

NPL REPORT
DEPC MPR 028

**Effect of PCB Finish,
Processing and
Microstructure on Lead-free
Solder Joint Reliability**

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NOT RESTRICTED

SEPTEMBER 2005

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ABSTRACT

The electronics assembly industry often gauges the long-term reliability of its products (and provide good process control) by assessing the life-time of the solder joints, which are known to be the weakest link in the assembly. Such a lifetime assessment is often obtained by monitoring the degradation of the joints under severe accelerated conditions, and this process has become critical in the change to lead-free soldering. Although many studies have investigated lead-free solder joint reliability, this work has focused on some specific aspects highlighted by the UK industry. It has compared the effects of thermally induced microstructural changes on the performance of lead-free and SnPbAg solder joints formed on PCBs after accelerated thermal cycling. Test vehicles were assembled with combinations of three alloys (SnAgCu, SnAg and SnPbAg), two board finishes (ENIG and immersion silver), various component sizes and two substrate materials (FR4 and CTE matched). A conformally coated PCB was also included. Thermal history effects were established using multiple reflow passes, or wave soldering, or isothermal ageing for 1000 hours at 125°C. The manufactured assemblies were then subjected to thermal cycling between -55 and 125 °C with 5 min dwells and 10°C/min ramp rate. The intention was to accelerate fatigue and develop cracks in the solder joints. As cracks propagate through a solder joint, they reduce the overall solder joint strength. The degree of cracking was monitored on micro-sectioned specimens of chip resistors, BGAs and SOICs, and the reliability was measured using electrical continuity and shear testing. The salient points from these studies were that there were significant (measurable) difference between the reliability of joints soldered with SnAgCu and SnPbAg alloys. There was no evidence to suggest that thermal pre-treatment was detrimental to the long-term reliability of the joint. Additional reflow passes or extended thermal ageing did produce some differences in reliability, but these were component specific. The reliability of joints made using SnAgCu solder was significantly better than that of joints made using the simple binary SnAg alloy. Comments are offered on the techniques used to assess solder joint reliability.

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ISSN 1744-0270

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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

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1 INTRODUCTION

Small to medium sized electronic components are usually mechanically connected to a substrate via solder joints, which provide electrical as well as mechanical bonds to the substrate. It has been shown [1] that solder joints are the weakest points in the assembly, and usually determine the life-time of the electronic products. An estimate of a specific solder joint life-time is often obtained by monitoring the degradation of the joints under severe accelerated conditions. Such estimates of life-times are desirable, if not necessary, as a feedback to achieve and maintain good design/process control, especially for high reliability applications. Previous work [2] on mechanical studies of solder joints has demonstrated that mechanical fatigue failure of a solder joint does not happen in a sudden, catastrophic manner, but occurs as a gradual change, usually in the form of cracking. Typical cracking of a SnAgCu solder joint of a R1206-type chip resistor is illustrated in Figure 1.

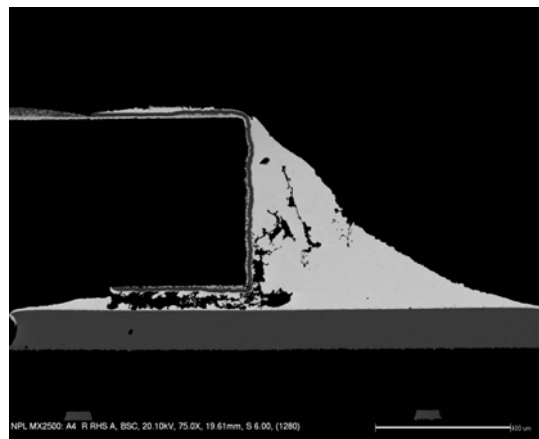


Figure 1. A R1206-type chip resistor showing cracking in the solder joint.

Many studies have investigated lead-free solder joint reliability, but this work focused on some specific process and material combinations. In this work, test techniques have been used to study the comparative behaviours of the solder joints made using conventional SnPb and new lead-free solders. The alloys studied were SnAgCu (SAC) and SnAg eutectic, and their behaviours were compared with that of the SnPbAg (Sn62) alloy. Two board finishes were included, ENIG and immersion silver, with the majority of the work on the ENIG finish. Reflow was investigated, with one and two passes, or one reflow and a wave process. The effect of an additional isothermal heat-treatment of 1000 hours at 125°C before thermal cycling was also explored. Finally the impact of a conformal coating was evaluated.

2 TEST SPECIMENS

The fatigue strength of the solder joints is particularly affected when there is a large component body soldered directly to a substrate with a large CTE (coefficient of thermal expansion) mismatch. Such a mismatch was provided in the test PCB assembly, as illustrated in Figure 2. The board comprised multilayer FR4 epoxy glass laminate (thickness 1.6 mm) with copper tracks and pads 35 μm thick (copper plating 1 oz/sq.ft) and an ENIG surface finish. The vias used to connect the top side to the bottom side were 300 μm diameter when plated, and were used because of limited connectivity through the connector on the top side.

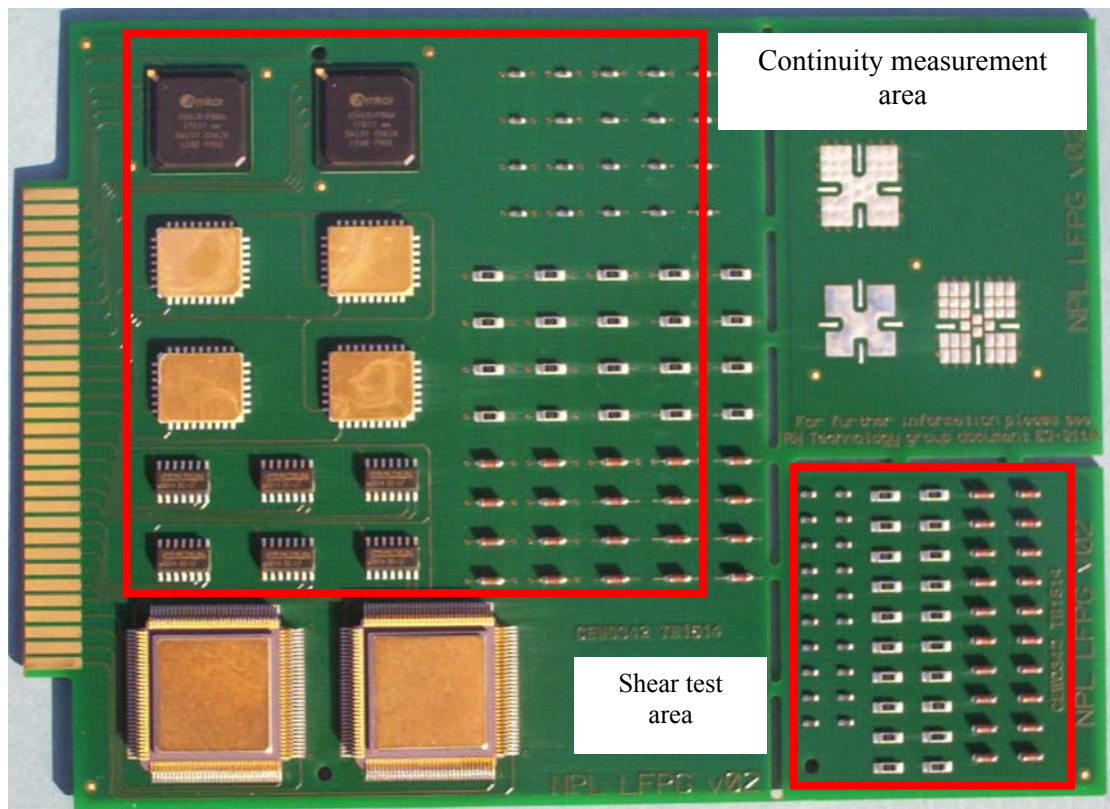


Figure 2. FR4 laminate substrate with daisy-chained components for continuity measurements and resistors for shear test

All the substrates were stencil printed with solder paste using a 150 μm thick stainless steel stencil. The components were placed onto the substrates using an automatic placement system. The solder alloys used in the study were 95.5Sn3.8Ag0.7Cu, 96.5Sn3.5Ag and 62Sn36Pb2Ag in no-clean type 3 solder paste compositions. Reflow of the solder paste was achieved in a convection reflow oven. The temperature reflow profile for lead-free soldering process is shown in Figure 3.

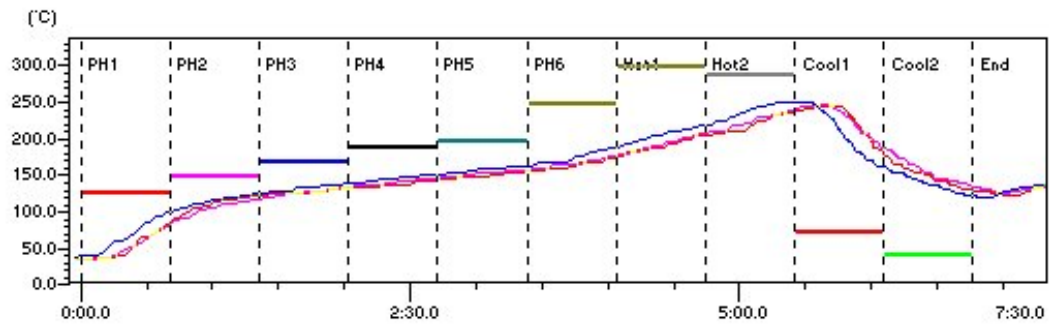


Figure 3. Lead-free reflow profile

The components used in the study are listed in Table 1. The assemblies were separated into 12 sets of 10 identical substrates according to the solder alloy, process and conditioning used. All the sets and their descriptions are listed in Table 2.

Table 1. List of all components used in the experiment per test vehicle

Components	Quantity	Termination finish	I/O
R0603	40	Sn	2
R1206	40	Sn	2
SOIC	6	Sn	14
Plastic BGA**	2	SAC	256
Ceramic QFP	2	Sn	132
mimi MELF ⁺	40	Sn	2
TH crystal	2	Sn	2
LCCC*	2	Sn	32

** Not present in set L

+ Only present on sets A and J

* Only present on sets A and L

A typical build for set B was 10 assemblies soldered with SnAgCu solder alloy with a normal single pass through the reflow cycle (Figure 3), after which the assemblies were thermally aged at 125°C for 1000 hours. The thermal ageing treatment was selected because it is known to accelerate the growth rate of grains in solder joints. Set J contained 10 identical assemblies soldered with SnPbAg solder on immersion silver surface finished PCB. These boards were initially sent through reflow process followed by a single pass through a wave soldering process. The units from set L were the only assemblies manufactured using a substrate with a CTE matched to that of the ceramic components.

Table 2. Process conditions applied to test samples

Set	Alloy	Process	Conditioning	PCB
A	SAC	Reflow 1x	None	ENIG
B	SAC	Reflow 1x	1000 h @ 125°C	ENIG
C	SAC	Reflow 1x	Conformal Coat	ENIG
D	SAC	Reflow 2x	None	ENIG
E	SAC	Reflow 1x + Wave	None	ENIG
F	SnAg	Reflow 1x	None	ENIG
G	SnAg	Reflow 1x	1000 h @ 125°C	ENIG
H	SnAg	Reflow 2x	None	ENIG
I	SnAg	Reflow 1x + Wave	None	ENIG
J	SnPbAg	Reflow 1x + Wave	None	Ag
K	SAC	Reflow 1x + Wave	None	Ag
L	SAC	Reflow 1x	None	Aramid CTE matched

3 THERMAL CYCLING

The traditional method for accelerating the generation of cracks in solder joints is to subject the assemblies to a thermal cycling regime. During this cycle the crack develops by creep when shear and tensile stresses cause plastic deformation of a particular solder alloy. These localised stresses can be imposed either mechanically (e.g. by bending) or thermally. Thermally induced stresses in solders are the result of unequal elastic expansion of the various materials in the printed circuit assembly (PCA). The difference in these expansions is largely accommodated by the elastic and plastic deformation of solder. Since the yield shear stress of solders is very low ($\sim 2.5\text{MPa}$) compared to that of other materials in the assembly, most of the localised stresses cause plastic deformation within the solder joint and consequential development of cracks. In case of a simple chip resistor there are mismatches in CTEs between the component body (alumina $6.5\text{ppm}/^\circ\text{C}$), the solder ($21\text{-}25\text{ppm}/^\circ\text{C}$), the copper termination pad ($17.6\text{ppm}/^\circ\text{C}$) and the FR4 laminate ($\text{CTE}_{xy} = 12\text{-}18\text{ppm}/^\circ\text{C}$). In addition, all these coefficients will vary with temperature. The largest mismatch over the longest absolute dimension is between the resistor's body and the FR4 substrate under the component.

Table 3. Tested temperature cycling regime with $\pm 4^\circ\text{C}$ temperature tolerance

Low Temperature dwell	High Temperature Dwell	Ramp rate	Dwell time	Period
[$^\circ\text{C}$]	[$^\circ\text{C}$]	[$^\circ\text{C}/\text{min}$]	[min]	[min]
-55	125	10	5	45-48

The parameters of the thermal cycling regime used in this evaluation study are listed in Table 3, and Figure 4 provides a graphical representation of a thermal cycle. This thermal cycling test regime is that widely used for testing military, avionics and automotive applications, which accounts for the wide temperature range of the cycle. The ramp rate of $10^\circ\text{C}/\text{min}$ is a moderate ramp rate, slower than a thermal shock

regime, which is typically above 30°C/min [3]. The relatively short dwell time of 5 minutes is to minimize the cycle period and shorten the overall test time.

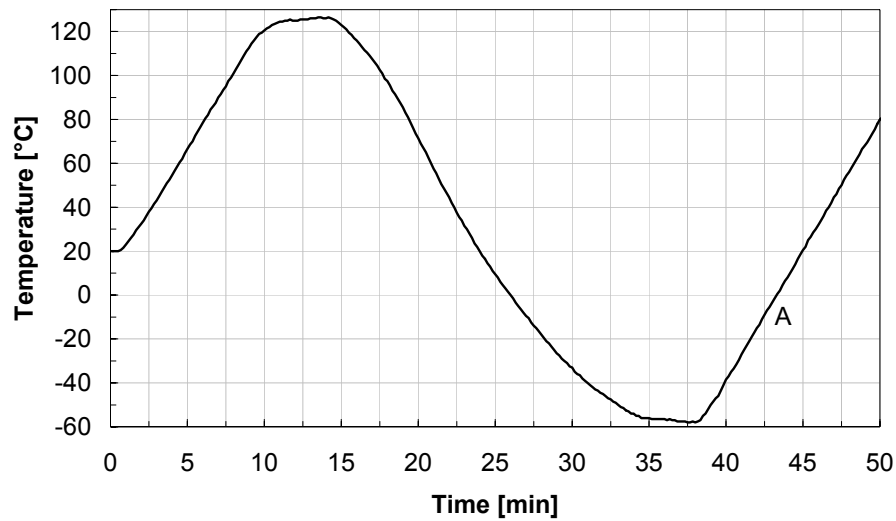


Figure 4. The thermal cycle used to deteriorate solder joints

4 RESULTS

The manufactured and treated assemblies were subjected to 2000 thermal cycles. Some assemblies were removed from the thermocycling chamber for microsectioning and shear testing. The assemblies left in the chamber (5 units of each test) were periodically tested for continuity of daisy-chained components.

4.1 CONTINUITY RESULTS

Electrical continuity data were obtained from measurement of electrical resistance of daisy-chained components. Five PCBs were measured from each set after the following number of cycles: 0, 500, 1000, 1222, 1400, 1500, 1600, 1700, 1800, 1900 and 2000. The measurements were performed at room temperature, with a switch multiplexer and digital multimeter as shown in Figure 5. The failure criteria were set where a measured resistance was more than 200 Ohms above the nominal resistance.



Figure 5. Apparatus used to measure continuity of daisy-chained components (PC controlled multiplexer and digital multimeter)

The continuity data obtained for chip resistors and mini MELFs were partially corrupted by via failures, connecting these components with the edge connector. Typical via failures are illustrated in Figure 6 and Figure 7. The cracking of vias occurred during thermal cycling and it was observed on PCBs assembled with SnPb as well as lead-free solders.

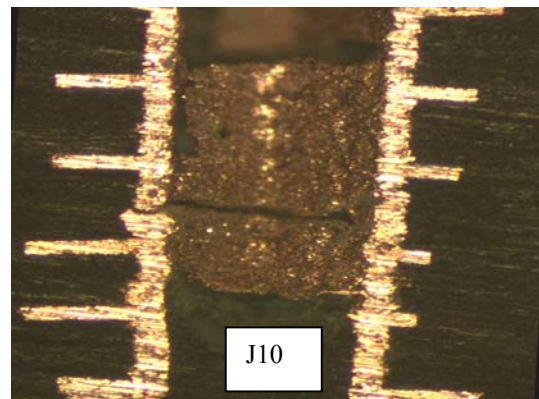
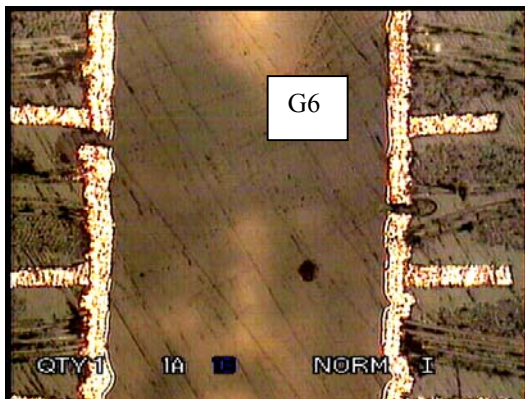


Figure 6. Cracked vias in G and J set PCBs (SnAg and SnPbAg) after 2000 cycles

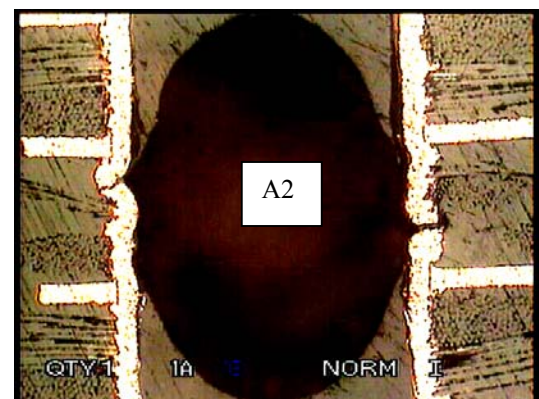
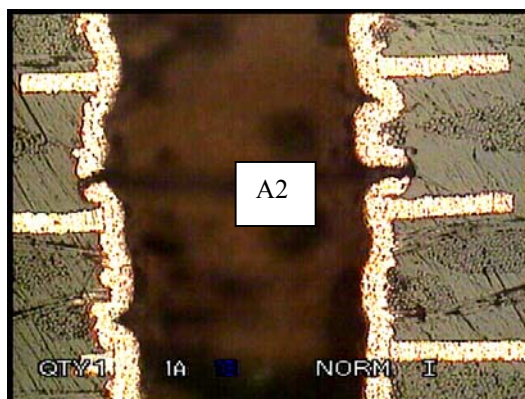


Figure 7. Vias in A set PCBs (SnAgCu) after 500 cycles

All the chip resistors were connected using vias, and hence these failures obscured resistor solder joint failures. Data shown in Figure 8 include failures of vias as well as potential solder joint failures. Because the small pad size of a chip R0603 resistors, it was not possible to probe continuity manually without touching the solder joint, and hence it was not possible to distinguish between via and resistor failures.

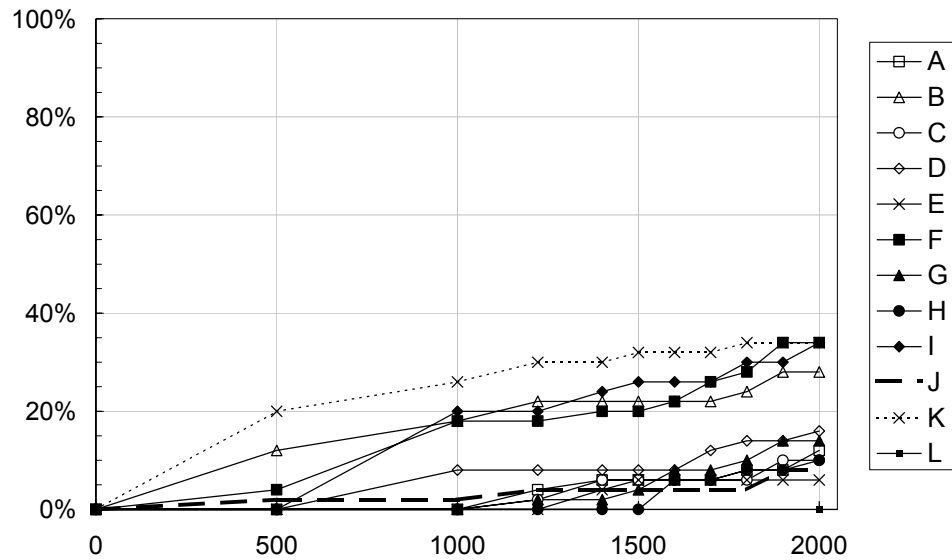


Figure 8. Cumulative failures of R0603 resistors up to 2000 thermal cycles including via failures

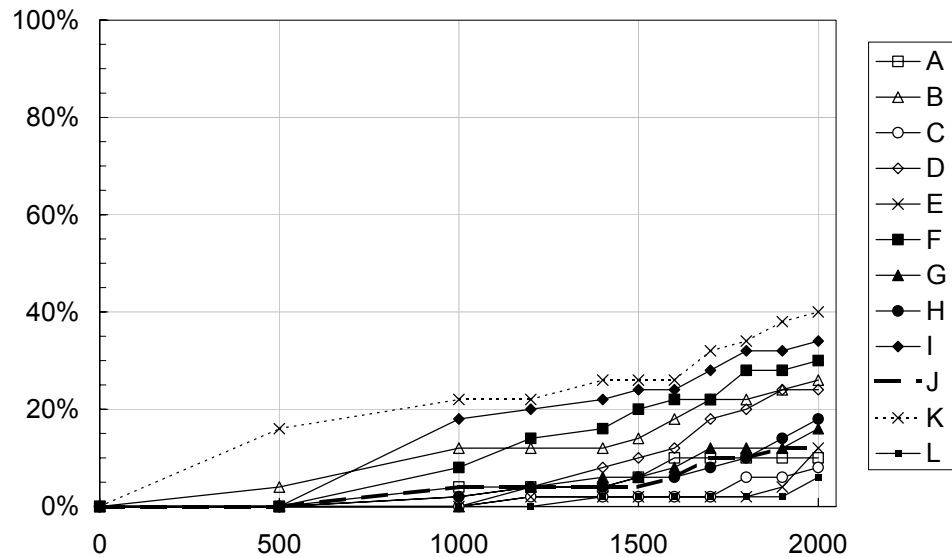


Figure 9. Cumulative failures of R1206 resistors up to 2000 thermal cycles including via failures

In the case of the R1206 resistors the via failures can be subtracted from total failures, since the larger pad size allowed direct probing without touching the smaller joints. The continuity data for the R1206 resistors, including the via failures, are shown in Figure 9 and adjusted data are shown in Figure 10.

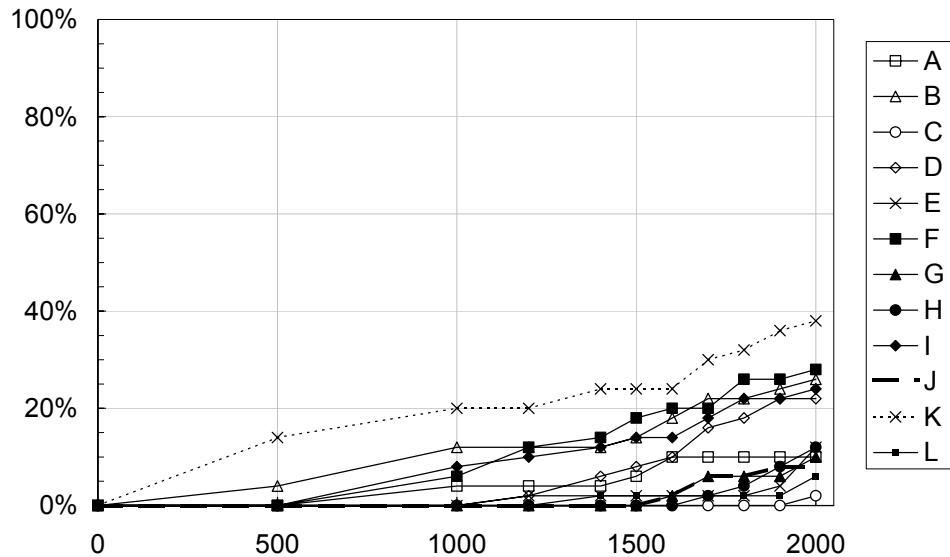


Figure 10. Cumulative failures of R1206 resistors up to 2000 thermal cycles excluding via failures

In Figure 11 a crack on a MELF resistor is shown. These MELF components were only assembled in the A and J sets and the majority of joints failed between 1500 and 2000 cycles – see Figure 12. However, in the case of the R0603 resistors there were some via failures as well as solder joint failures.

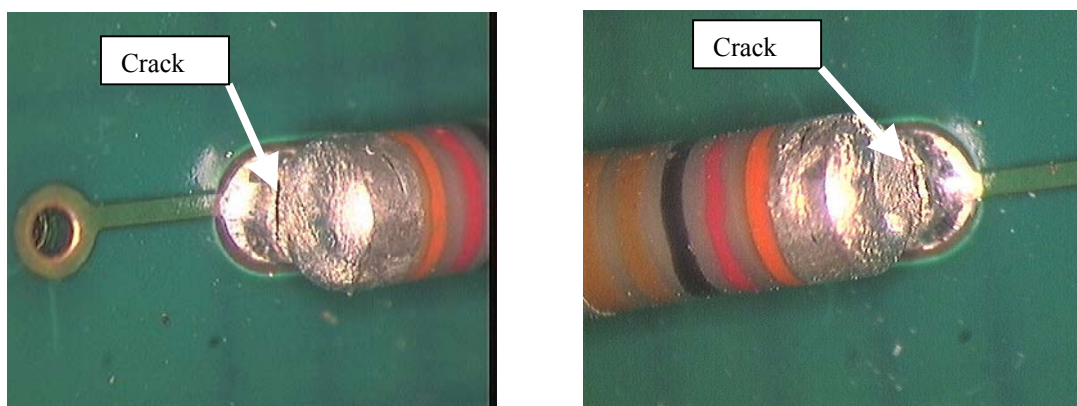


Figure 11. Cracks in the mini MELF resistors SAC solder joints after 2000 cycles (Set A)

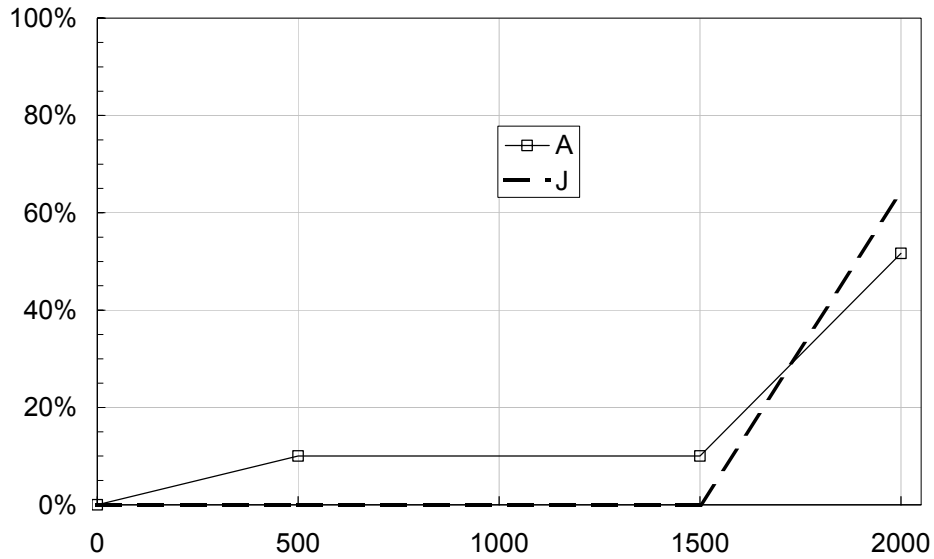


Figure 12. Cumulative failures of mini MELFs up to 2000 cycles

The continuity data for LCCC (lead-less ceramic chip carrier) are presented in Figure 13 for sets A and L. These components were connected to the top layer edge connector through tracks, hence no vias were necessary. All LCCCs assembled in set A failed during the first 500 cycles.

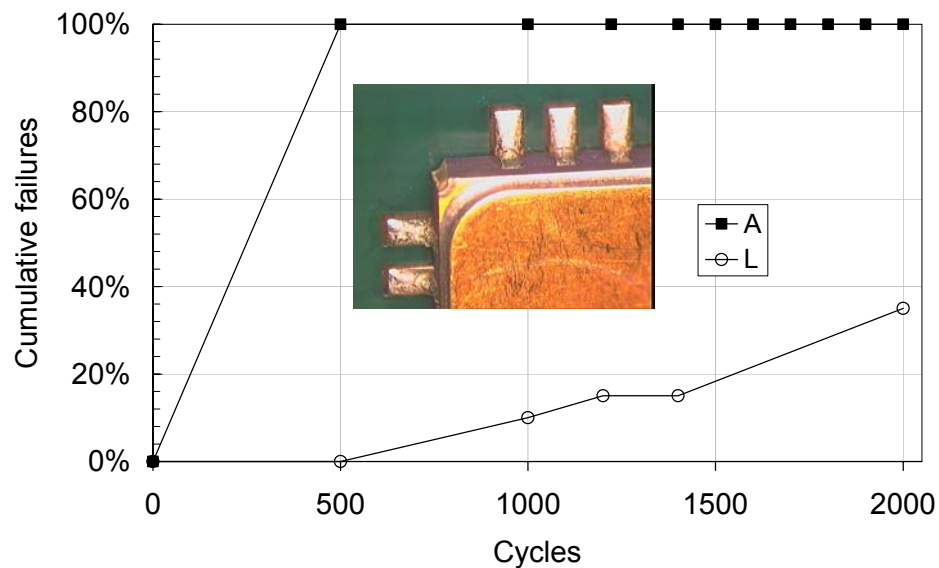


Figure 13. Continuity data for LCCCs assembled in set A and L

Continuity data from the BGA components are separated into those from four independent daisy chained circuits, with each circuit comprising a double ring, as

shown in Figure 14. The A circuit contained 112 bumps (solder joints), the B circuit contained 80, the C circuit contained 48 and the D circuit contained 16 solder joints.

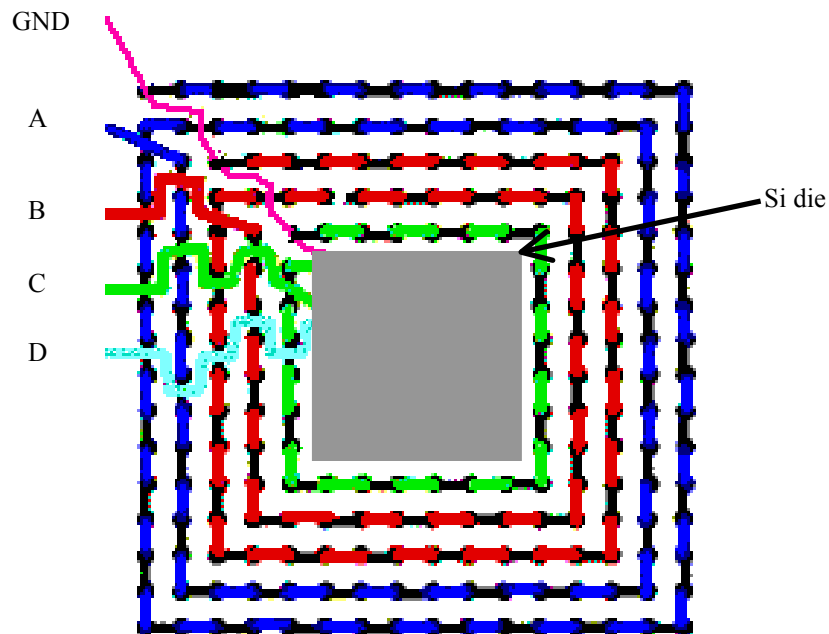


Figure 14. Four independent circuit loops in BGA component (black tracks are on component side, colour tracks are on a PCB).

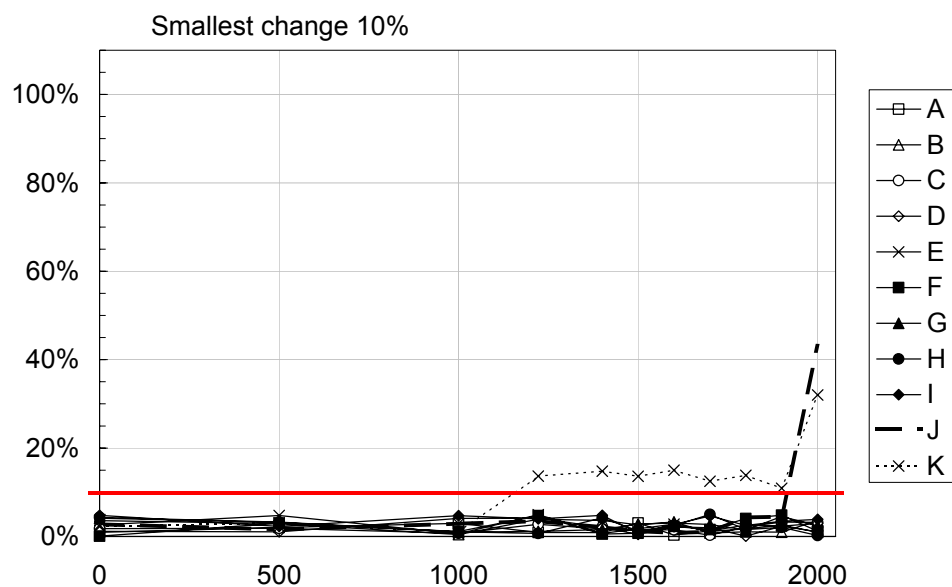


Figure 15. Failures in the A circuits of BGAs (refer to Table 2 for key to materials and processes)

The number of opportunities for failure is higher for the A and B circuits with the larger number of bumps in each circuit, but very low failure rates were observed with failures

detected only with the SnPbAg (J) and SAC (K) solder joints formed on immersion silver PCB finish, (Figure 15 and Figure 16). The horizontal line in these Figures represents the percentage failure level in which one bump, or circuit, fails.

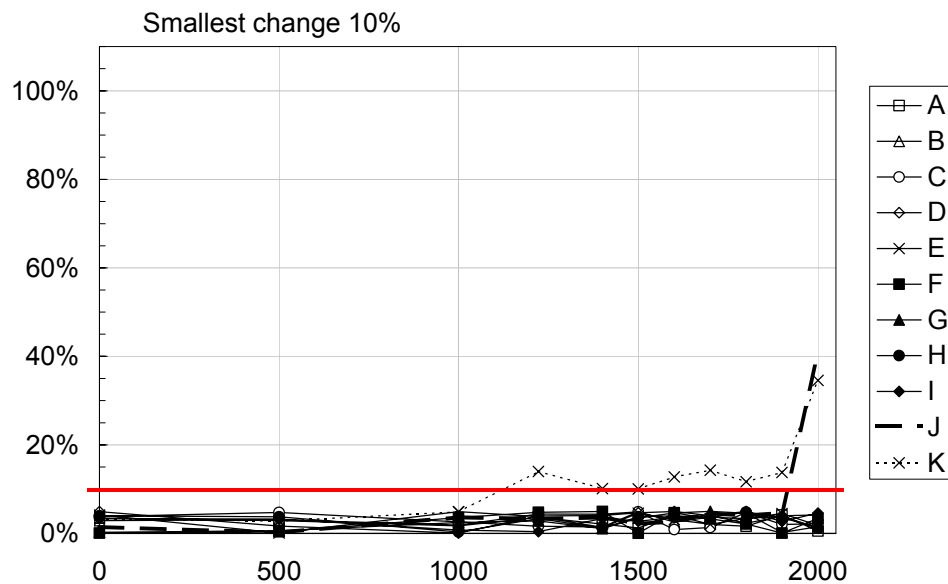


Figure 16. Failures in the B circuits of BGAs

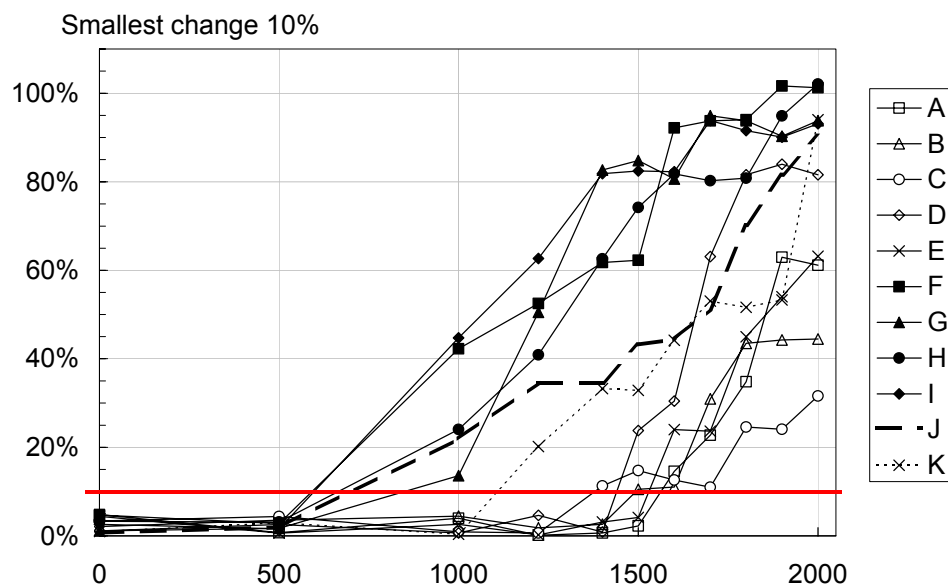


Figure 17. Failures in the C circuit of the BGAs (refer to Table 2 key to materials and processes)

The most comprehensive data were collected from circuit C on the BGA components. In all sets (A to K) there were 5 identical units (PCBs) with 2 BGA components on each PCB. The c circuit results are presented in Figure 17. To avoid curves overlapping a

random noise was added to the cumulative failure value. The amplitude of this noise is below half of the smallest possible change [i.e. 5% = $\frac{1}{2}(10\% = 1 \text{ failure} / 10 \text{ opportunities})$].

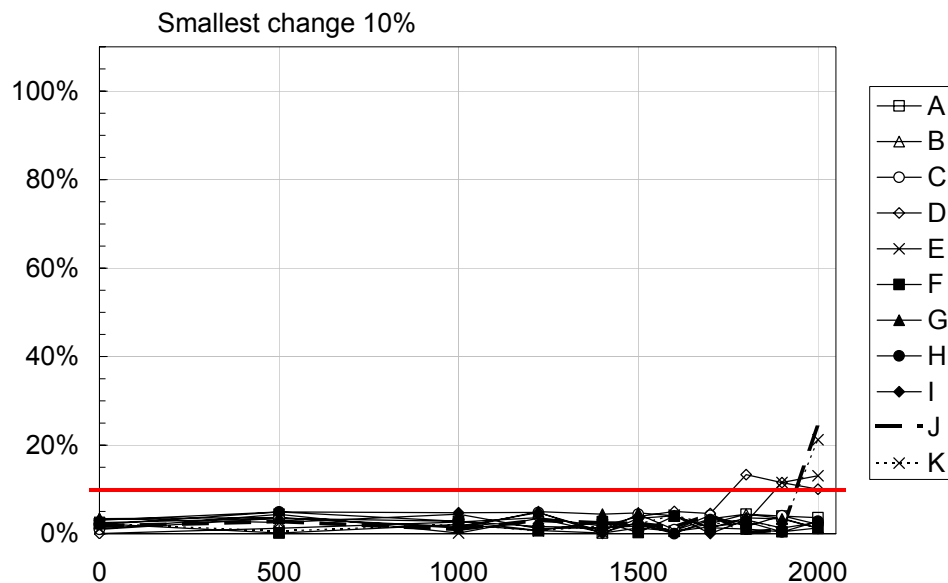


Figure 18. Failures in the D circuit of BGAs

There were only six failures in the “D circuits” after the 2000 cycles (see Figure 18), and, these occurred in the SnPbAg (set J) and sets E, D and K. It is apparent that of all the four circuits it was the C circuit that was the weakest link in the BGA integrity. Hence the analysis of BGA failures was concentrated on the C circuit.

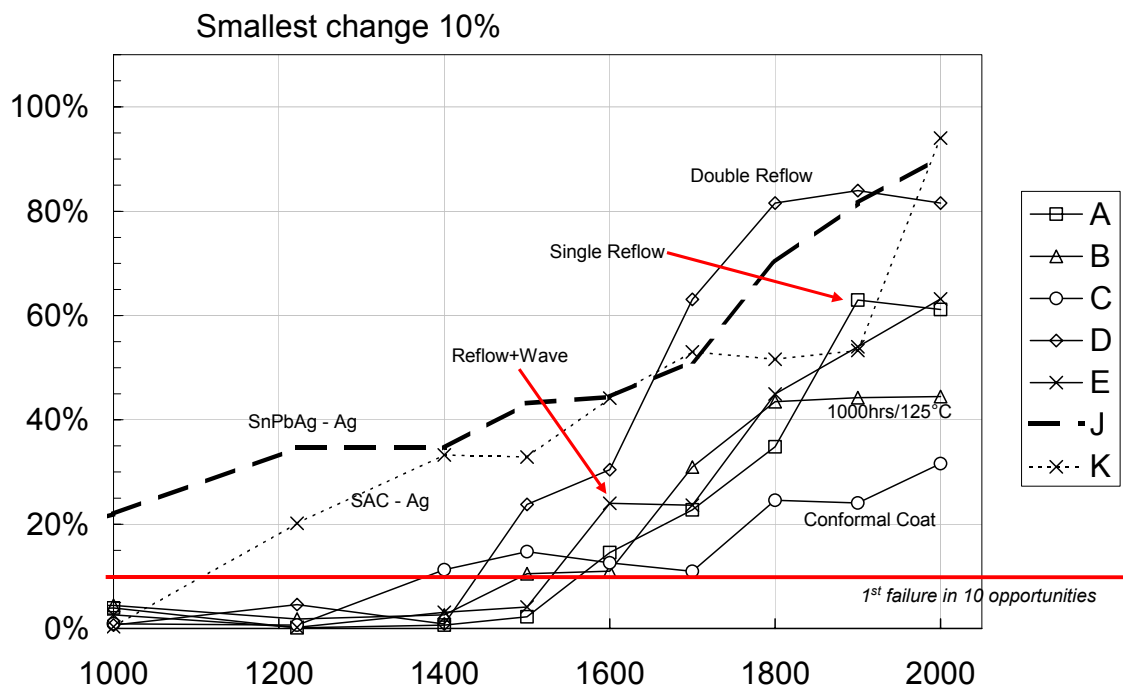


Figure 19. Failures in the C circuit of BGAs for SAC and SnPbAg alloy joints only

Figure 19 provides a detailed analysis of the failures in circuit C for the SnPbAg and SAC solder joints, after removing the results from the SnAg-soldered joints. That the C circuit is the most unreliable is evidenced by a typical X-ray image of a BGA component, in which the silicon die is clearly identifiable, and is reproduced in Figure 20. The die restrains the expansion of the component with its low CTE, and this effect is felt most at the edge of the die, the greatest distance from the centre point.

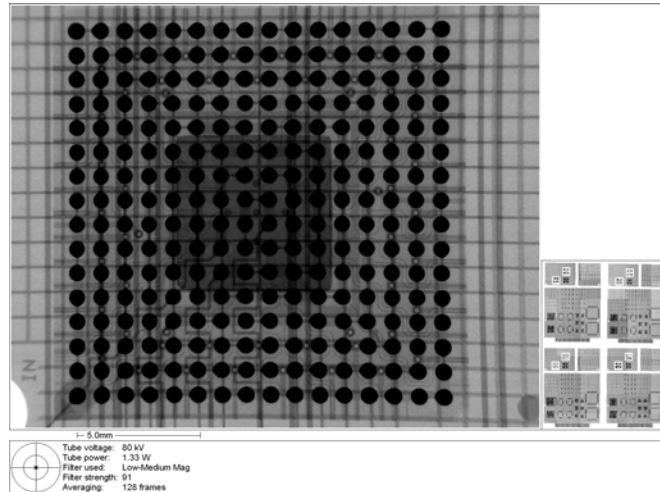


Figure 20. X-ray image of BGA showing perimeter of Si chip inside

4.2 SHEAR TESTS

Shear testing is an established destructive method for evaluating the degree of crack propagation and damage to the solder joint after thermal cycling. The method is based on the assumption that the presence of a crack in the solder joint, its size and the extent of its propagation will limit the strength of the joint. Hence a correlation can be established between the strength of the solder joint and joint failures. A typical shear test set up is presented in Figure 21. The tests in this study were undertaken on a Dage Series-4000 modular multi-function bond-tester.

The following procedure was carried out:

- Substrates were separated from the main PCB for the shear tester holding jig
- The stand-off height of the shear tool was set to 80 μm between the bottom of the shear tool and board surface
- During each test, the shear tool was moved forward at a defined speed (200 $\mu\text{m/s}$) against the test component, and the applied force measured until the attachment was broken

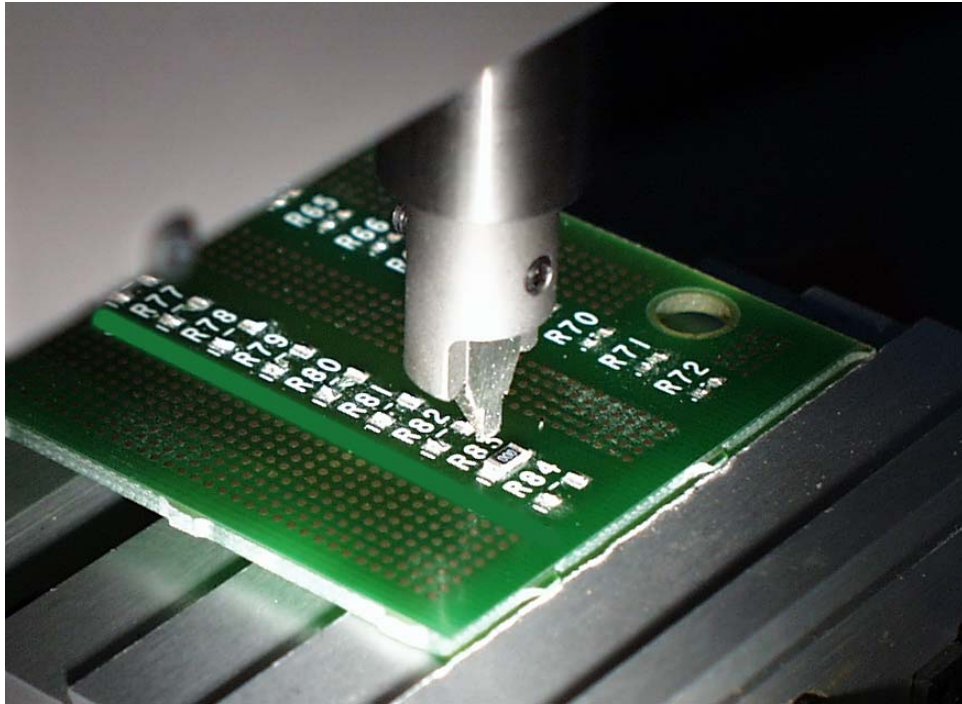


Figure 21. Shear test jig and push-off tool before a shear test

The data obtained in the test were collected as the maximum force required to shear the components' solder joints, and displayed in box whisker plots as a function of thermal cycles to which an assembly had been subjected. Median and mean values were calculated from the 20 individual measurements and plotted together with the first and third quartiles 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 the 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:

$$\text{Lower Limit: } Q1 - 1.5 (Q3 - Q1), \quad \text{Upper Limit: } Q3 + 1.5 (Q3 - Q1)$$

The circle represents the population mean, and the asterisks (*) are outliers (data points above the fourth quartile or below the first quartile). If necessary, bars are artificially shifted on the x-axis so they do not overlap another set of bars, thus allowing direct comparison. All shear force measurements were carried out after 0, 500, 1000, 1500 and 2000 cycles.

Figure 22-Figure 28 show shear force results obtained using a Dage 4000 testing machine at room temperature 25°C. In general there is a trend showing that the shear force decreases as the number of cycles increases.

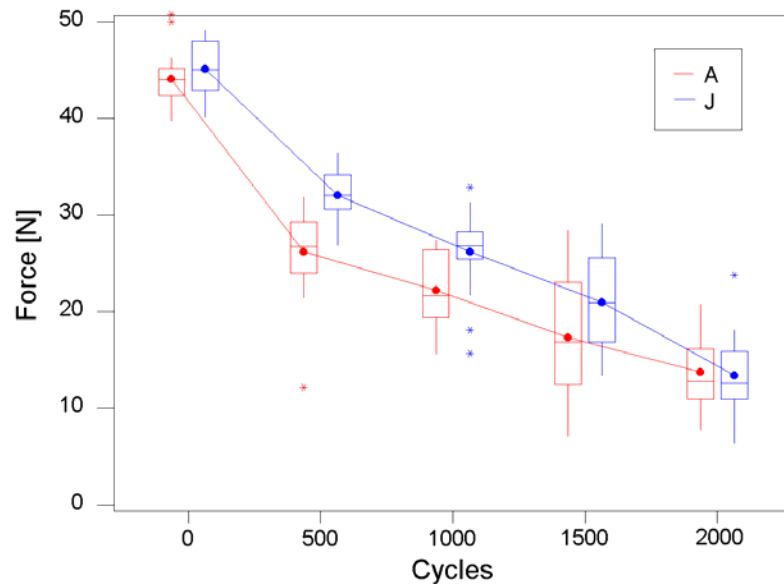


Figure 22. Comparison of mini-MELF shear forces for A and J sets

The trend apparent in Figure 22 is consistent with a reduction in shear force to remove a component as the crack length within the solder fillet increases. The sensitivity of this approach decreases with reducing numbers of cycles, and hence useful comparisons of performance should only be undertaken after a minimum number of cycles, such as 1000.

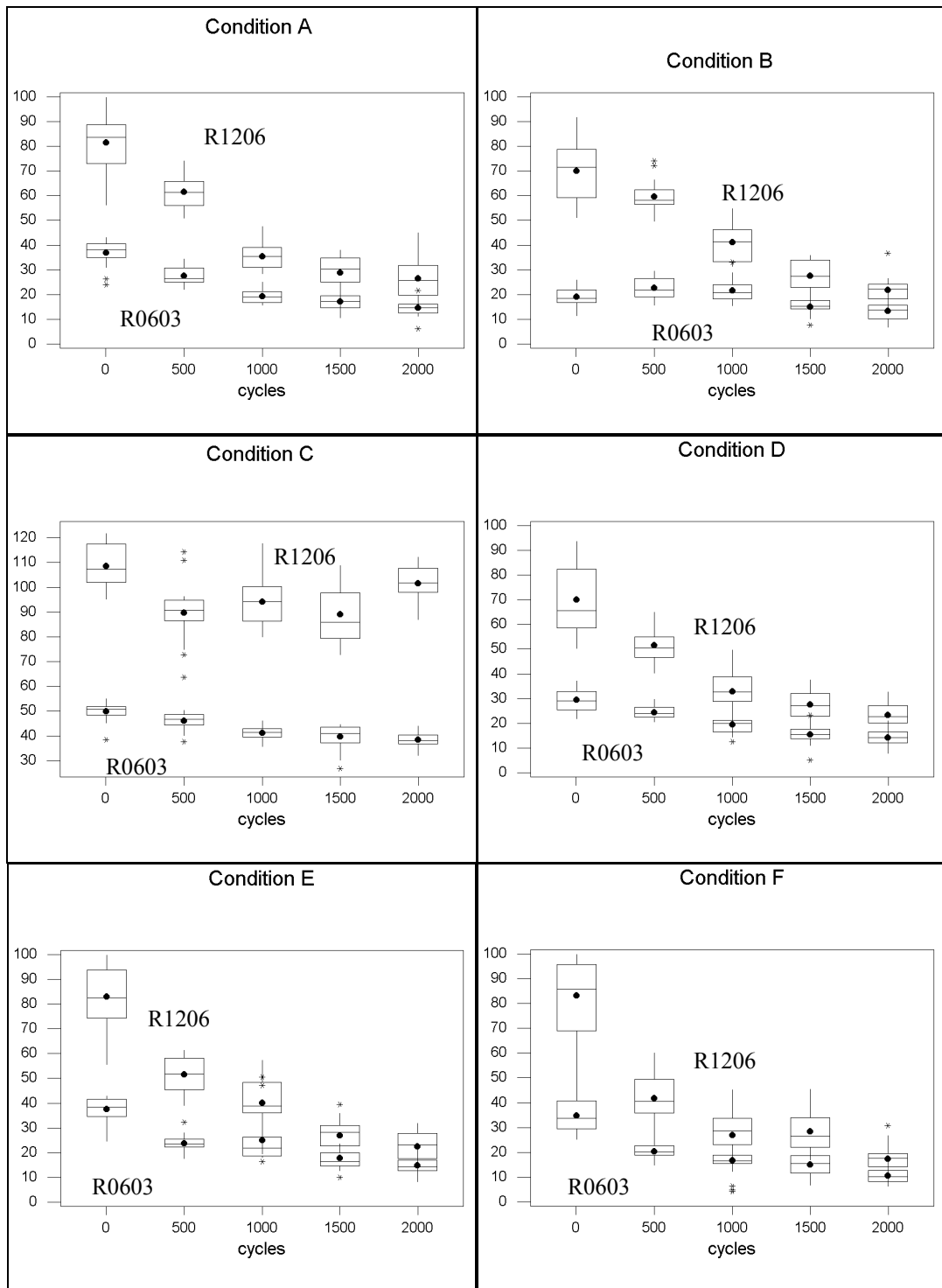


Figure 23. Shear strength of R1206 and R0603 resistors during thermal cycling (sets A-F)

In Figure 23 shear forces are plotted for two resistor sizes, R1206 and R0603, and sets A to F. There is a general trend of decreasing shear force with number of thermal cycles except for set C R1206 resistor. This is due to the fact that this set of resistors was protected by an acrylic coating and the required shear force to separate the resistor from

the substrate had to be increased to overcome the adhesion of the acrylic coating. It is important to note that no cracking in the conformal coating was observed.

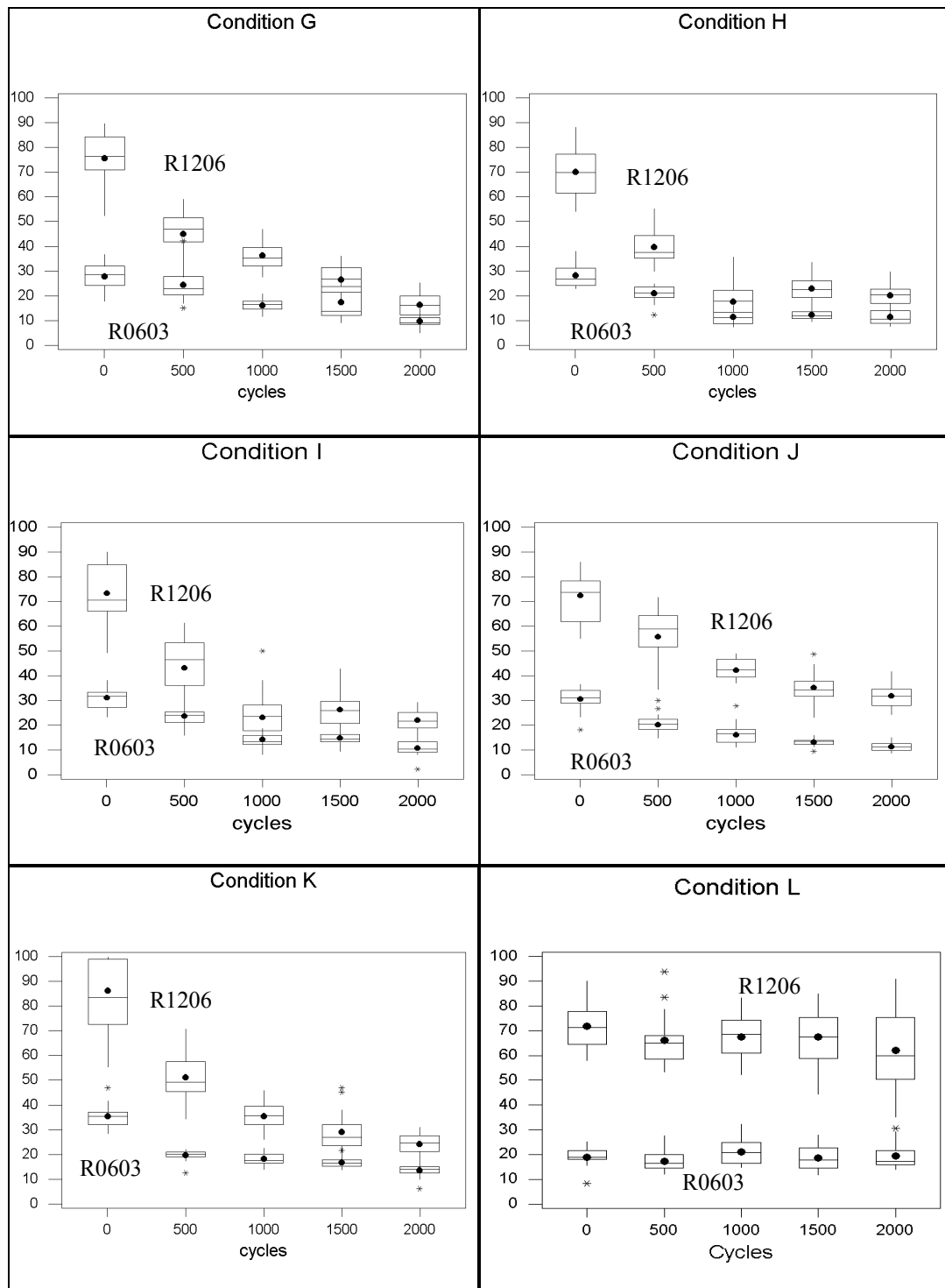


Figure 24. Shear strength of R1206 and R0603 resistors during thermal cycling (sets G-L)

In Figure 23 shear forces are plotted for two resistor sizes R1206 and R0603, sets G to L. There is a general trend of decreasing shear force with number of thermal cycles, except for set L R1206 and R0603 resistors. This is due to the fact that using the CTE matched substrate minimised the difference in coefficients of thermal expansion between substrate and resistor body (alumina). Hence there was no, or minimal, development of solder joint cracks during thermal cycling and solder joint integrity did not suffer.

The effect of coating was investigated, with shear testing conducted on boards from set C from which the coating had been stripped. The conformal coating covered the solder joint and components during thermocycling and was removed after thermocycling and just prior to shear forces were measurements. Figure 25 reveals in detail a comparison of the results from coated and uncoated set C R1206 resistors, and also with the uncoated R1206 resistors from set A.

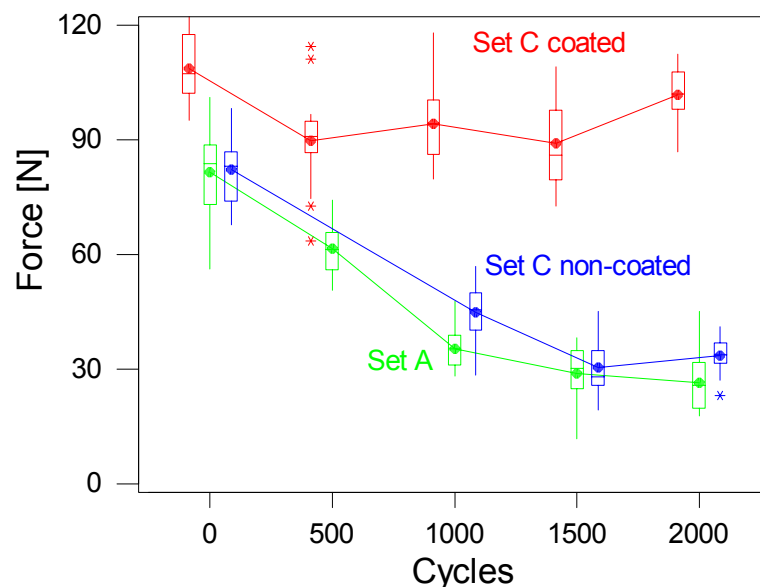


Figure 25. Comparison of shear forces of R1206-resistors set A (green), set C (red) with, and set C (blue) without, the protective acrylic coating

A comparison of the results from set A and set C where the coating has been removed, highlights very similar behaviours, and hence it can be concluded that cracking of the solder joint had occurred in the same manner in both cases. Hence, it is clear that the coating did not stop development of cracks (degradation of solder joints during thermocycling) in set C, but the coating did provide some level of attachment retention, as shown in the shear tests. Creep damage to solder will occur in the high temperature part of the cycle, and under these conditions the coatings have very little strength, and hence will exert minimal restraining force on the solder.

A similar comparison is presented in Figure 26 for R0603 resistor, and reveals very similar behaviour between set A and the uncoated set C, supporting the conclusion above that the coating has not prevented the formation of cracks within the solder joints.

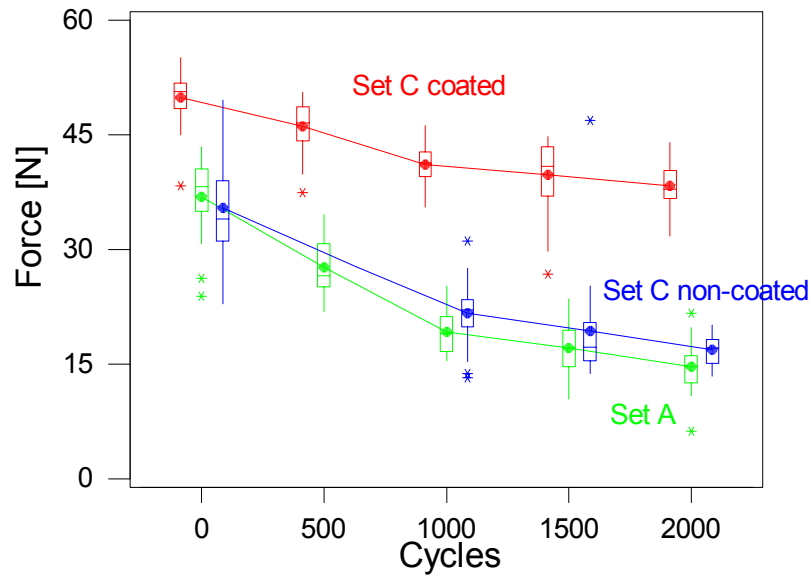


Figure 26. Set C shear forces of R0603-resistors with (coated) and without (non-coated) the protective acrylic coating

The experimental matrix included investigating the effect of the substrate material. In Figure 27 shear force results on R1206 resistors are compared for set L and the CTE matched substrate set L. The laminate used in set L was epoxy woven aramid with copper clad invar. The shear strength results for set L are approximately independent of the number of cycles, although the spread of data points increases with the number of cycles. Hence the mean value of solder joint shear strength at 2000 cycles is significantly higher for set L than for set A, and demonstrates the clear performance advantage of CTE matched substrates over FR4.

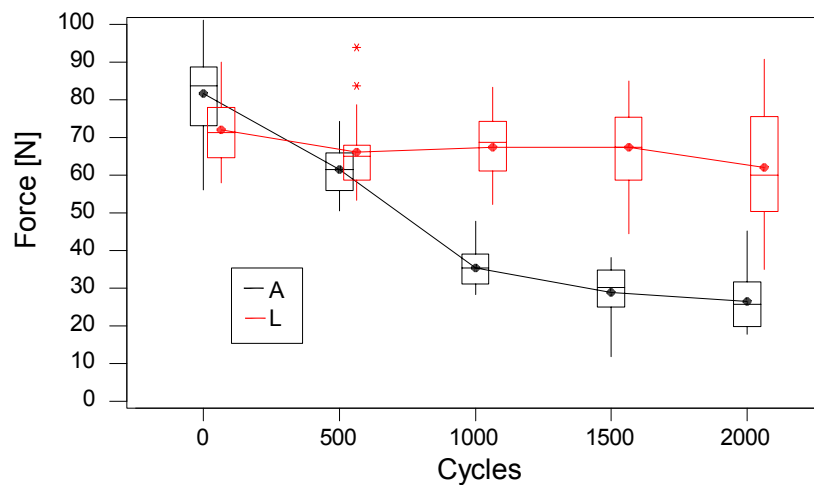


Figure 27. Comparison of R1206 resistors shear forces for A and L sets

A further data comparison between sets A and L is presented in Figure 28, which shows the shear forces for R0603-resistors. However, with this data set there was an issue with the adhesion of the resistor pads in set L, where the force needed to peel the pad off the substrate was too small. The area of R0603-resistor pads is small and forces below 20N are sufficient for separation of copper foil from aramid-reinforced epoxy substrate. The design and stencil apertures between the FR4 and aramid boards were identical, and this adhesion issue was only encountered with the R0603s

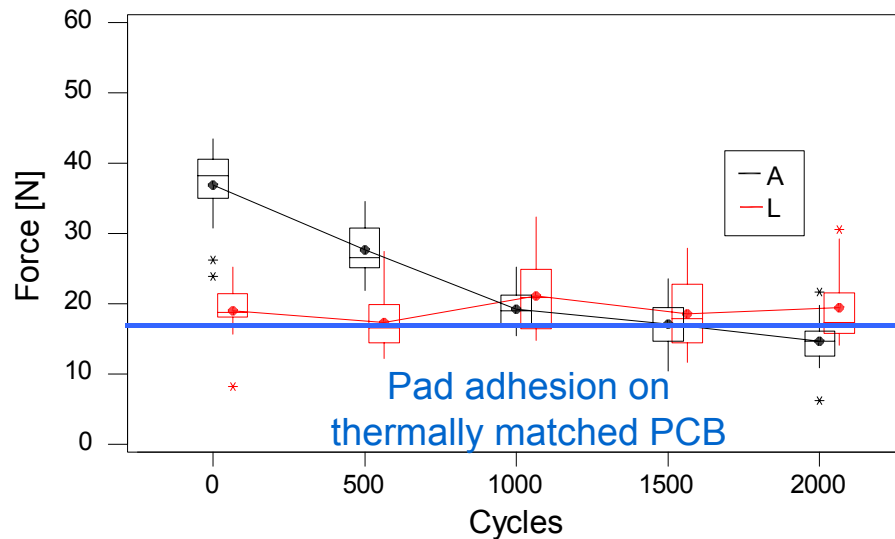


Figure 28. Shear force of R0603-resistor, for A and L set

4.3 MICROSECTIONS AND MICROSTRUCTURE

Samples were cut from test boards using a conventional diamond blade. The cut samples were cleaned using conventional IPA (iso-propyl alcohol) to ensure complete removal of any residue left from the cutting stage. Samples were ground with successive grades of silicon carbide paper of 120, 240, 500, 800, 1200 and 4000 grit, followed by polishing with diamond particle sizes from 6 to 1 μm in diameter. Final polishing of the samples was carried out by hand using a gamma aluminate powder (OP-S) suspended in lapping fluid.

The typical microstructure of a joint formed using SnPb type alloy, with the crack developing from under the component, is illustrated in Figure 29.

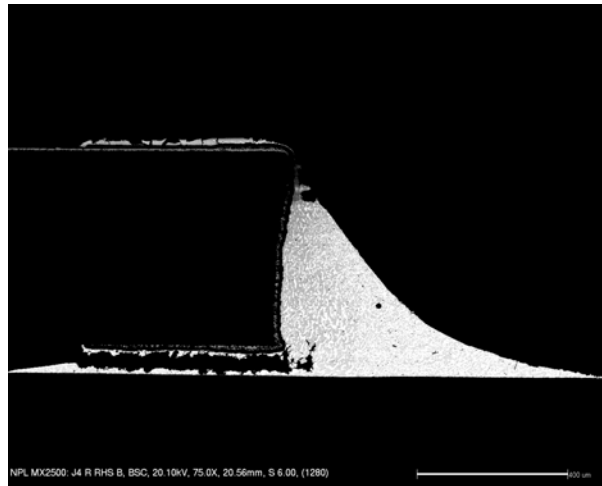


Figure 29. R1206 resistor after 2000 cycles soldered with 62Sn36Pb2Ag

Interestingly, the microstructure of the R1206 resistors after 2000 cycles (see Figure 30) contains intermetallic phases within the solder fillet. These are a mixture of Ag_3Sn and Cu_6Sn_5 intermetallics, with predominantly Ag_3Sn , reflecting the preponderance of silver in the SAC alloy. Figure 1, a microsection of another typical SAC joint, also displays cracking developing under the component and migrating out through the fillet. All these cracks are typical of low cycle fatigue resulting from thermal cycling.

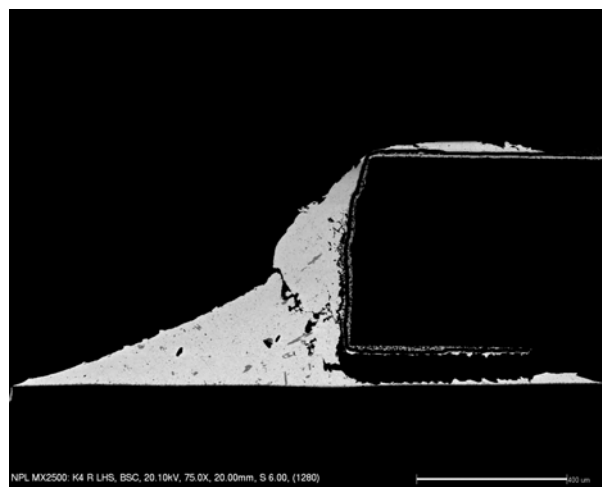


Figure 30. R1206 resistor after 2000 cycles, soldered with 95.5Sn3.8Ag0.7Cu

Microsections of SOICs soldered with 62Sn36Pb2Ag alloy are presented in Figure 31, and interestingly some voiding is apparent under the termination in the heel area. This voiding area is shown at higher magnification in Figure 32. Whilst there appears to be a coalescence of the voids this does not appear to be associated with crack formation and failure of the joint, and hence is not thought to present a particular problem.

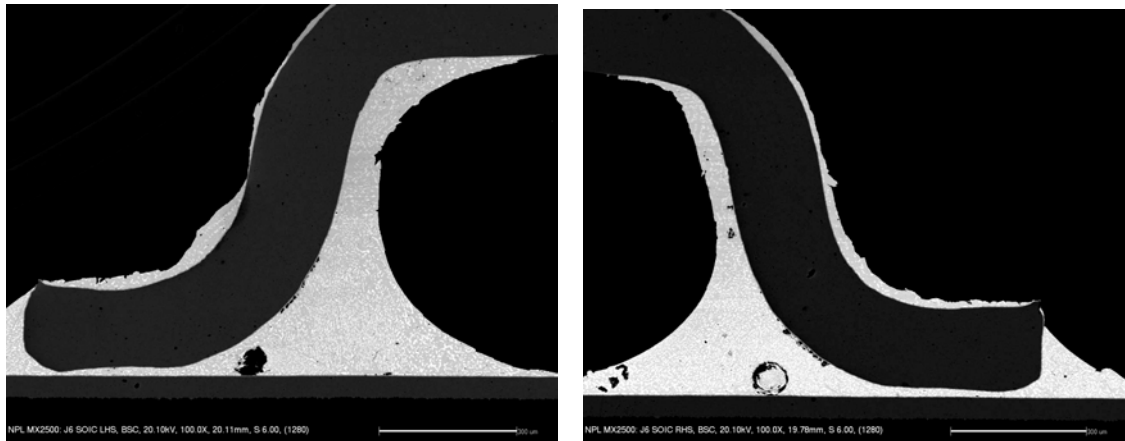


Figure 31. Set J: SOIC component soldered with SnPbAg alloy, after 2000 thermal cycles

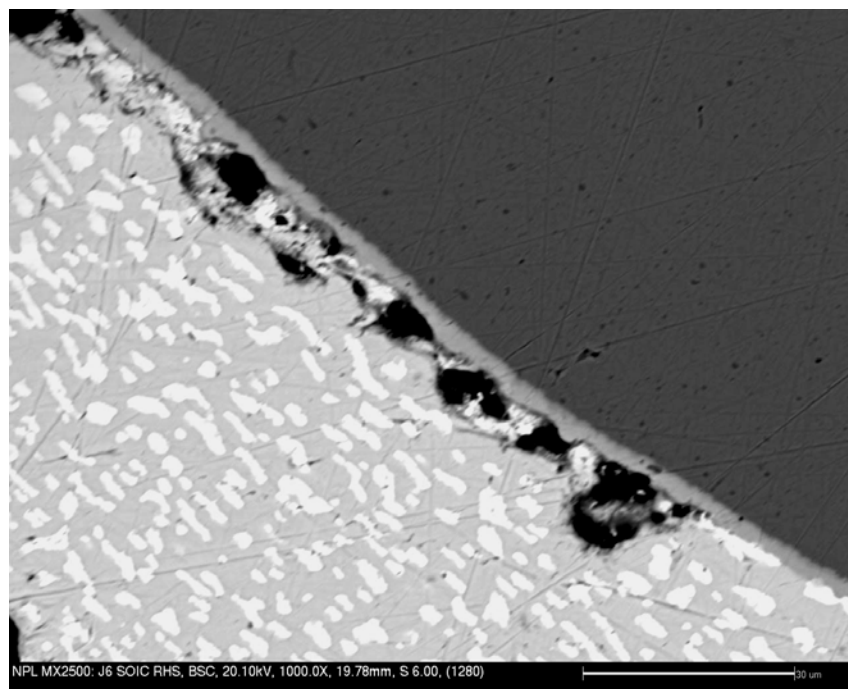


Figure 32. Detail of voiding formation at the lead termination interface

It should be noted that whilst the micro-sectioning technique is suitable for the assessment of the failure mode, it cannot provide information on crack growth rates in solder joints.

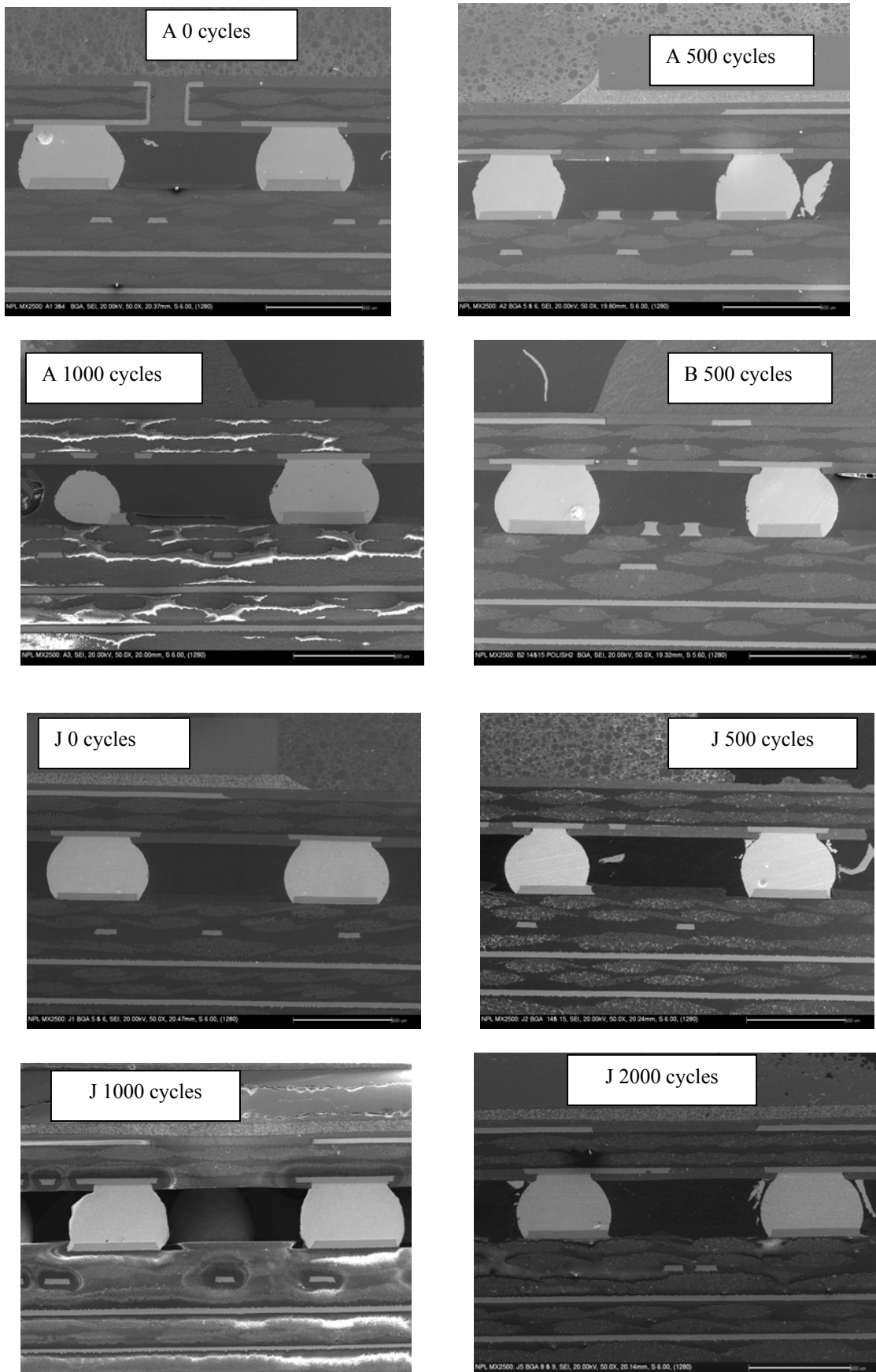


Figure 33. Microsections of BGA solder joints after 0 to 2000 thermal cycles

Microsections of BGA soldered joints obtained after 0, 500 and 1000 thermal cycles for various combinations of solder and board finish, are presented in Figure 33. In general the cracks in BGA solder joints developed at the component - solder interface (see Figures 34 and 35).

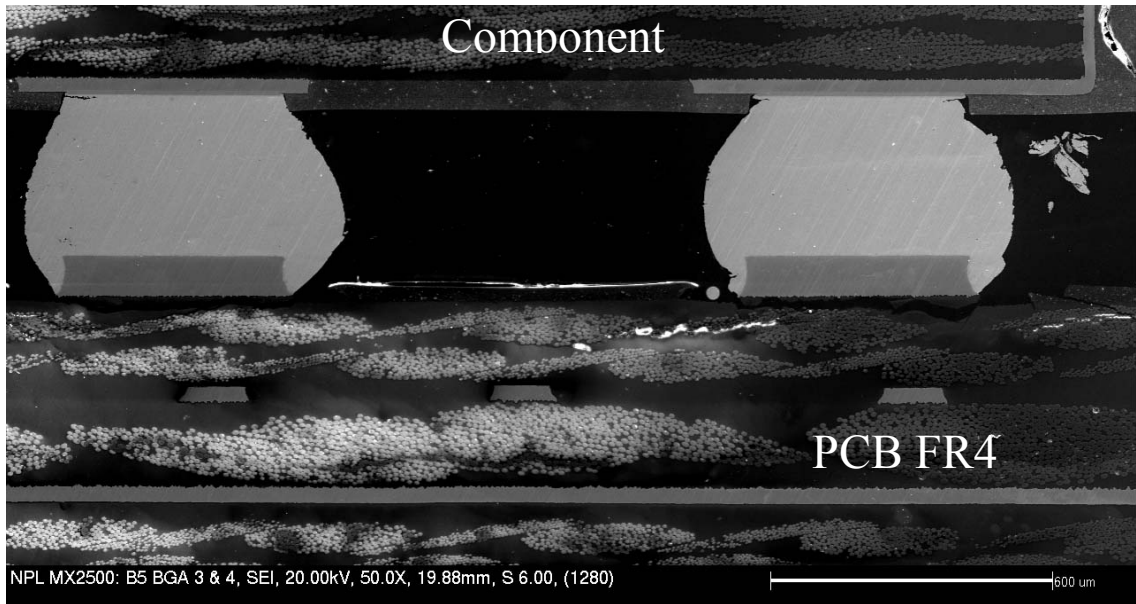


Figure 34. Set B after 2000 cycles; cracks initiate at the solder-component interface

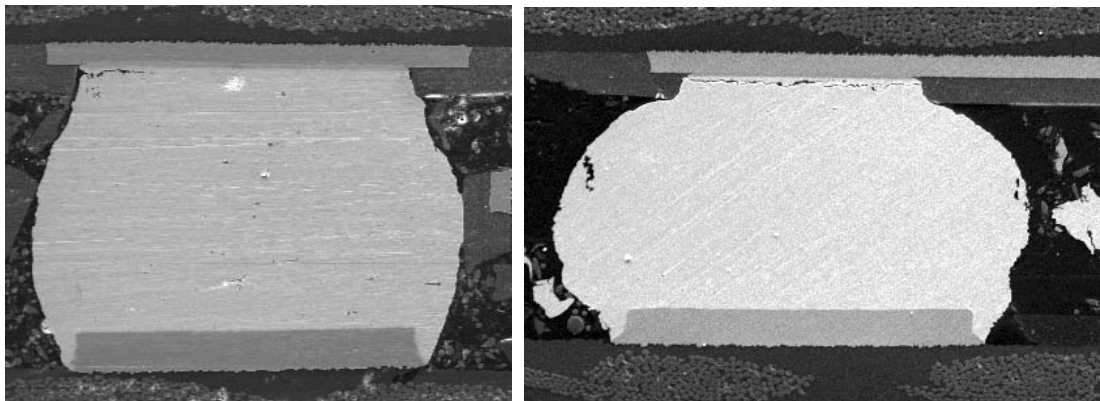


Figure 35. Set C after 1000 cycles, and set F after 1000 cycles

5 DISCUSSION

The electrical continuity data (Figures 9 and 10) clearly suggest that the R1206 resistor joints made from immersion silver finished boards and SAC solder, experienced far greater reductions in reliability after thermal ageing, compared with those having an ENIG finish. Although the shear strength data do not support this difference, it must be remembered that this technique is not as sensitive to small changes in reliability, as is continuity testing. However, the continuity results for R1206 resistors soldered to silver-finished board with SnPbAg alloy, showed only a minor effect on reliability.

It is not clear from this limited study whether these observations relate to this particular chemistry of the immersion silver finish, or to any interaction between the immersion silver and the SAC solder. The latter would be surprising as the (large) literature on soldering using SAC alloy and immersion silver finished, boards contains no reports of any detrimental effects. It is possible that SAC alloy is a less forgiving solder than SnPbAg, and joints made using SAC alloy will reflect reliability changes arising from other materials issues.

There was an interesting comparison between the continuity data for joints soldered with SnAg and SAC alloys, in which the former gave consistently poor performance for the R1206 resistors and BGA on ENIG-finished boards (Figures 10 and 17). The BGA continuity results suggest that in general the different heat-treatments have little effect on the reliability of joints made using ENIG-boards and SnAg alloy (Figure 17). In the equivalent case, but with the R1206 resistors, the greatest reduction in reliability was obtained using the single reflow profile, and extending the heat-treatments (Figure 10) appeared beneficial, possibly by “maturing” the intermetallics.

Extending the heat-treatment of 1206 resistor joints made with ENIG-finished boards and SAC alloy, did have a detrimental effect on the continuity results (Figure 10) – isothermal treatment for 1000 hours at 125°C, and double reflow treatment, both led to reductions in reliability. However, this was observed only in the continuity data. There was no similar effect with the BGA components, for which only the double reflow treatment produced any reduction in reliability. These results tentatively suggest that thermal processing history might contribute to the joints’ reliability performance.

A comparison of the performances of R1206 resistors and BGA joints made using SnPbAg and SAC solders is quite interesting. The reliability of BGA joints using SAC alloy outperformed those using SnPbAg alloy (Figure 19), but the opposite was true for the R1206 resistors (Figure 10). The relative shear strain range exerted on the soldered joints by these two component types is quite different, the lower values of strain favouring joints made with SnAgCu, while the SnPbAg alloy is more accommodating for the higher strain ranges associated with the R1206 resistor joints. Hence these results suggest a “cross-over” in reliability performance between joints made using lead-free and tin-lead alloys.

The shear strength data for the uncycled resistor joints also showed that comparing data sets J and K (SnPbAg and SAC), the SAC joints were 10-20% stronger than the SnPbAg joints. Further, comparing data sets K and E (immersion silver and ENIG finishes) indicates that the PCB finish has no effect on the shear strength values.

The failure of the plated through holes was unexpected and may suggest a possible concern with vias in lead-free technology. While no failures were encountered after component assembly, failures did begin to occur after 500 thermal cycles. Latent defects following reflow and extra Z-expansion with the higher temperature lead-free profile may be an issue for the future. The via size of 300µm is not large, but is not uncommonly small in today's PCBs, with undemanding 1 to 5 aspect ratio.

The experiment including conformal coating produced some interesting results. Coating seemed universally beneficial for BGA and R1206 solder joints. This effect is probably attributable to the coating providing a retaining force as the joint weakens. It is not thought that the low Young's modulus coatings will interfere with the microstructural ageing of the solder and the development of cracks during thermal cycling.

The data obtained from set L (using the CTE matched substrate) clearly demonstrated the merits of this approach with significantly low failure rates for the R1206 resistor joints soldered with SAC alloy.

In this work the assessment of failure has been through two main routes, electrical continuity measurements and push off tests measuring the shear strength. These two measurements did not always provide similar results, and it is instructive to consider the differences in approach. The most significant difference is that a 50% reduction in shear force occurs when the crack has grown significantly, but certainly not through the whole fillet, whereas the continuity measurements only record a failure when the crack has propagated through the complete fillet. The shear strength changes most in the first 500 to 1000 cycles as the first 50% of the crack develops, and is less sensitive to the final part, whereas the continuity values change more rapidly towards the end of the 2000 cycles. The shear measurements are in fact a measure of breaking the two fillets at both ends of the resistor, and one of these fillets is typically more cracked than the other. Furthermore with the shear measurements, the results reported at any given cycle time is an average of many readings, but for the continuity measurements the cumulative failure is built up on single failure events.

Comparing continuity and shear data it is likely that continuity data are more sensitive to subtle changes in reliability. By contrast the shear measurements are dominated by the initial crack growth under the component and its propagation into the first part of the fillet, which happens quickly and is relatively insensitive to many experimental variables. Typically, manufacturers will be more interested in when the first failures occur, rather than when 50% have failed.

In this work, agreement between the continuity and shear data was variable. For example, the data shown in Figure 24 (set L) highlight significant shear strength even after 2000 cycles for the R1206-resistor joints, and this is in good agreement with the continuity results for R1206 resistors from the same set, see Figure 10. There were only 3 failures out of 50 after 2000 cycles. But comparing set A and B for the R1206s the continuity results show higher failures for set B at all cycling points, whereas the shear data do not show such an unequivocal difference.

Comparing the practicalities of the continuity and shear approaches, the continuity data provide a more complete picture, but the push off test is quicker, and can be carried out on any circuit. To acquire continuity data a test vehicle is required with the requisite

connections, an approach that takes forward planning of the experiment. The push off test, by contrast, can be carried out on any circuit, as long as there is access for the tool in the immediate vicinity of the component. It can also indicate fatigue damage occurring at an early stage, where perhaps any failure has yet to be captured using continuity testing. The continuity data, however, are more sensitive and can capture the failure of the single joint, and from this work was able to differentiate more successfully between the effects of different thermal treatments than was the push-off test.

6 CONCLUSIONS

A number of important conclusions can be drawn from this work:

- The reliability of joints made using SAC solder was significantly better than that of joints made using the simple binary SnAg alloy.
- A comparison between the long-term reliability of joints made using SAC solder and that of joints using SnPbAg alloy, was not so clear cut, being both component- and strain range-sensitive. Joints in BGA components exhibited a better reliability performance when soldered using SAC alloy than when using SnPbAg alloy. The reverse was true for joints of R1206 resistors, suggesting that the lower values of strain exerted by the BGA favours the SAC solder, whilst SnPbAg alloy provides advantages when the higher values of strain are exerted e.g. with the R1206 resistors.
- There was no evidence to suggest that thermal pre-treatment (reflow, wave or isothermal ageing) was detrimental to the long-term reliability of the joint. The results suggest that ageing and microstructure are not linked in a straightforward way.
- Lead-free processing can affect the reliability of plated-through holes (vias). The latter generated cracks when subjected to more than 500 thermal cycles.
- Conformal coating improved the joint reliability performance, possibly by a retaining action of the more pliable coating, preventing complete detachment.
- The techniques suitable for examining SnPb soldered joints are also suitable for examining joints made using the new lead-free solders, although some minor amendments of the proven procedures may be necessary e.g. a different etch for the lead-free microsections.
- Micro-sectioning is useful in identifying and locating cracks and revealing microstructural changes after thermal cycling. Examining microsections in an SEM rather than in an optical microscope is advantageous, enhancing the capability of distinguishing fine crack features. This qualitative method is suitable for following microstructural developments in solder joints.
- The push-off test and continuity testing proved useful tools for detecting fatigue

damage in solder joints. The techniques are complementary, yielding data that characterise different aspects of crack growth. In this work the continuity data provided more discrimination between the effects of the various thermal pre-treatments.

7 ACKNOWLEDGEMENTS

The work was carried out as part of a project in the Materials Processing Metrology Programme of the UK Department of Trade and Industry. The authors are grateful to Goodrich, AMS, BAE Systems and MBDA for their contribution to the project. The authors are grateful to Ling Zou with the experimental work and to Madeline Peck for preparations of the microsections.

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