination between 1 and 10%. All these assemblies have subsequently been thermally cycled (-55 to 125 °C) to 2000 cycles, continuity tested, shear tested, pull tested and vibration tested.

The work has indicated that there should be few solder joint reliability problems when mixing SnPb and LF components and solder alloys (with Pb contamination in the range 1 to 10%). Very few thermal cycle fatigue failures were experienced other than within two component groups. Shear testing of chip resistor components showed no difference in crack propagation rate between any of the component/alloy combinations. No failures were generated during vibration testing.

Some ball grid array joints did fail but these were largely restricted to SnPb alloy dominated systems, i.e. SnPb terminated components soldered with SnPb or SAC alloy solder pastes. Uncontaminated SAC systems or those systems contaminated with low levels of Pb showed fewer failures. Failures in Sn-plated QFP components were probably due to batch related solderability issues.

Work with hot peel testing of SOIC components has indicated that Pb-contamination may cause end-users problems during processing. The addition of small quantities of Pb (< 10%) to a LF joint significantly reduce its peel strength above 180 °C. This may cause the first side solder joint to separate or deform during second side reflow, if the assembly is subjected to mechanical forces during assembly.

© Crown copyright 2005
Reproduced with the permission of the Controller of HMSO
and Queen's Printer for Scotland

ISSN 1744-0270

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Extracts from this report may be reproduced provided the source is acknowledged and the extract is not taken out of context.

We gratefully acknowledge the financial support of the UK Department of
Trade and Industry (National Measurement System Policy Unit)

Approved on behalf of the Managing Director, NPL,
by Dr M G Cain, Knowledge Leader, Materials Processing Team
authorised by Director, Engineering and Process Control Division

CONTENTS

1	INTRODUCTION.....	1
2	TEST BOARD DESIGN.....	3
3	EXPERIMENTAL	5
3.1	TEST VEHICLE MANUFACTURE	5
3.2	THERMAL CYCLING	7
3.3	SHEAR TESTING.....	8
3.4	PULL TESTING.....	8
3.5	MICRO-SECTIONING.....	10
3.5.1	Sample preparation.....	10
3.5.2	Microscopy	10
3.6	VIBRATION TESTING.....	10
4	RESULTS.....	11
4.1	COMPOSITION ANALYSIS OF MIXED SOLDER PASTES	11
4.2	COMPOSITIONAL ANALYSIS OF CONTROLLED PB-CONTENT COMPONENTS	14
4.3	ELECTRICAL TEST FAILURES	17
4.3.1	SOIC, R1206 and DIP Electrical Testing.....	17
4.3.2	R0603 Electrical Testing	17
4.3.3	MELF Electrical Testing	18
4.3.4	CCGA Electrical Testing.....	18
4.3.5	QFP Electrical Testing	18
4.3.6	BGA Electrical Testing	18
4.4	R1206 SHEAR TESTING	19
4.5	R0603 SHEAR TESTING	21
4.6	VIBRATION TESTING.....	22
4.7	HOT PEEL AND SHEAR TESTING	24
4.7.1	Hot shear chip resistor testing	24
4.7.2	Hot peel testing of controlled lead-content SOIC components	24
5	DISCUSSION	25
5.1	RELIABILITY OF MIXED ALLOY SYSTEMS.....	25
5.1.1	Sn-plated QFPs with SAC Solder.....	26
5.1.2	BGA Component Joint Reliability	28
5.2	TESTING OF MIXED ALLOY SYSTEMS AS ELEVATED TEMPERATURES	31
5.3	THERMAL CYCLING RELIABILITY.....	32
6	CONCLUSIONS	32
7	ACKNOWLEDGEMENTS.....	33
8	REFERENCES.....	34

1 INTRODUCTION

European legislation means that lead-containing solders will be eliminated from mainstream electronics manufacture, by 1st July 2006. The current preferred solder replacements are based on the Tin-Silver-Copper (SAC) system, which have melting points of 217 °C and above. This 30+°C increase in melting point from the established SnPb solder alloys, necessitates a corresponding increase in processing temperature for both reflow and wave soldering.

The requirement to comply with these European regulations, is driving the electronics manufacturing industry to the adoption of new component termination finishes and solder alloys. The first phase of this transition is already underway with many component suppliers offering lead-free components, alongside conventional tin-lead terminations. End-users have approached NPL with concerns about the reliability of these new components during the interim period, when they will be used with SnPb solders. Many manufacturers have reported reliability results for combinations of lead-free components and both SnPb and LF solders (References 1, 2, 3 and 4), but few offer comparative studies with similar SnPb terminated components.

Similarly, when users change to lead-free solder alloys, there is concern that some SnPb finished components will still be present in the supply chain and that these could constitute a reliability risk. Work at the Swedish Metals Research Institute (SMRI) (reference 5) showed that Pb-contamination in lead-free joints segregated mainly to grain boundaries. After thermal cycling, micro-cracks were observed passing through the Pb phases, which they felt may have a possible detrimental effect on reliability. Further work at the SMRI with plug and ring tensile test specimens, showed a reduction in strength for Pb-contaminated samples of SAC alloy in the range 0 to 15% lead. AIM Solder USA have also reported reduced performance of lead-free alloys in low cycle bulk solder fatigue testing when contaminated with lead (reference 6). Michigan State University have published work (reference 7) showing the formation of a low melting point phase in Pb-contaminated SnAg alloy and the Shanghai Institute of Metallurgy (reference 8) have reported reduced hot shear strength in chip capacitors soldered with SnAg solder paste with additions of SnPb paste. Counter to these examples, much anecdotal evidence exists that Pb-contamination of SnAg solders is not a reliability risk. SnAg solders have been used extensively with SnPb terminated components without reports of reliability problems.

To clarify the issues of solder joint reliability during the transition to lead-free soldering, this study has investigated likely combinations of lead-containing and lead-free materials by using accelerated ageing through thermal cycling to promote joint failures. Electronics assemblies are manufactured from a range of materials with different coefficients of thermal expansion (CTE) – see Figure 1 for a cross-section of a typical joint. As these assemblies experience temperature/power changes during use (e.g. power consumption; switching equipment on/off; day/night temperature changes), the CTE mismatches place shear strains on the various components in the assembly. The properties of the materials used in assemblies mean that these strains are relieved in the solder joint, which become damaged as a consequence of continual thermal excursions. Such strains can result in crack initiation (usually in the solder joint under the component), subsequent crack propagation through the solder fillet, and finally failure of the joint. Thermal cycling, which accelerates the development of the cracks and

structural changes that weaken the solder joint, can therefore be conveniently employed in accelerated testing of the joint, geared at assessing their reliability.

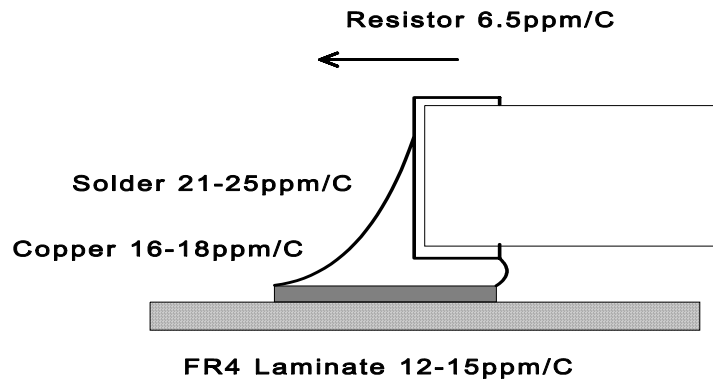


Figure 1. Schematic cross-section of a SM assembly highlighting the CTE (X-axis) mismatches.

A traditional method for assessing reliability has been to use electrical continuity measurements, which provide a technique in which a large number of joints can be monitored simultaneously. However, the technique is dependent on a complete electrical failure occurring before any defect is registered, which can be a severe disadvantage when 2000-5000 cycles may be required to reach such a failure. Due to the time constraints imposed by achieving results prior to the widespread introduction of lead-free solders, continuity failures across all component types utilised could not be induced, limiting the value of electrical continuity measurements.

Consequently, other complementary techniques were used:

Shear Testing/Pull Testing - The measurement of the solder joint mechanical strength, which is a complex function of microstructural damage, and specifically the degree of crack propagation.

Micro-sectioning – Taking a physical cross section of the joint to study changes in microstructure and development of any crack growth.

A method based on shear and pull testing for the evaluation of accelerated thermal cycling is one that has been developed recently for reliability assessment and lifetime prediction. In order to enhance the failure rate, and obtain data in the shortest timescales, known “weak links” have been selected for the tests. These “weak links” are components, in which the CTE mismatch is high, and in which early joint failures might be expected, and for which failures have been reported in commercial product.

2 TEST BOARD DESIGN

The test board (TB64) was specially designed to incorporate a range of common component styles currently in everyday use within the electronics assembly industry. A list of components is given in Table 1. Assemblies were populated with either SnPb or LF terminated components.

Table 1. Component list for TB64

Component	Pitch	Finish	No.
PBGA256	1.0 mm	SAC or SnPb	4
SOIC14/16W	1.27 mm	Sn or SnPb	4
	1.27 mm	SnCu	4
	1.27 mm	SnBi	4
	1.27 mm	PdNi	4
LQFP100	0.65 mm	Sn or SnPb	2
R1206		Sn or SnPb	20 + 20
R0603		Sn or SnPb	20 + 20
MELF		Sn or SnPb	20
DIP16/20	2.54 mm	Sn or SnPb	4
	2.54 mm	SnBi	4
	2.54 mm	PdNi	4
CCGA	1.0 mm	PbSn	2

All components were interconnected to edge fingers for insertion into an edge connector. As components were internally daisy-chained or were low resistance, this enabled electrical resistance of the components to be periodically monitored to determine electrical failures. Each BGA has four separate, concentric interconnected rings as shown in Figure 2.

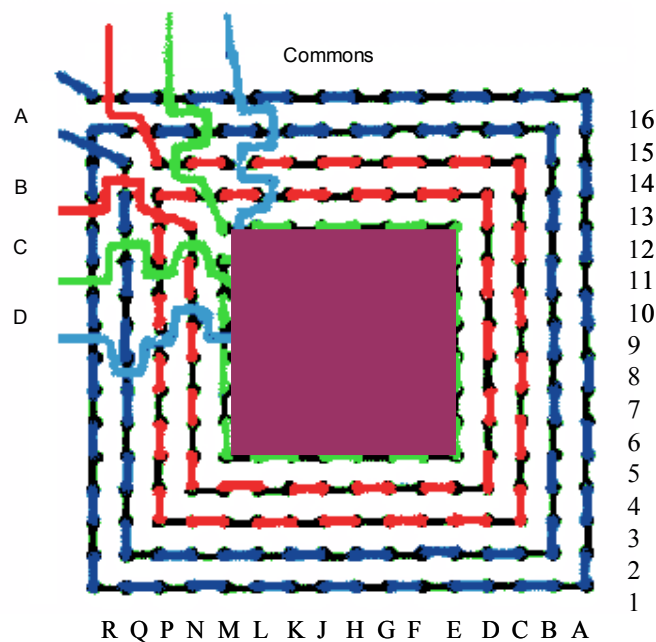


Figure 2. Diagram of daisy-chaining within BGAs showing four concentric interconnected rings (A, B, C and D)

The test board design incorporated 3 routed sections for easy breakout. This can be seen on the left-hand side of the board in Figure 3. These sections were utilised for shear and pull testing. The controlled lead content section on the left side of the design was utilised for assembling specially manufactured SOIC16W components which had termination platings of 100%Sn, 90Sn10Pb, 80Sn20Pb, 70Sn30Pb and 60Sn40Pb. When assembled with SAC solder paste, these assemblies were pull tested to determine the effect of Pb-contamination of joint strength. The resultant joints were also analysed using energy dispersive X-ray analysis (EDX) to determine Pb content.

The specification for the PCBs used is given in Table 2.

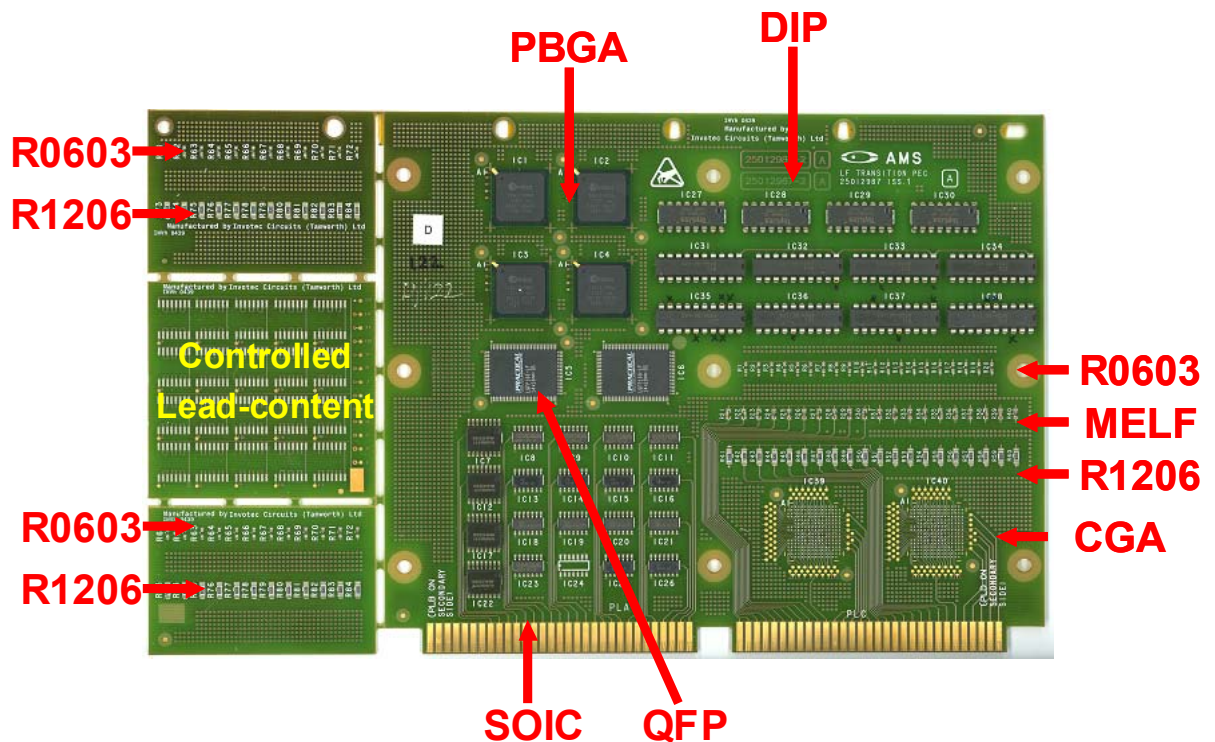


Figure 3. TB64 test board

Table 2. PCB TB64 technical specification

Dimensions of the PCB:	264 × 162 mm
Base material:	FR4 (IPC4101/21, Tg=140 °C) ENIG finish
Thickness:	1.6 mm, 1oz/sq foot Cu

3 EXPERIMENTAL

3.1 TEST VEHICLE MANUFACTURE

A total of 125 assemblies in 10 batch variants were manufactured by an experienced surface mount assembly contract manufacturer. The combinations for the component finishes and solder paste alloys for each batch of assemblies are given in Table 3. Batch C had been intended to cover variations in Pb plating on PCBs, but this was dropped for manufacturing reasons. The Pb-containing paste used was a tin-lead-silver, no-clean paste (62%Sn36%Pb2%Ag, Henkel-Multicore Sn62CR36AGS89.5). The lead-free paste was no-clean paste (95.5%Sn3.5%Ag0.7%Cu, Henkel-Multicore 96SCCR35AGS88.5). The solder pastes for batches E2, E3, E4 and E5 were mixed from both these pastes. The resultant joints were analysed using energy dispersive X-ray analysis (EDX) to determine Pb content.

These combinations represented the full range of combinations likely to occur before, during and after the transition to lead-free soldering. Two combinations (Bvibration and Dvibration) underwent vibration testing.

Table 3. Manufacturing Batch Variants

Batch	Components	Paste
A	SnPb	SAC
B	SnPb	Sn62
Bvibration	SnPb	Sn62
D	Lead-free	Sn62
Dvibration	Lead-free	Sn62
E1	Lead-free	SAC
E2	Lead-free	SAC/1%Sn62
E3	Lead-free	SAC/2%Sn62
E4	Lead-free	SAC/5%Sn62
E5	Lead-free	SAC/10%Sn62

Solder paste was screen printed using a standard 150µm thick stencil, and the SM components were placed using a automatic placement system. Boards were exclusively populated with either SnPb or lead-free components.

The boards were reflowed in line with manufacturers guidelines. The temperature at a variety of different points was measured with a thermal profiler and the results for both reflow profiles (SnPb and Lead-free) were as shown in Figures 4 and 5.

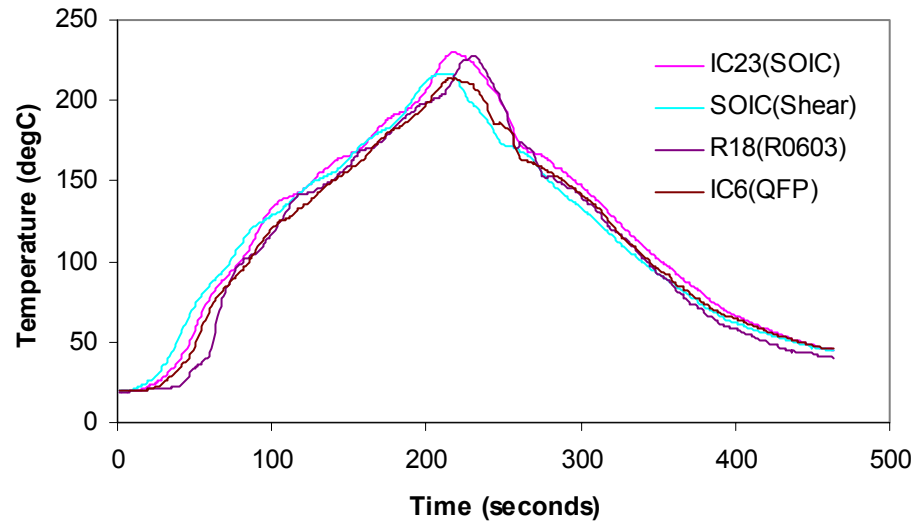


Figure 4. Thermal profile for SnPbAg reflows.

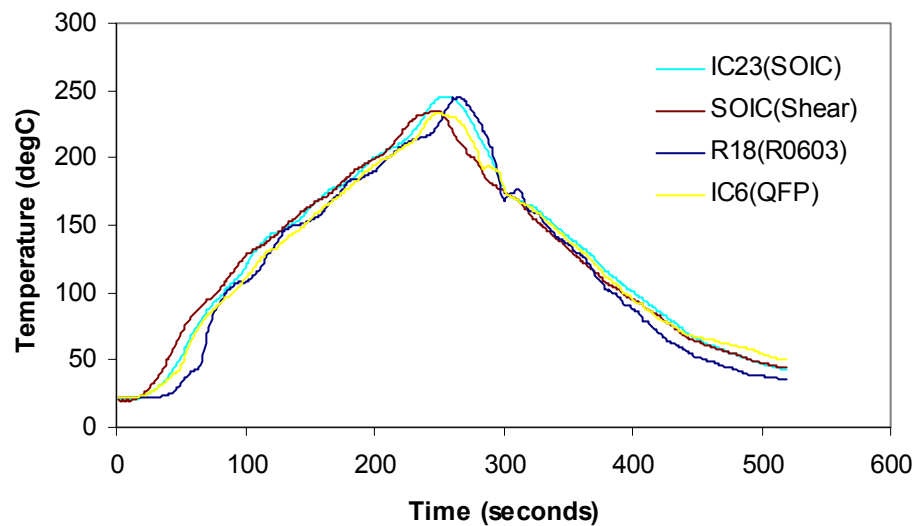


Figure 5. Thermal profile for SAC reflows.

After reflow soldering, DIL packages were hand inserted and the assemblies were wave soldered. SnPb wave soldering was undertaken using the contract manufacturers' conventional 63%Sn37%Pb alloy, flux and profile.

The lead-free wave soldering used a Vitronics Soltec Delta wave soldering system with "chip wave" (agitated leading edge to main wave). This systems incorporated a spray fluxer using Interflux Pacific 2009M, a VOC-free no-clean flux. Fluxing and pre-heat settings are detailed in Table 4. The SAC alloy used was 96.5%Sn3.0%Ag0.5%Cu with a solder bath temperature of 260 °C.

Table 4. Wave solder system settings

	Parameters	Units	SnPb	SAC
Fluxer	Atomisation air	Bar	0.5	0.5
	Nozzle fluxer speed	Cm/sec	35	35
	Nozzle fluxer pitch	Mm	30	30
	Double/single	D/S	D	D
	Nozzle type	FC	16	16
Preheat	Calrod	°C	380	380
	Forced convection	°C	160	160
	Quartz	%	30	30
Wave	Smart wave	RPM	1200	1200
	Chip wave	RPM	315	270
	Main wave	RPM	275	295
	Solder temperature	°C	250	260
	Nitrogen	Yes/No	No	No
	Conveyor speed	cm/min	120	120

After soldering, all assemblies were 100% visually inspected by a single operator using a 10X to 30X stereo microscope. The assemblies were inspected to IPC A610 Rev C class 3. No rework was undertaken. Any defective solder joints were logged and removed from subsequent test results.

3.2 THERMAL CYCLING

The thermal profile used to condition the samples is shown in Figure 6. Temperatures were measured at four points on a populated assembly on solder joints of an R0603, 2 SOIC joints and a QFP joint. All measured points were within a few degrees of each other throughout the thermal cycle.

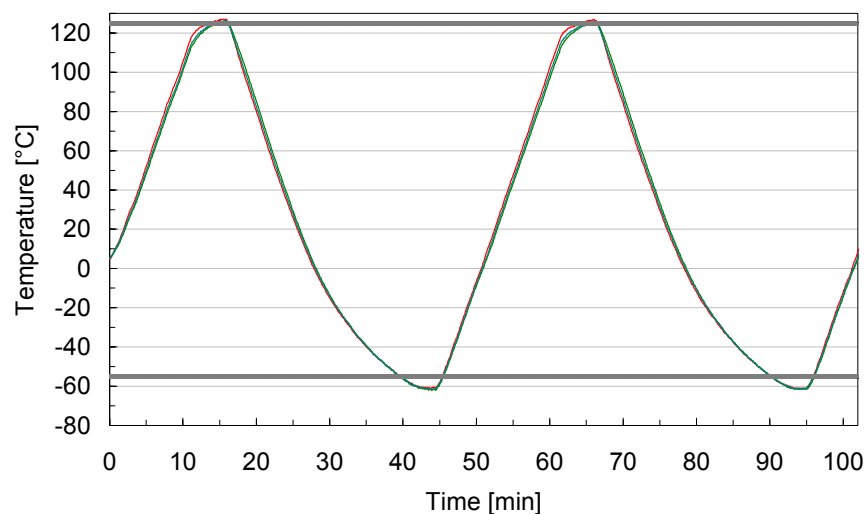


Figure 6. Thermal cycling profile (-55 to 125°C, 5min dwells, ramp 10°C/min)

One assembly from each batch was removed after 0, 500, 1000, 1500 and 2000 thermal cycles. These assemblies were subjected to shear testing and micro-sectioning. Five assemblies from each batch were subjected to the full 2000 thermal cycles with periodic electrical measurement using an automatic switching system and digital ohmmeter at 0, 500, 1000, 1250, 1500, 1750 and 2000 cycles.

3.3 SHEAR TESTING

The chip resistors are well suited to shear testing, having a flat edge to which a chisel tool can be easily positioned. Shear testing of resistors is shown in Figure 7.

The R1206 and R0603 components were tested on the board in order to determine the ultimate shear strength for the SM joints (the maximum force prior to fracture). All testing of thermally cycled samples was undertaken at room temperature. Some Pb-contaminated samples were tested at elevated temperatures.

The shear test samples were on a routed section of the assembly, which could be easily removed to allow mounting in the shear test equipment. The stand-off height of the chisel tool above the PCB surface was 80µm. During each test, the shear tool was moved forward at a defined speed of 200µm/s against the test component, and the force was monitored until the solder joint broke. The shear tester is a Dage Series 4000, with a DS 100Kg testing head. Twelve R0603 and R1206 chip resistors were tested for each condition (24 on each PCB).

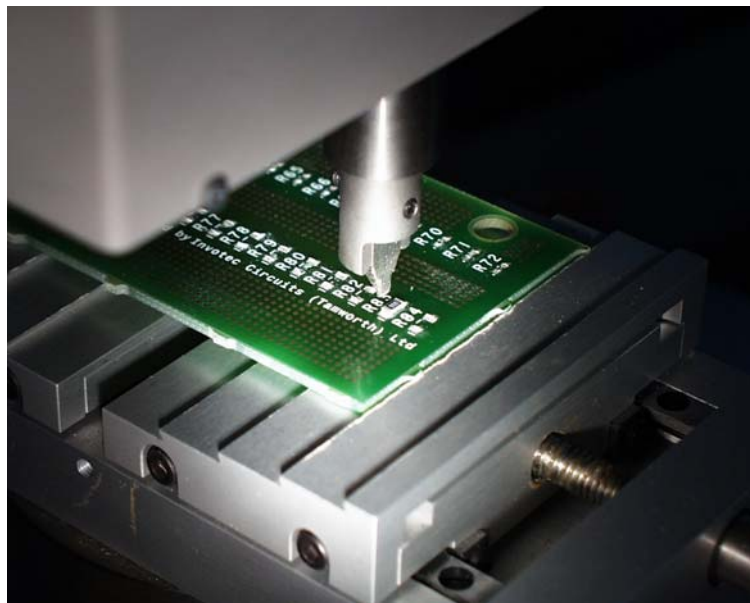


Figure 7. Shear test jig and push-off tool

3.4 PULL TESTING

SOICs are better suited to pull testing, where a hook can be easily positioned under the lead of the device and the joint pulled vertically off the pad.

SOIC components were tested on the board in order to determine the ultimate shear strength for the SM joints (the maximum force prior to fracture).

The pull test samples were on a routed section of the assembly, which could be easily removed to allow mounting in the pull-test equipment. During each test, the pull tool was moved upwards at a defined speed of $200\mu\text{m/s}$, and the force was monitored until the solder joint broke. For some SOIC components, where there was little clearance between the lead and the component body, a wire loop was placed under the lead and the pull tester attached to the loop. The pull tester was a Dage Series 4000, with a WP10 10Kg testing head. The four corner joints on each of two SOIC components were tested for each condition. All pull testing was undertaken at room temperature. A typical pull test is shown in Figure 8.

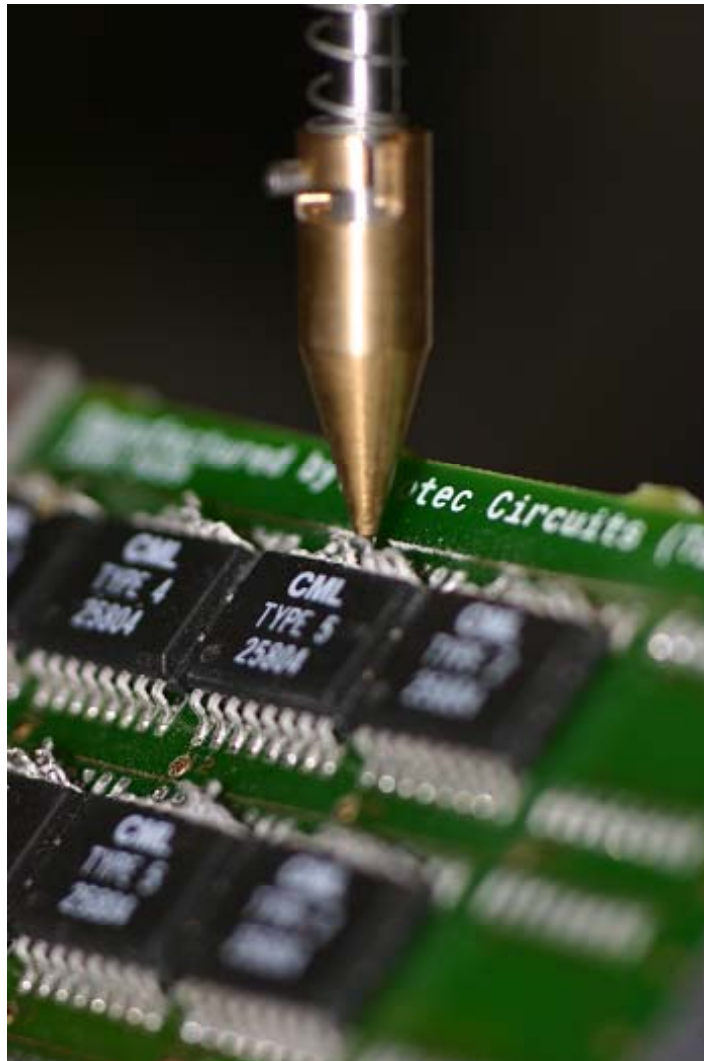


Figure 8. Typical SOIC pull test

3.5 MICRO-SECTIONING

3.5.1 Sample preparation

Samples were cut from test boards in such a way as to minimise stress using a diamond saw. This method of cutting ensures that soldered joints are not overheated or stressed to levels that might affect joint microstructure. Cold curing epoxy resin was chosen as the most suitable mounting compound for similar reasons. Samples were ground with successive grades of silicon carbide grit papers, followed by polishing with diamond pastes/sprays with successive smaller particle sizes. Micro-sectioning of the larger resistor components was undertaken as these are more likely to exhibit fatigue cracks due to their size.

3.5.2 Microscopy

The micro-sections were inspected using a scanning electron microscope in backscatter mode. This enabled ready differentiation between Sn rich and Pb rich phases within the solders and also enabled easy identification of cracks within the samples.

3.6 VIBRATION TESTING

Batches BVibration (SnPb surface mount components and SnPbAg solder paste) and Dvibration (Lead-free surface mount components and SnPbAg solder paste) were vibration tested using random vibration (0.1 g²/Hz, 10Hz to 600 Hz) for up to 500 hours. 5 boards from each batch were electrically tested after 0, 1, 4, 15, 50, 100, 150, 200, 250, 318, 445 and 500 hours of testing. The vibration test equipment is shown in Figure 9.



Figure 9. Vibration Test Equipment

4 RESULTS

4.1 COMPOSITION ANALYSIS OF MIXED SOLDER PASTES

The EDX analysis of the R1206 components manufactured with mixed pastes is given in **Table 5**. Figures 10 to 14 show micro-sections of the joints. In these sections the Pb-rich phase appears as white areas within the solder. Both the table and the images, clearly show increasing Pb-content within the joints. The Pb-rich areas also appear to have segregated to the grain boundaries.

When Pb-content is very low, the segregation of the Pb-rich phases to the grain boundaries, means that the position where the EDX sample is taken can be important. The analysis of sample E2 registers no lead, but a limited number of Pb-rich phase can be clearly seen in **Figure 11**.

Table 5: EDX Analysis Composition of Mixed Solder Paste Joints

Assembly	Nominal Pb	%Sn	%Ag	%Cu	%Pb	%Ni
E1	0%	94.9	1.5	0.4	0	3.3
E2	1%	97	3	0	0	0
E3	2%	94.7	3.2	0	2.1	0
E4	5%	93.7	2.1	0	4.2	0
E5	10%	90.6	1.7	0	7.3	0.4

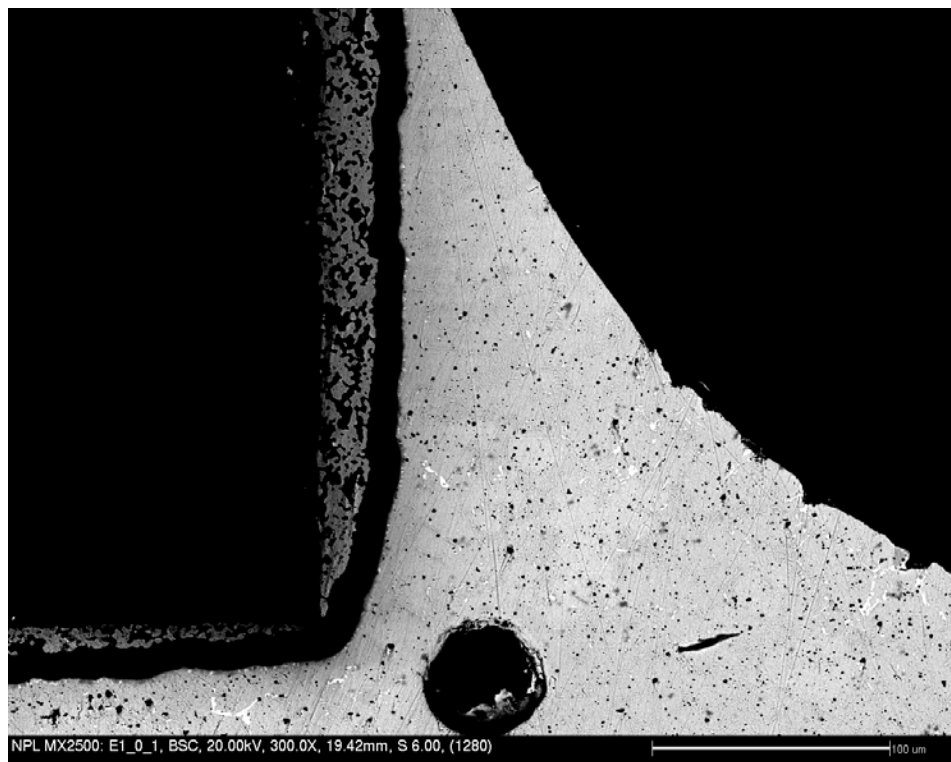


Figure 10: Micro-section of E1 composition

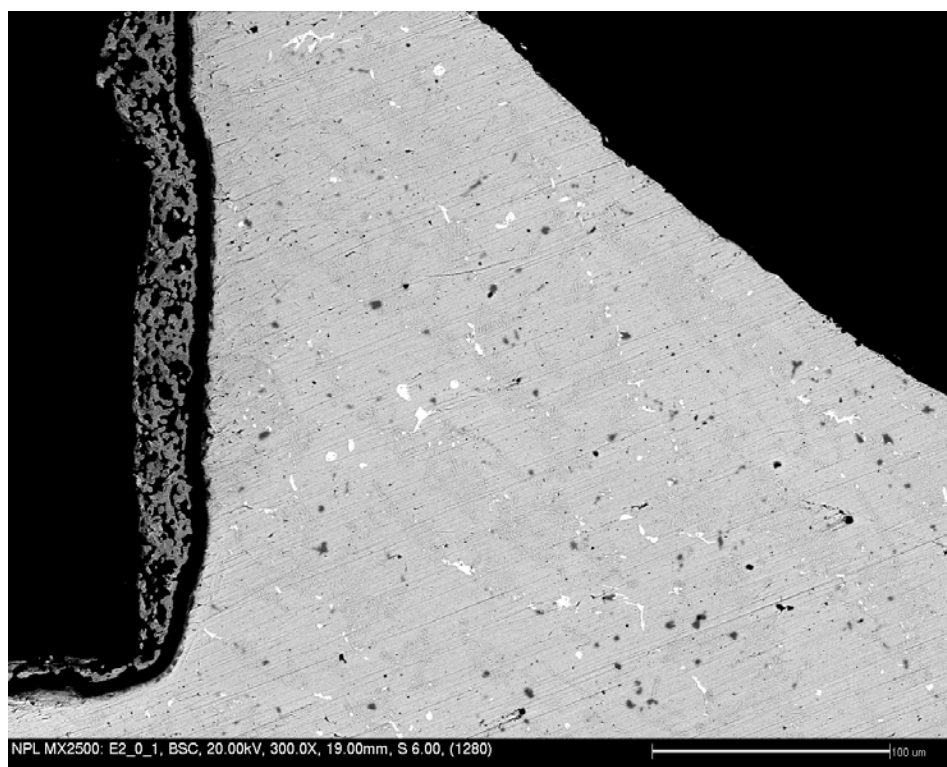


Figure 11. Micro-section of E2 composition

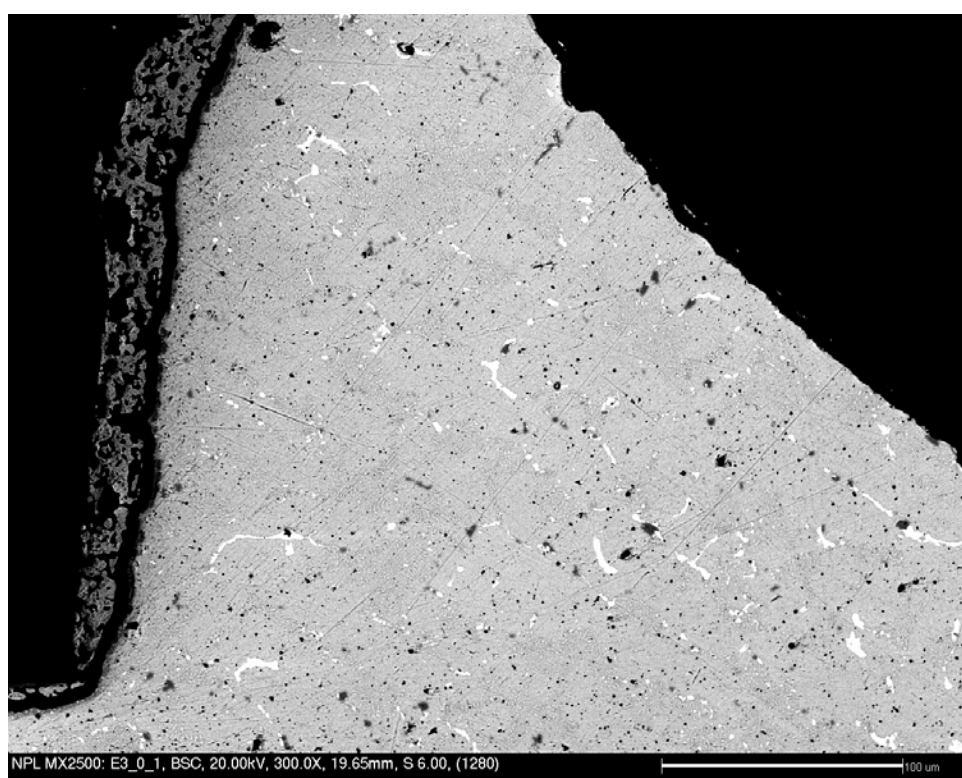


Figure 12. Micro-section of E3 composition

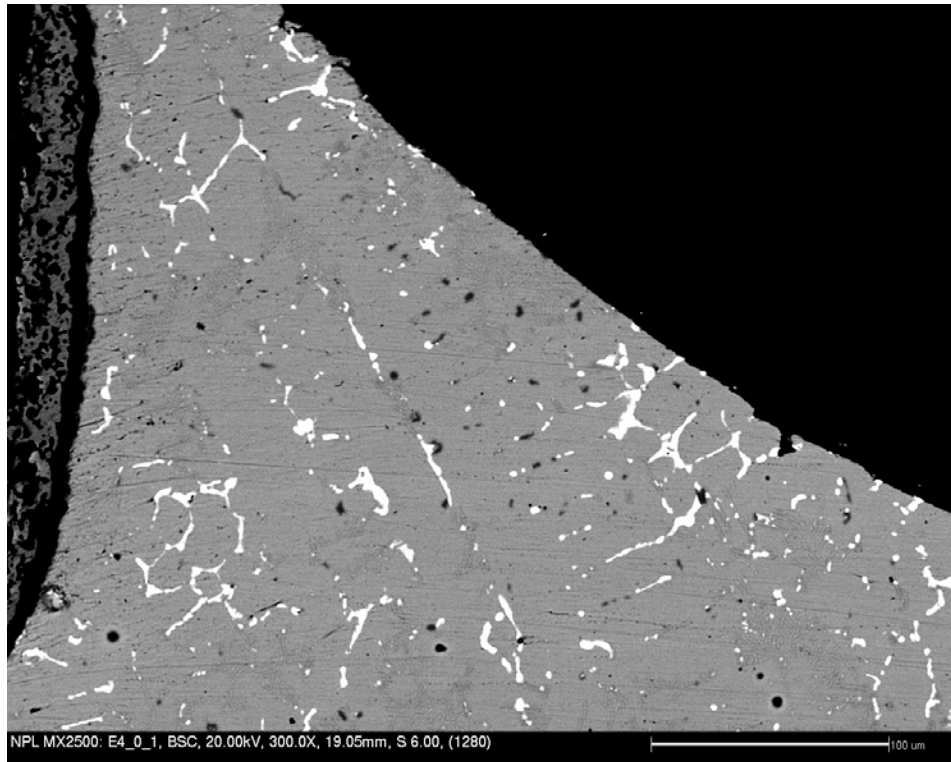


Figure 13. Micro-section of E4 composition

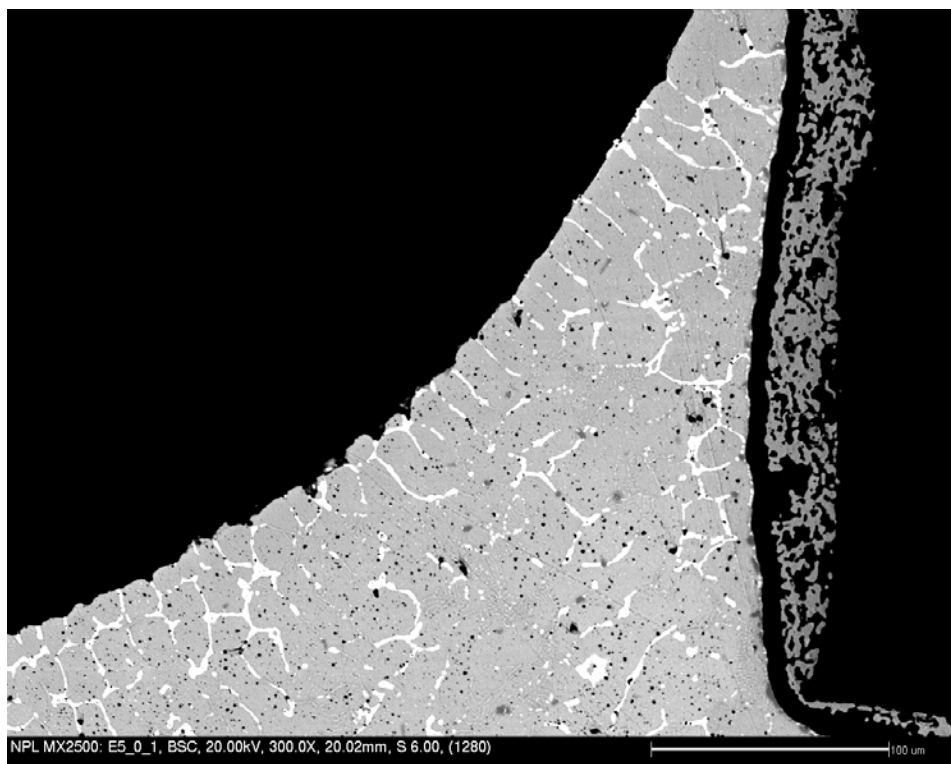


Figure 14. Micro-section of E5 composition

4.2 COMPOSITIONAL ANALYSIS OF CONTROLLED PB-CONTENT COMPONENTS

The EDX analysis of the controlled Pb-content SOIC components manufactured with LF paste is given in **Table 6**. Figures 15 to 19 show micro-sections of the joints. In these sections the Pb-rich phase shows as white areas. Both the table and the images, clearly show increasing Pb-content within the joints. The Pb-rich areas also appear to have segregated to the grain boundaries.

Table 6. EDX Analysis Composition of Joints to Controlled Pb-content SOICs

Assembly	Nominal Component Plating Composition	%Sn	%Ag	%Cu	%Pb	%Ni
Type 1	100Sn	96.8	2.2	0.8	0.0	0.2
Type 4	90Sn10Pb	92.0	2.8	1.2	3.2	0.9
Type 5	80Sn20Pb	92.1	3.0	0.8	4.0	0.1
Type 2	70Sn30Pb	88.4	1.9	0.7	8.8	0.2
Type 3	60Sn40Pb	86.6	1.7	0.6	11.1	0.1

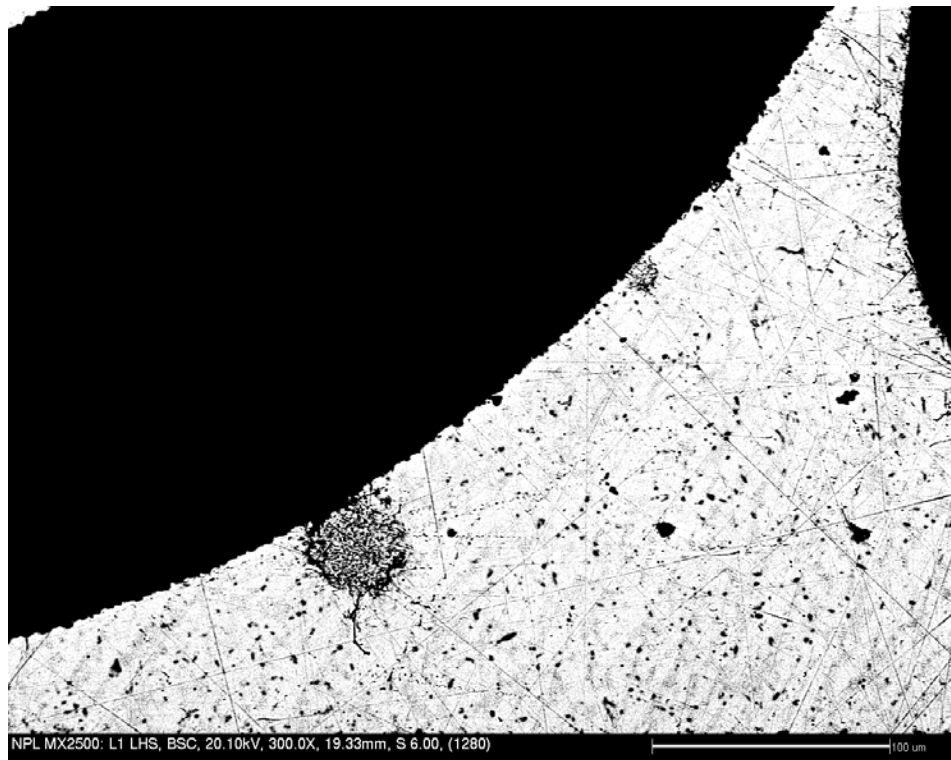


Figure 15. Micro-section of joint formed with 100% Sn-plated SOIC

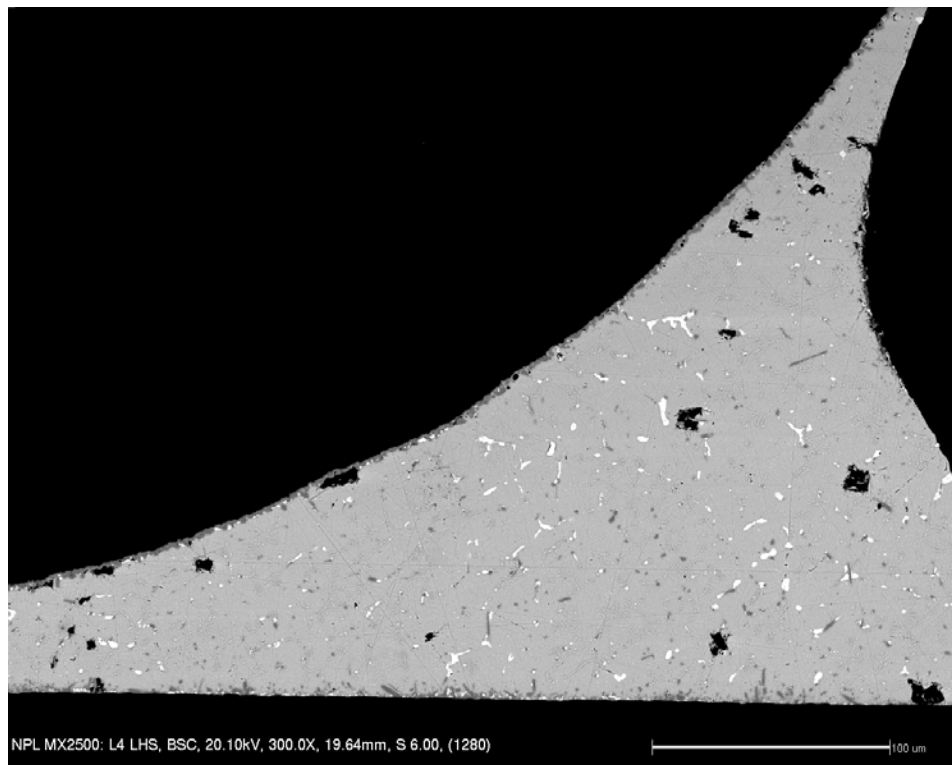


Figure 16. Micro-section of joint formed with 90%Sn10%Pb-plated SOIC

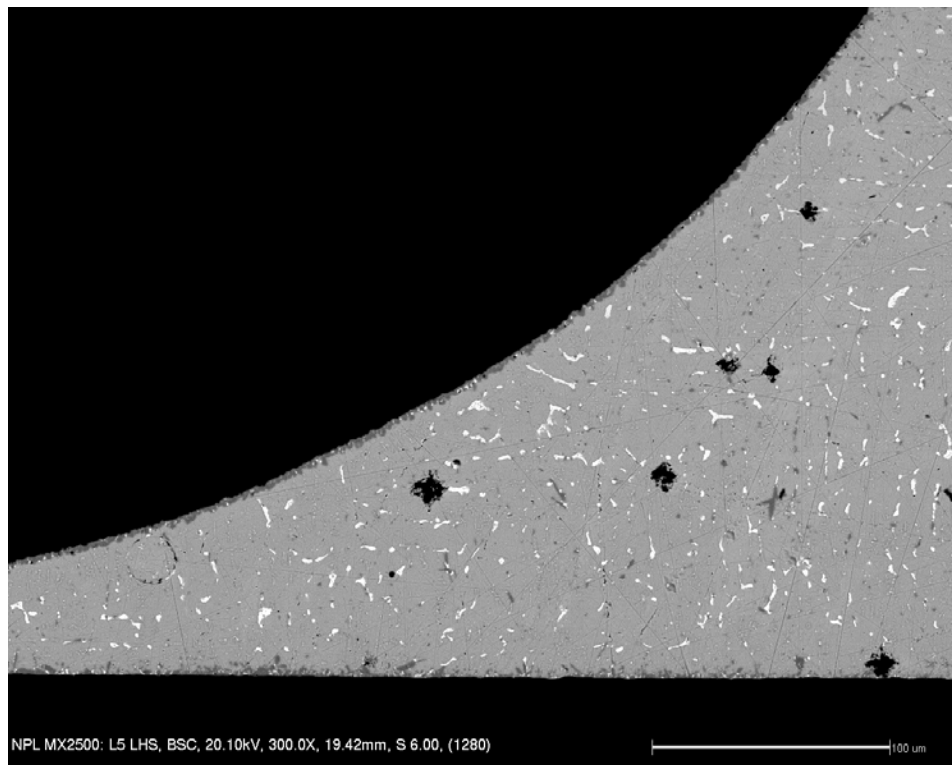


Figure 17. Micro-section of joint formed with 80%Sn20%Pb-plated SOIC

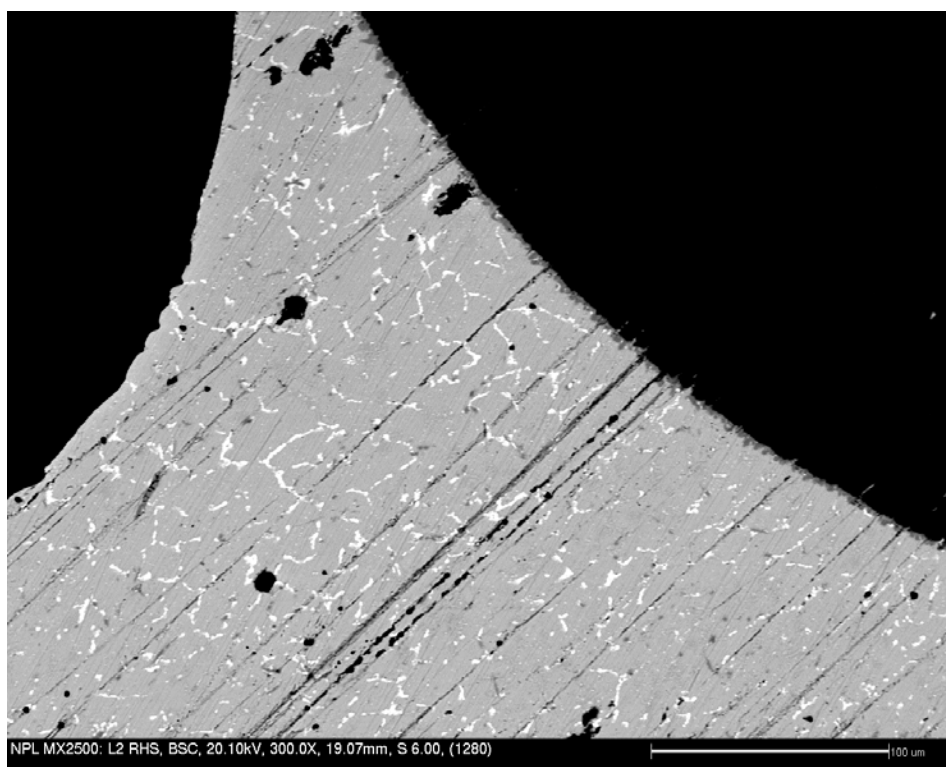


Figure 18. Micro-section of joint formed with 70%Sn30%Pb-plated SOIC

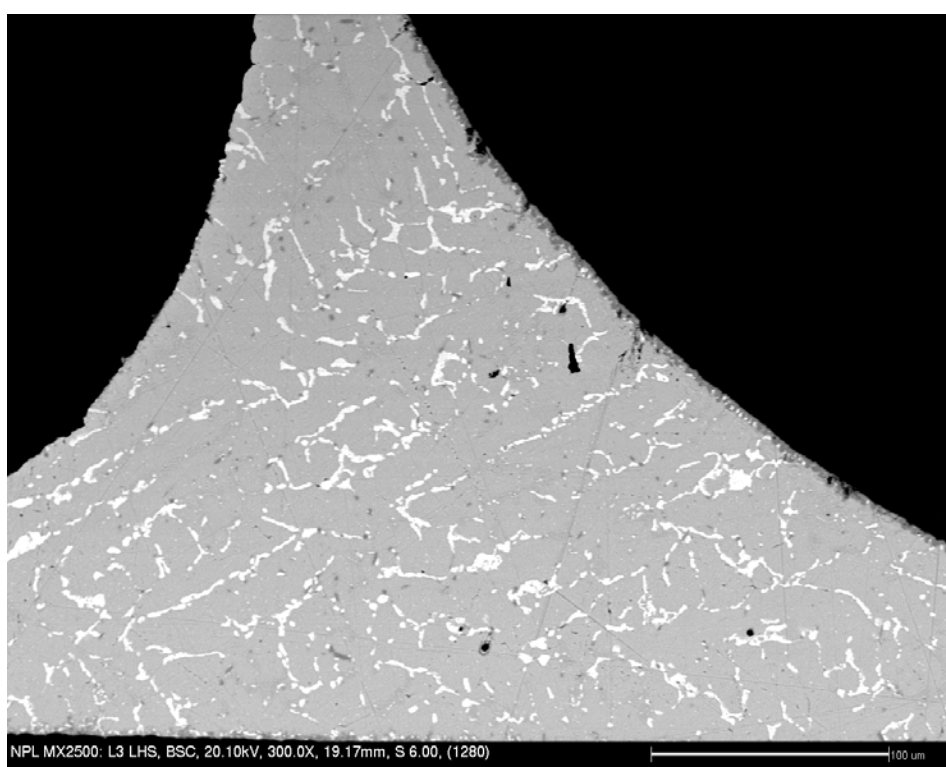


Figure 19. Micro-section of joint formed with 60%Sn40%Pb-plated SOIC

4.3 ELECTRICAL TEST FAILURES

For the purposes of this report, an electrical failure was defined as an interconnect loop resistance greater than 100Ω. The electrical faults detected at 2000 thermal cycles by the automated switch system, were confirmed manually with a digital ohmmeter. Where possible the location of failure was more accurately determined by probing with the ohmmeter between individual pins. This was not possible with QFP joints as probe pressures caused the joints to return to the closed circuit state. Confirmed joint failures are detailed in Table 7.

Table 7: Electrical Failure Summary after 2000 thermal cycles

Component (All types, SnPb, LF, Pb contaminated)	% failures at 2000 cycles for all types	Comments
SOIC	0%	No failures on any assembly
R0603	0.24%	1 failure @ 1000 cycles for 2% Pb contamination
R1206	0%	No failures on any assembly
DIP	0%	No failures on any assembly
MELF	1.5%	3 failures SnPb comp/SAC paste 1 failure each, 1%Pb, 2%Pb, 10%Pb
CCGA	?	Similar failures for SnPb and SAC pastes
QFP	2.5%	4 failures Sn comps/SAC paste (1000-2000 cycles)
BGA	10%	Mostly (84%) SnPb components with SnPbAg or SAC paste.

4.3.1 SOIC, R1206 and DIP Electrical Testing

No electrical test failures occurred in any of the following combinations:

- Batch A (SAC solder with SnPb SOICs, R1206s and DIPs)
- Batch B (SnPbAg solder with SnPb SOICs, R1206s and DIPs)
- Batch D (SnPbAg solder with Sn, SnBi and SnCu SOICs, Sn R1206s and Sn, SnBi and PdNi DIPs)
- Batch E1 (SAC solder with Sn, SnBi and SnCu SOICs, Sn R1206s and Sn, SnBi and PdNi DIPs)
- Batches E2, E3, E4 and E5 (Contaminated solder with Sn, SnBi and SnCu SOICs, and Sn R1206s (*no DIP components*))

4.3.2 R0603 Electrical Testing

No electrical test failures occurred in any of the following combinations:

- Batch A (SAC solder with SnPb R0603s)
- Batch B (SnPbAg solder with SnPb R0603s)
- Batch D (SnPbAg solder with Sn R0603s)
- Batch E1 (SAC solder with Sn R0603s)
- Batches E2, E4 and E5 (1, 5 and 10% Pb-contaminated solder with Sn R0603s)

A single component failed at 1000 cycles in the E3 batch (2%Pb-contaminated solder with Sn R0603s)

4.3.3 MELF Electrical Testing

No electrical test failures occurred in any of the following combinations:

- Batch B (SnPbAg solder with SnPb MELFs)
- Batch D (SnPbAg solder with Sn MELFs)
- Batch E1 (SAC solder with Sn MELFs)
- Batches E4 (5% Pb-contaminated solder with Sn, SnBi and SnCu SOICs)

Electrical failures occurred at or before 2000 thermal cycles in the following batches:

- Batch A, 3 failures (SAC solder with SnPb SOICs)
- Batches E2, 1 failure (1% Pb-contaminated solder with Sn MELFs)
- Batches E3, 1 failure (2% Pb-contaminated solder with Sn MELFs)
- Batches E5, 1 failure (10% Pb-contaminated solder with Sn MELFs)

4.3.4 CCGA Electrical Testing

Electrical failures occurred at similar levels in both batches of boards containing CCGAs as follows:

- Batch A, 9 failures (SAC solder with PbSn CCGAs)
- Batch B, 6 failures (SnPbAg solder with PbSn CCGAs)

4.3.5 QFP Electrical Testing

No electrical test failures occurred in any of the following combinations:

- Batch A (SAC solder with SnPb QFPs)
- Batch B (SnPbAg solder with SnPb QFPs)
- Batch D (SnPbAg solder with Sn QFPs)
- Batches E2, E3, E4 and E5 (Contaminated solder with Sn QFPs)

Electrical failures occurred only in the following batch between 1000 and 2000 thermal cycles

- Batch E1, 4 failures (SAC solder with Sn QFPs)

4.3.6 BGA Electrical Testing

Only one batch survived 2000 thermal cycles with no electrical test failures:

- Batch D (SnPbAg solder with SnAgCu BGAs)

Electrical failures occurred only in the following batches

- Batch A (SAC solder with SnPb BGAs)
 - 19 failures in the C-rings between 1000 and 2000 cycles
- Batch B (SnPbAg solder with SnPb BGAs)
 - 3 failures in A-rings between 1500 and 2000 cycles
 - 7 failures in B-rings at 2000 cycles
 - 22 failures in C-rings between 1000 and 2000 cycles
 - 7 failures in D-rings between 1500 and 2000 cycles
- Batch E1 (SAC solder with SAC BGAs)
 - 3 failures in C-rings between 1750 and 2000 cycles
- Batches E2, (1% Pb-contaminated solder with SAC BGAs)
 - 1 failure in C-rings at 2000 cycles
- Batches E3 (2% Pb-contaminated solder with SAC BGAs)
 - 2 failures in C-rings at 2000 cycles
- Batches E4 (5% Pb-contaminated solder with SAC BGAs)

- 3 failures in C-rings between 1500 and 2000 cycles
- Batches E5 (10% Pb-contaminated solder with SAC BGAs)
 - 2 failures in C-rings between 1500 and 2000 cycles

4.4 R1206 SHEAR TESTING

Figure 20 shows the shear force required to remove R1206 components at room temperature from batches A,B D and E1 (batches without mixed solder paste). Figure 21 shows similar results from batches E1, E2, E3, E4 and E5 (mixed solder paste batches plus lead-free control). The data obtained in the test were analysed in terms of the ultimate shear force required to rupture the solder joint, and then plotted as a function of the number of thermal cycles to which the assembly had been subjected. A mean value was calculated from the 12 individual measurements and plotted as a full circle, together with the first and third quartile of a box-whisker diagram.

The box-whisker diagrams reveal the distributions of ultimate shear forces measured after reaching a certain number of cycles. Although the testing was performed after a defined number of cycles, the locations of boxes plotted in the diagram have been moved sideways around the nominal number of cycles to avoid overlaying of data. The top and bottom sides of the boxes indicate first and third quartile (Q1, Q3) values of the population sample. The line drawn across a box is an indication of the median (quartile Q2). The vertical lines (whiskers) from these boxes extend to the last data point within the range of the limits. The upper and lower limits are calculated according to the relationships:

$$\text{Min. Lower Limit} = Q1 - 1.5 (Q3 - Q1), \quad \text{Max. Upper Limit} = Q3 + 1.5 (Q3 - Q1)$$

The full dot represents the population mean, and the asterisks (*) are outliers (data points above the fourth quartile or below the first quartile).

These data clearly show a reduction in shear strength as thermal cycling progresses, due to the formation of fatigue cracks within the soldered joints of the chip resistors. However, the data does not show any significant advantage/disadvantage in utilising the alternative combinations of SnPb/LF components and solder incorporated in this study. Generally, the shear strengths of the SAC alloy soldered components reduce more during the initial thermal cycling but by 2000 cycles, the shear strengths of all combinations have reduced to similar levels. Small additions of lead, as shown in Figure 21 appear to have the same effect.

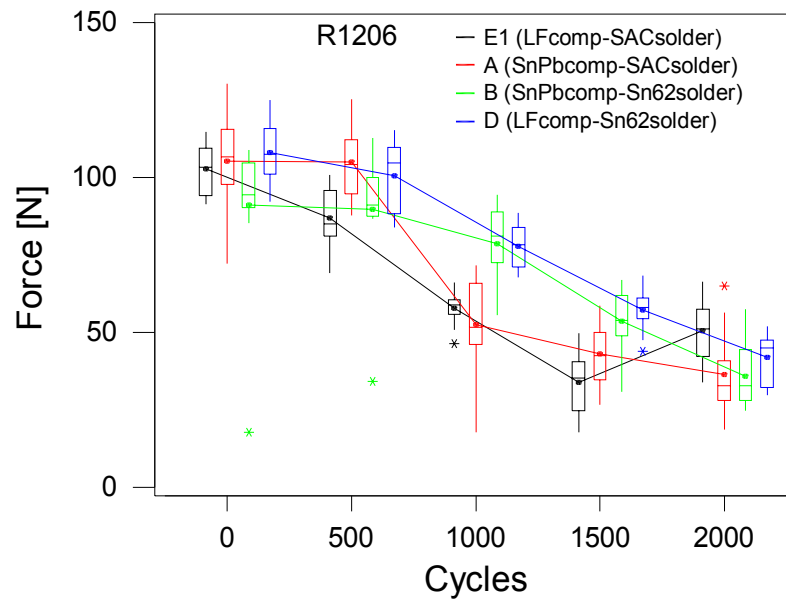


Figure 20. Shear strength results for R1206 components from batches A, B D and E1 (batches without mixed solder paste)

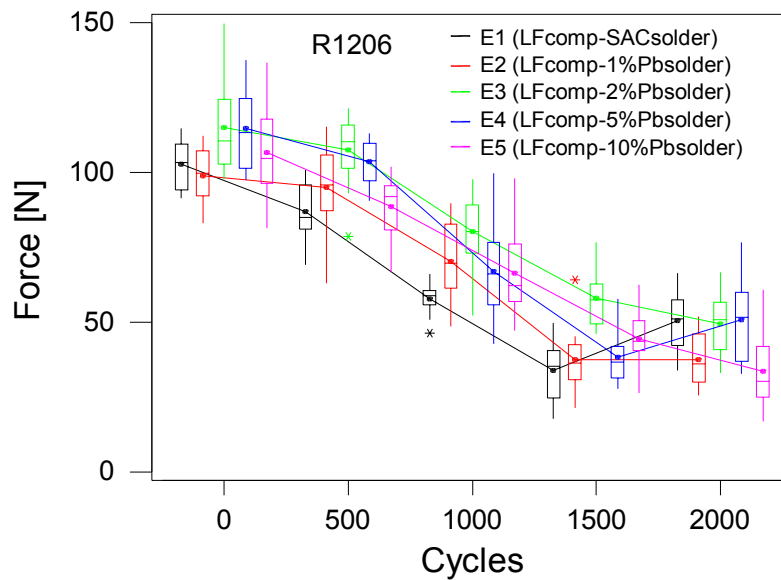


Figure 21. Shear strength results for R1206 components on batches E1, E2, E3, E4 and E5 (mixed solder paste batches plus lead-free control)

4.5 R0603 SHEAR TESTING

Figure 22 shows the shear force required to remove R0603 components from batches A, B D and E1 (batches without mixed solder paste). Figure 23 shows similar results from batches E1, E2, E3, E4 and E5 (mixed solder paste batches plus lead-free control). The data are plotted in the same manner as detailed in 4.2 above.

These data clearly show a reduction in shear strengths as the thermal cycling progresses, due to the formation of fatigue cracks within the soldered joints of the chip resistors, for all materials combinations tested. The rate of reduction in shear strengths for the R0603 components is less than for R1206 components because the smaller size of the former components results in less strain in the joints during thermal cycling and therefore a lower crack propagation rate. However, the data do not show any significant advantage/disadvantage in utilising the alternative combinations of SnPb/LF components or solder incorporated in this study.

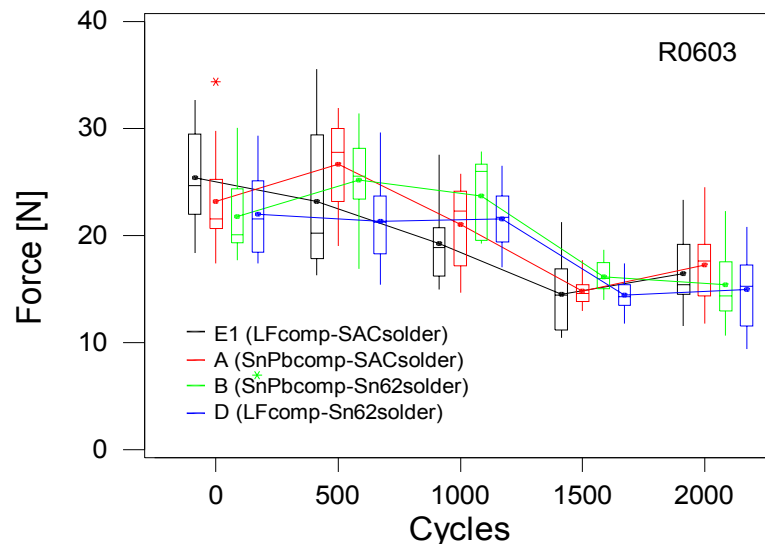


Figure 22. Shear strength results for R0603 components on batches A, B D and E1 (batches without mixed solder paste)

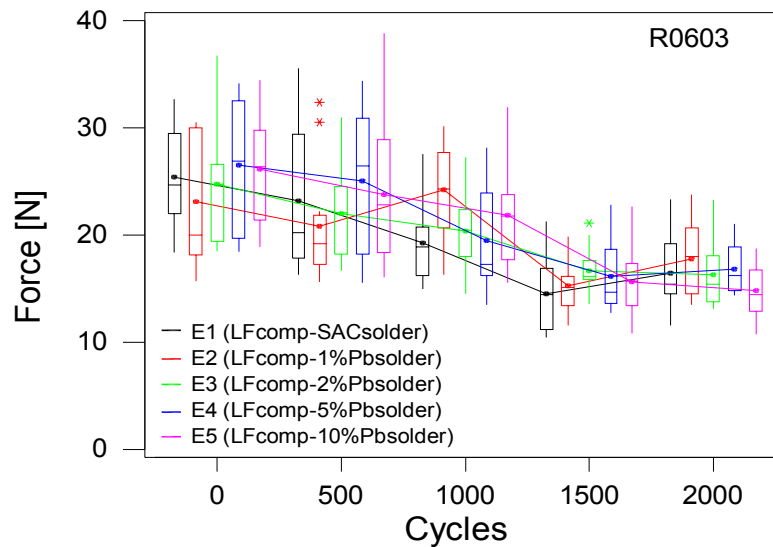


Figure 23. Shear strength results for R0603 components on batches E1, E2, E3, E4 and E5 (mixed solder paste batches plus lead-free control).

4.6 VIBRATION TESTING

No electrical test failures were noted in either of the two batches of assemblies (Bvibration - SnPb SM components with SnPbAg solder paste, and Dvibration - lead-free SM components with SnPbAg solder paste). Shear testing, before and after vibration testing, was undertaken and the results can be seen in **Figure 24** and **Figure 25**. For the R1206 chip resistors, there is no apparent difference between the two data sets, but for the R0603 chip resistors, although there are no electrical failures, the shear force for the lead-free components has reduced below that of the SnPb components. This may be a function of component manufacture as the two component types had to be sourced from alternative manufacturers.

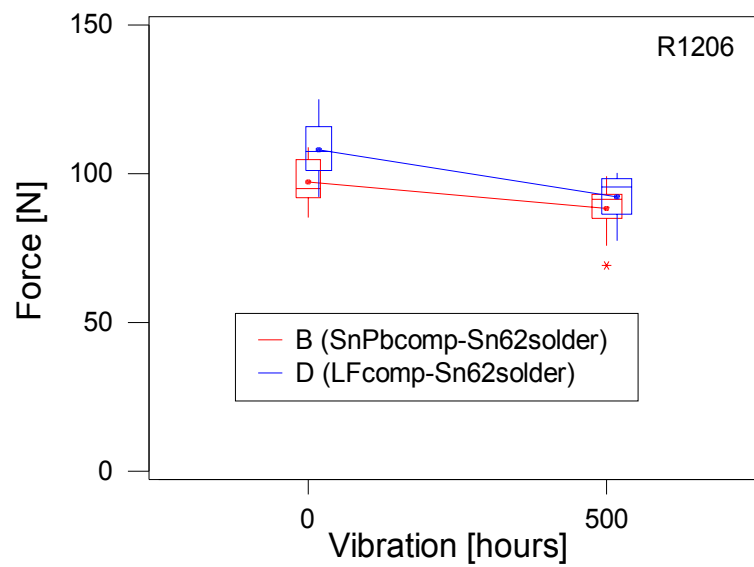


Figure 24. R1206 shear test results, before and after vibration testing

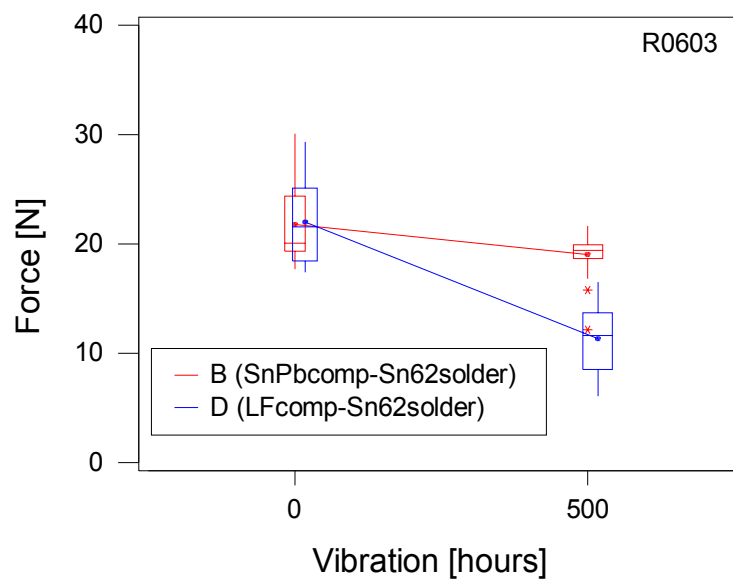


Figure 25. R0603 shear test results, before and after vibration testing

4.7 HOT PEEL AND SHEAR TESTING

4.7.1 Hot shear chip resistor testing

Shear testing on as manufactured R1206 and R0603 components was undertaken at 3 elevated temperatures, the results being shown in Figure 26. The lower data set is for the R0603 components, where the shear force in all cases was sufficient to cause pad failures at these elevated temperatures rather than joint failures. Results for the larger R1206 components are similar with pad failures beginning to occur at 150 °C and all pads failing at 170 °C. It was therefore not possible to differentiate between shear strengths for joints with different levels of Pb-contamination, at elevated test temperatures.

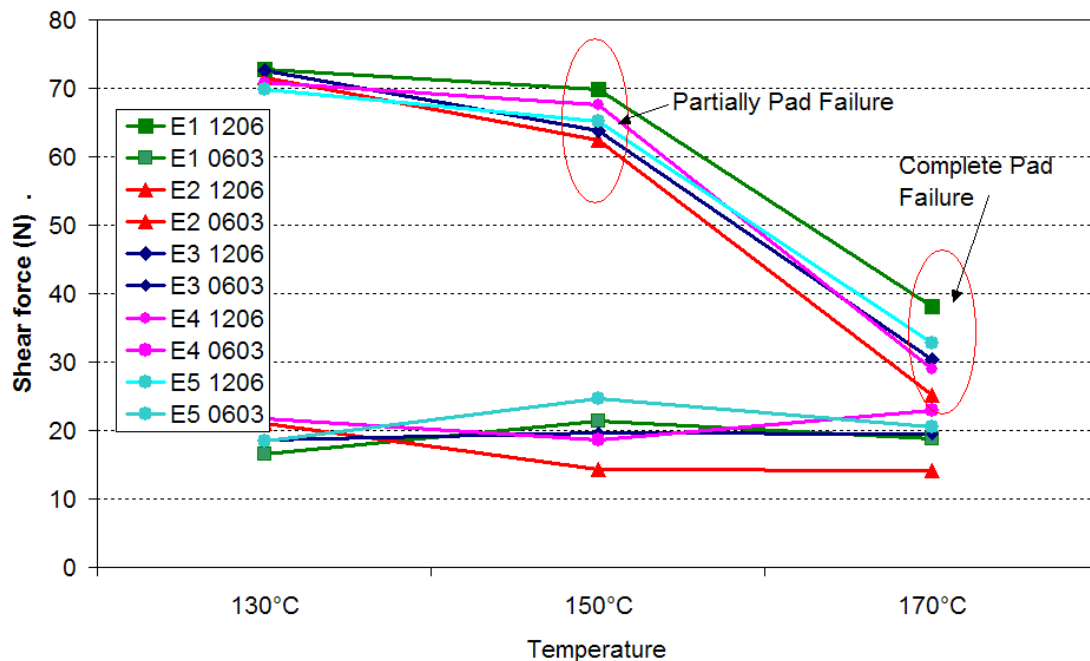


Figure 26. Hot shear measurements on Pb-contaminated chip resistor joints

4.7.2 Hot peel testing of controlled lead-content SOIC components

Figure 27 shows the results for the peel testing of SOIC leads at elevated temperatures. As the test temperature increases, the peel strengths for all samples reduce. The values for SOIC joints not containing lead are consistently higher than for Pb-contaminated joints. Indeed at the higher temperatures, the Pb-free joints continue to remain intact, with pads failing rather than joints. At 190°C (above the melting point of eutectic SnPb), all the Pb-contaminated joints failed at the minimum force required to bend the lead, indicating that the joint strength is minimal. There appeared to be no difference in the required force between 1 and 10% Pb content in the solder joint.

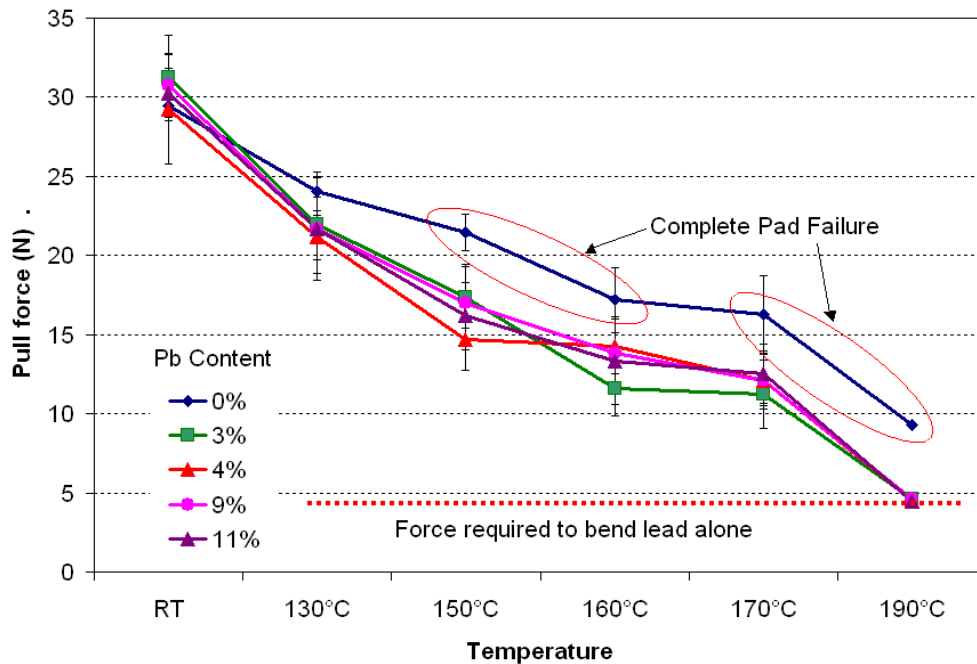


Figure 27. Hot peel testing results for controlled Pb-content SOICs

5 DISCUSSION

The principal purpose of this work was determine if either Pb-contamination of SAC soldered joints, or lead-free surface finishes contamination SnPb solder joints, presented any issues with solder joint reliability. To this end, a range of assemblies has been manufactured using both SnPb and LF components and SnPb and LF solder pastes. In addition, joints have been seeded with known quantities of Pb to produce joints in the range of 0 to 10% Pb-contamination. This was achieved over a range of SM components by mixing SAC and SnPb solder pastes. It was also achieved with SOIC components by altering the composition of the plating of the leads to contain different amounts of Pb, and soldering with lead-free paste.

5.1 RELIABILITY OF MIXED ALLOY SYSTEMS

Assemblies with different mixtures of SnPb and LF solder pastes were subsequently thermal cycled with electrical continuity measurement and periodic shear testing of chip resistors. The majority of the combinations did not show any weak links with little differential between the reliability of SnPb and SAC alloy joints up to 2000 thermal cycles over a wide range of components and component termination materials, including R0603 chip resistors, MELFs, SOICs, ceramic column grid arrays and dual-in-line packages. Performance was also similar for special Pb-contaminated joints over this number of thermal excursions. R1206 resistors did show the pure Pb-free, batch E1, and batch A (SnPb component and SAC alloy), did yield poorer reliability than any of the alloys containing Pb. Two other component types did exhibit reliability differences between alloy combinations and these are discussed below.

5.1.1 Sn-plated QFPs with SAC Solder

Sn plated QFP components soldered with SAC alloy pasted did reveal reliability issues. This combination showed 4 component failures between 1000 and 2000 thermal cycles. None of the other combinations (Sn components with SnPb solder and Pb-contaminated solder, and SnPb components with either SnPb or SAC solder) showed any electrical failures over 2000 cycles. Figure 28 shows a typical failure of a Sn-plated component with SAC alloy. The failure occurs close to the interface between the component and the joint. This is confirmed by the micro-section of a failed joint shown in Figure 29. No similar failures were noted for Sn-plated SOIC components with SAC alloy joints.

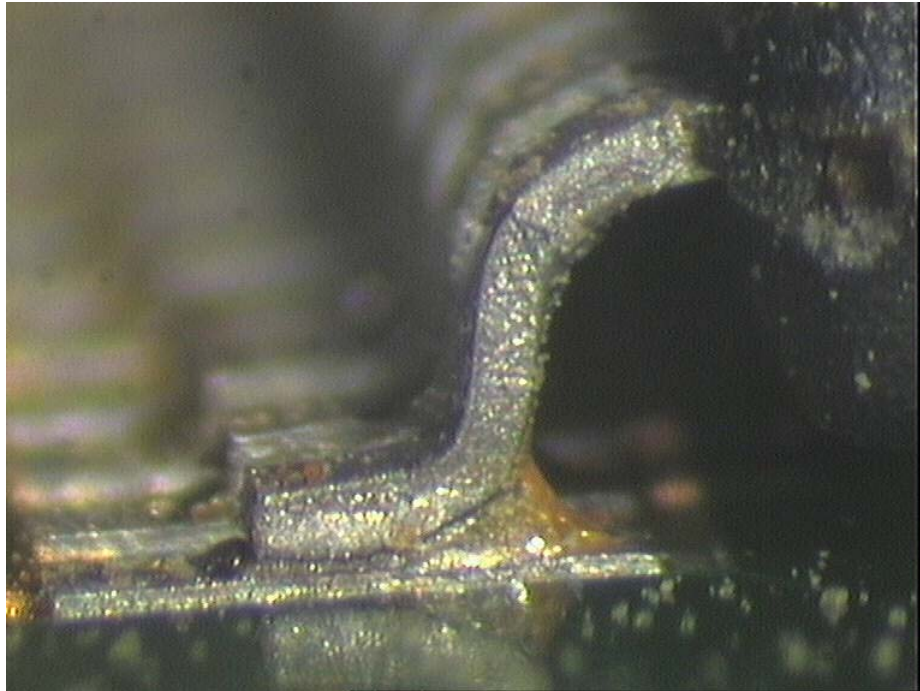


Figure 28. Typical failure of Sn-plated component with SAC solder

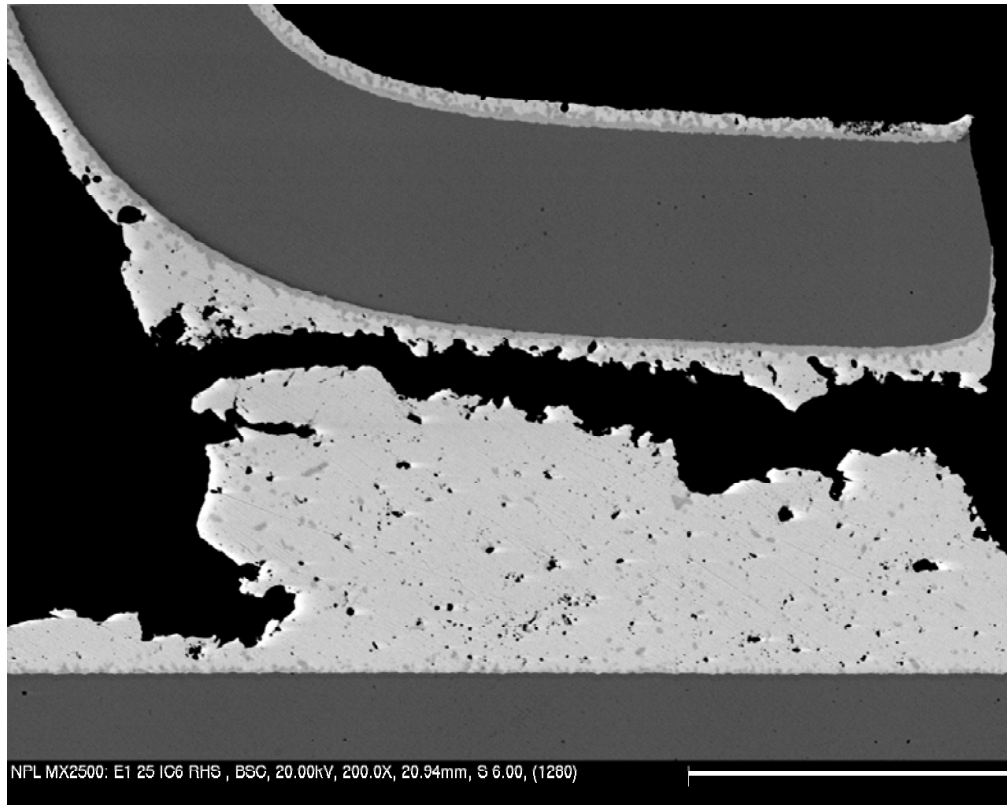


Figure 29. SEM image of micro-sectioned Sn-plated QFP with SAC alloy joint after 2000 thermal cycles

Solderability testing of samples from both the Sn-plated and SnPb plated batches was undertaken and the results are shown in Figures 30 and 31. These show that the Sn-plated component is slower to wet than its SnPb counterpart and it may be that this difference is sufficient to account for the reliability differences. The process window for SAC alloy soldering is narrower than for equivalent SnPb processing. Small additions of Pb may also help widen the process window. It is therefore considered that these differences in QFP component reliability are probably batch related.

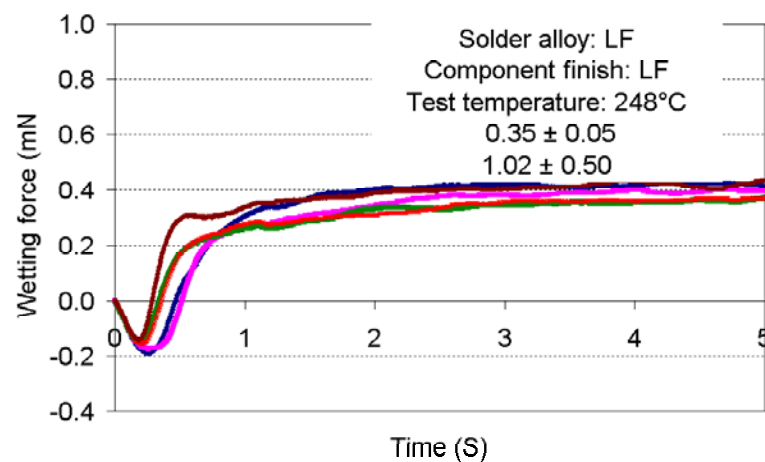


Figure 30. Solderability results for Sn-plated QFPs with SAC solder

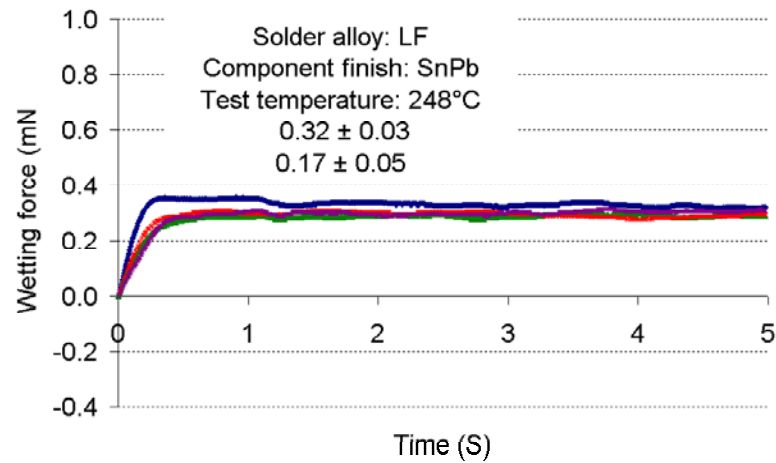


Figure 31. Solderability results for SnPb-plated QFPs with SAC solder

5.1.2 BGA Component Joint Reliability

The other component system to show significant failures during the 2000 thermal cycles, were the BGA components. Figure 32 shows the development of failures within the C-rings of the various BGA/solder alloy combinations. It is clear that the two batches with SnPb-terminated components, and either SnPb solder (Batch B) or SAC solder (Batch A) are consistently out-performed by the SAC alloy dominated systems (batches D and E1 to E5).

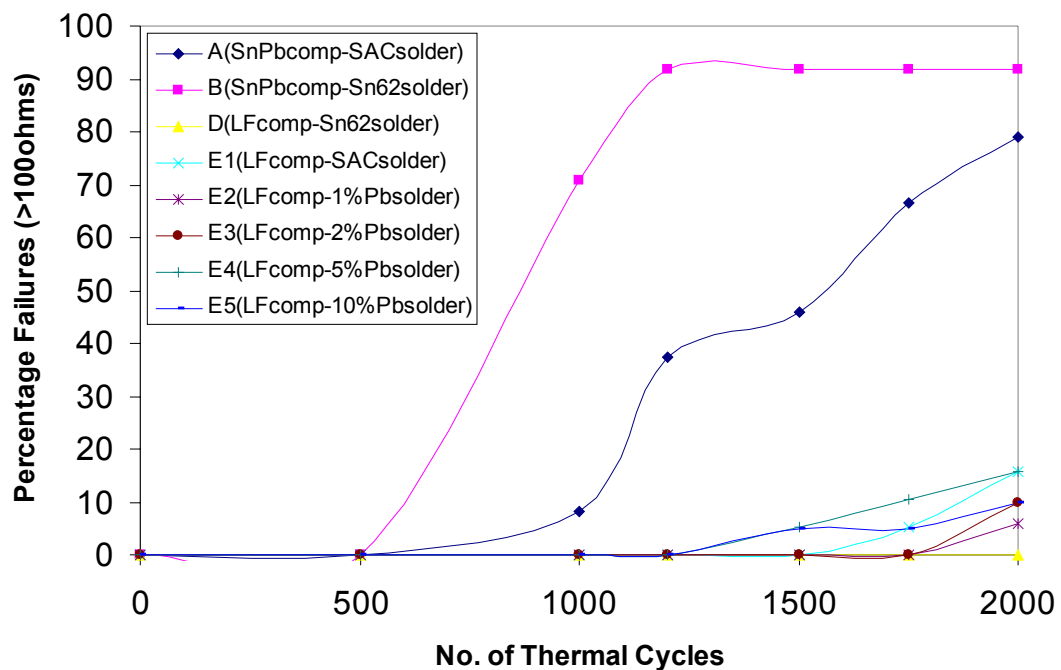


Figure 32. Development of BGA C-ring failures during thermal cycling

Other workers (Reference 9) have reported reliability problems with SAC components soldered using SnPb alloys, where the SAC ball has not reflowed during assembly. However the samples tested here, the SnPb reflow profile was sufficiently hot to ensure that the BGA balls did reflow. This can be seen in **Figure 33**, where the lighter Pb-rich phases can be seen distributed throughout the joint..

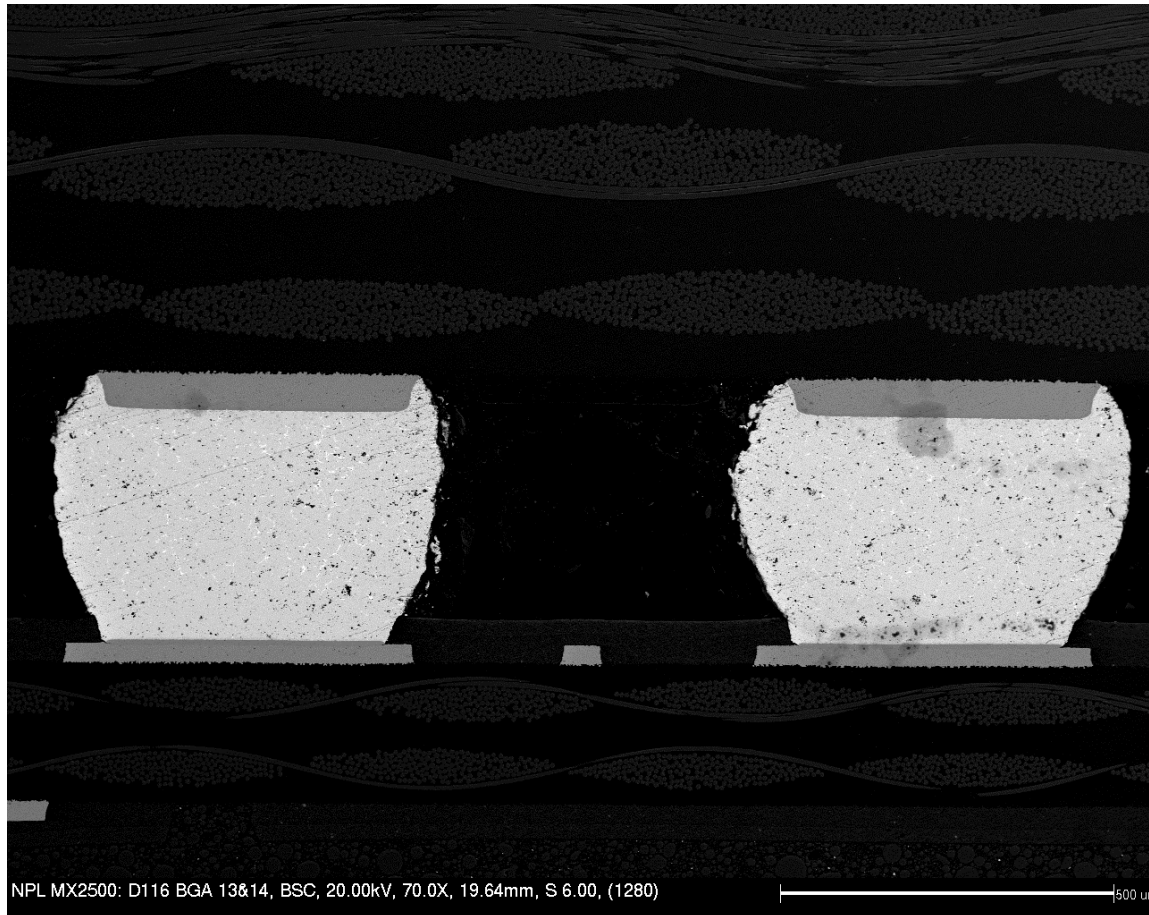


Figure 33. Section of two joints as manufactured from SAC BGA soldered with SnPbAg solder paste showing reflow of SAC ball (PCB uppermost) as manufactured

Sections of typical SnPb dominated BGA joints after 2000 cycles are shown in Figure 34 and Figure 35. Both systems show fatigue cracking adjacent to the component/solder interface. Batch A (SnPb BGA with SAC solder) also show fatigue cracking at component/PCB interface. Similar fatigue cracking can be seen in SAC dominated systems (see Figure 36) but such cracks are less advanced than in the SnPb dominated systems.

Clearly, SAC solder in BGA joints provides better fatigue resistance than SnPb solder. Small levels of Pb-contamination can be tolerated, provided that the BGA ball has been fully reflowed. Results here indicate that SnPb BGAs soldered with SAC alloy, have a reduced reliability compared to SAC dominated system. However, this systems' reliability would still be greater than SnPb BGAs with SnPb solder alloy,

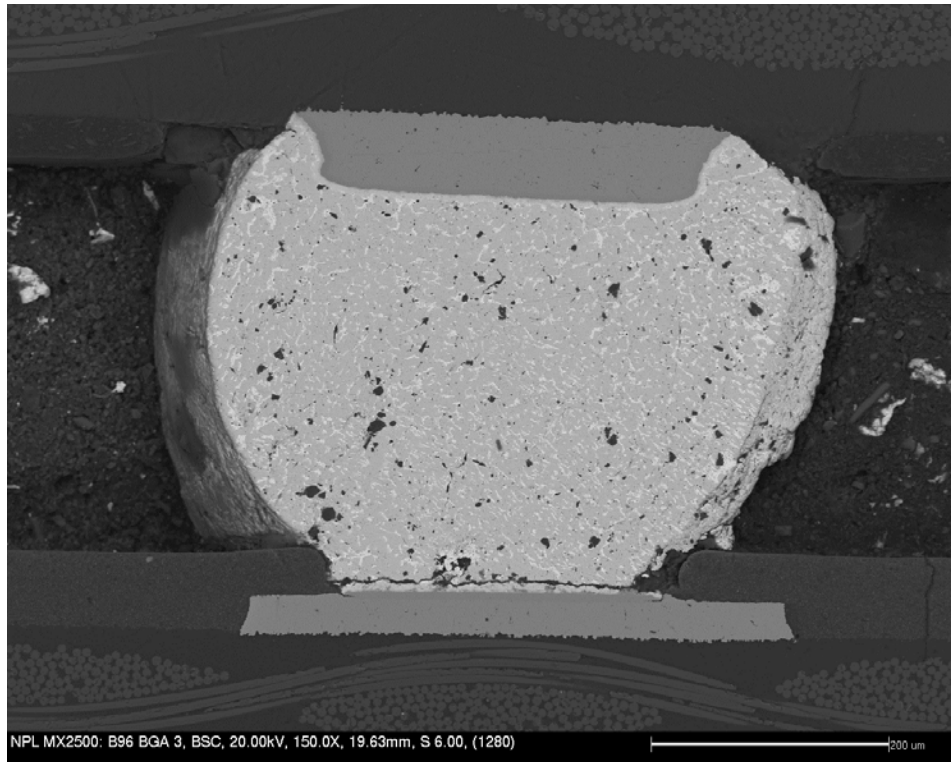


Figure 34. Section from batch B (SnPb BGA with SnPbAg solder) after 2000 cycles showing fatigue failure adjacent to BGA/solder interface (PCB uppermost)

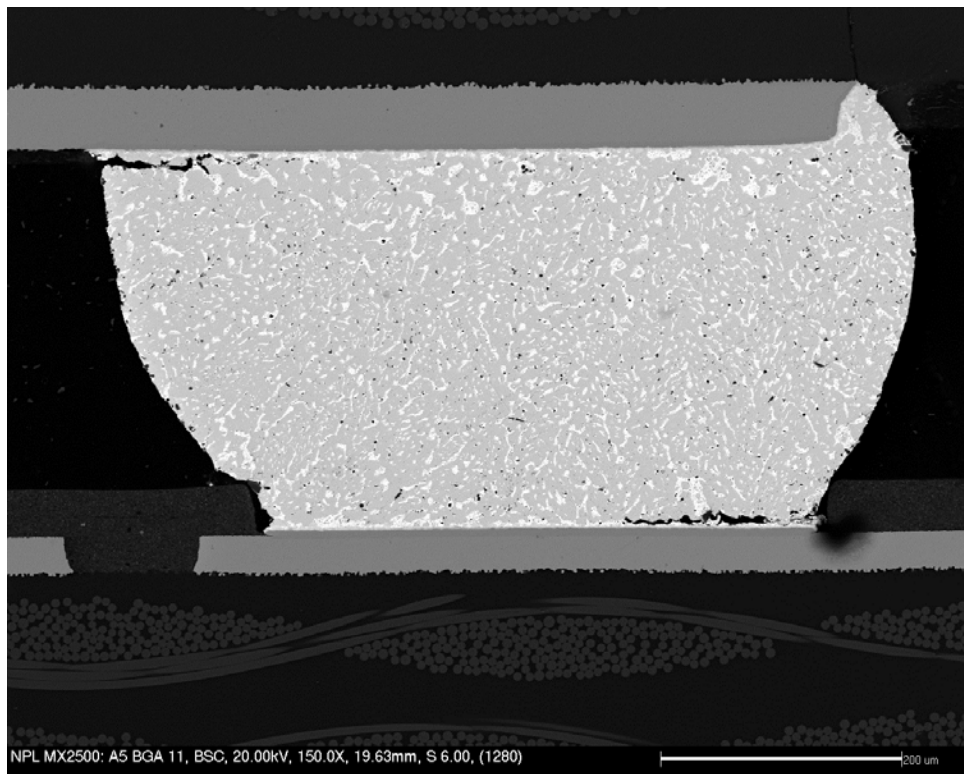


Figure 35. Section from batch A (SnPb BGA with SAC solder) after 2000 cycles showing fatigue cracks at both BGA/solder and solder/PCB interfaces (PCB uppermost)

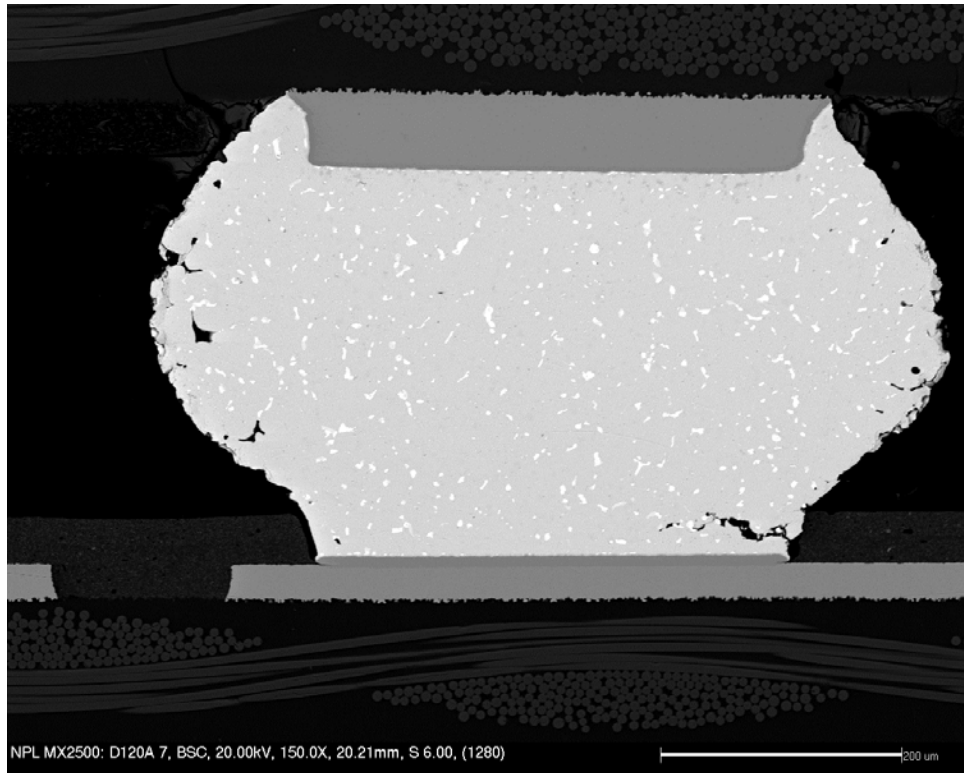


Figure 36. Section from batch D (SAC BGA with SnPbAg solder) after 2000 cycles showing fatigue crack adjacent to BGA/solder interface (PCB uppermost)

5.2 TESTING OF MIXED ALLOY SYSTEMS AS ELEVATED TEMPERATURES

Hot shear testing of resistors showed little differentiation between uncontaminated and Pb-contaminated systems up to 170 °C. Above this temperature, the PCB failed due to pad shear before joints fail.

Hot peel testing of Pb-contaminated SOIC joints provided more interesting results. Joints contaminated with lead failed at lower pull forces than pure LF systems between 130 °C and 170 °C. At 190 °C contaminated joints failed at the minimum pull force required to bend an SOIC lead. This phenomena can be further illustrated by heating a test sample containing SOIC joints with 0, 1, 2.5 and 10% Pb-contamination to 190 °C and holding it inverted. When given a sharp tap, the lead contaminated components fall from the assembly (with the exception of the 1% Pb-contaminated components), whilst the pure LF system components remain in place. The results of such a test can be seen in Figure 37.

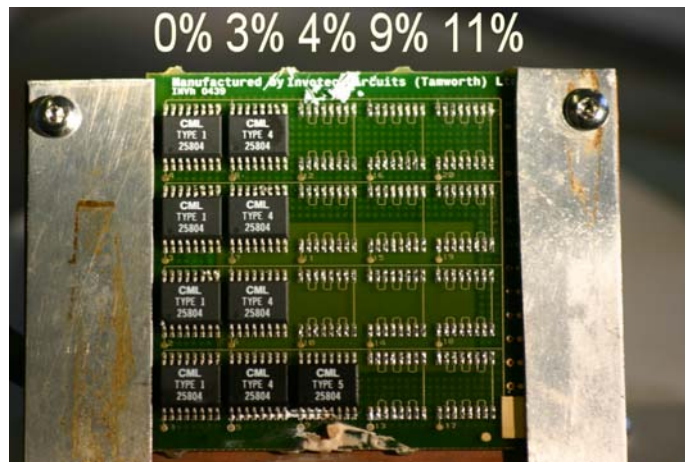


Figure 37. Pb-contaminated assembly after inversion at 190°C showing loss of Pb-contaminated components after sharp tap (annotated % refers to Pb in joint)

5.3 THERMAL CYCLING RELIABILITY

Thermal cycling has shown that Pb-contamination has no effect on reliability up to 2000 cycles but this lowering of pull forces for Pb-contaminated systems at elevated temperatures may be a significant issue. One clear scenario where this problem is likely to manifest itself during assembly. If components with Pb-containing finishes are used on initial assembly side, during second side reflow and wave soldering, if the assembly is bowed or twisted, Pb-contaminated joints may be separated or deformed, leading to open joints or joint with poor reliability.

6 CONCLUSIONS

A wide-ranging study of Pb-contamination of lead-free solder joints has been undertaken. Over 200,000 solder joints on assemblies incorporating the main types of surface mount and through components, have been manufactured with SnPb and LF terminated components using SnPb, LF and mixed alloy systems. The work has included manufacture of joints with specifically controlled levels of Pb-contamination between 1 and 10%. All these assemblies have subsequently been thermally cycled (-55 to 125 °C) to 2000 cycles, continuity tested, shear tested, pull tested and vibration tested.

The work has indicated that there should be few solder joint reliability problems when mixing SnPb and LF components and solder alloys (with Pb contamination in the range 1 to 10%). Very few thermal cycle fatigue failures were experienced other than within two component groups. Shear testing of chip resistor components showed no difference in crack propagation rate between any of the component/alloy combinations. No failures were generated during vibration testing.

Two groups of components did show significant thermal cycle failures. Ball grid array components did fail generally, in the rings of balls adjacent to the edge of the silicon die within the package. In this area the TCE of the package is constrained by the die, creating a maximum strain in these joints. However, the failures in these devices were largely restricted to SnPb alloy dominated systems, i.e. SnPb terminated components soldered with SnPb or SAC alloy solder pastes. Uncontaminated SAC systems or those

systems contaminated with low levels of Pb showed fewer failures and thus must be considered more reliable. Indeed, the system showing greatest thermal cycle fatigue in BGA components was the SnPb terminated BGAs with SnPb solder. All other systems were shown to perform better.

The other component type to show significant failures, were the QFP components where failures were confined to Sn-plated components with SAC solder. Solderability testing of these components showed that they were slower to wet than the SnPb counterpart and it may be that this difference is sufficient to account for the reliability differences. The process window for SAC alloy soldering is narrower than for equivalent SnPb processing and small additions of Pb may help widen the process window, improving the reliability for these soldering batches. It is therefore probable that these differences in QFP component reliability are batch related.

Work with hot peel testing of SOIC components has indicated that Pb-contamination may cause end-users some problems during processing. The addition of small quantities of Pb (<10%) to a LF joint will increase the pasty range of the alloy. If the initial side of a double sided assembly reaches temperatures above 180°C during second side assembly, stress on the joint (such as those that occur if the assembly is warped), may cause the first side solder joint to separate or deform. This could produce an open joint or perhaps worst, produce an electrically conducting joint, but one with low resistance to low cycle or mechanical fatigue. Such a joint would be a reliability “time bomb”. However, it should be reiterated that there are no indications in this work that Pb-contamination of well formed joints, has any effect on low cycle fatigue resistance.

7 ACKNOWLEDGEMENTS

The work was carried out as part of a project in the MPP Programme of the UK Department of Trade and Industry. We gratefully acknowledge the technical support, co-operation and funding from the following project partners without whose help this project would not have been possible.

Aeroflex
 Alcatel
 BAE (INSYTE)
 BAe Systems
 Bookham
 Bosch
 Celestica
 Dolby Laboratories Inc. (UK)
 Eurotherm Controls Ltd.
 Goodrich Engine Controls
 Hansatech (Poole) Ltd.
 MBDA
 Rolls Royce
 Thales Defence Electronics
 TRW Automotive

In addition, we would like to acknowledge the material support provided by the following companies, which made the project possible.

CML Microcircuits (UK) Ltd
Cemco-FSL
Henkel Loctite
Grosvenor Solder
Invotec Group
Rohm and Haas Electronic Materials Europe, Ltd.
Vitronics Soltec BV

8 REFERENCES

- (1) Fujitsu : <http://www.fma.fujitsu.com/pdf/leadfree.pdf>
- (2) Rohm : Change notification of Termination Solder Finish : March 2001
- (3) Sony : <http://www.sony.net/Products/SC-HP/GUIDE/PDF/free-eng.pdf>
- (4) Infineon :
http://www.infineon.com/cmc_upload/board_level_reliability_tin_plated_components_v1_1.pdf
- (5) Fatigue properties of Sn3.5Ag0.7Cu solder joints and effects of Pb-contamination: James Oliver, Margareta Nylen, Olivier Rod, Christofer Markou, SIMR: Apex 2003
- (6) Lead-free electronics assembly for the real world: Joint failures, lead contamination and other important considerations: Karl Seelig and David Suraski, AIM: Apex 2002 additional paper (Partly available on AIM web-site) Effects of Pb contamination on the eutectic Sn-Ag solder joint: S Choi, T R Bieler, K N Subramanian & J P Lucas, Michigan State University: Soldering & Surface Mount Technology 13/2 (2001)
- (8) The effect of Pb contamination on the microstructure and mechanical properties of SnAg/Cu and SnSb/Cu solder joints in SMT: Qinong Zhu, Mei Sheng, Le Luo, Shanghai Institute of Metallurgy: Soldering & Surface Mount Technology 12/3 (2000)
- (9) The Impact of Reflowing A Pbfree Solder Alloy Using A Tin/Lead Solder Alloy Reflow Profile On Solder Joint Integrity, David Hillman, Matt Wells and Kim Cho, Rockwell Collins, Cedar Rapids, USA. Centre for Microelectronics Assembly and Packaging International Lead-free Conference, May 2005, paper16.