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**Measuring the Impact of
Land Size and Solder Joint
Volume on Lead-free Solder
Joint Reliability**

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and C P Hunt**

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Measuring the Impact of Land Size and Solder Joint Volume on Lead-free Solder Joint Reliability

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ABSTRACT

In an attempt to ascertain the effect of pad size/design and solder joint volume on lead-free solder joint reliability, a range of test boards have been assembled using lead-free (SnAgCu) solder paste and assessed in a matrix experiment involving four components types (R0603, R1206, SOIC and BGA), ten pad designs and three stencil thicknesses. The assemblies were thermally cycled (-55 to + 125°C) for a maximum of 2000 cycles, and the joints were studied visually, and using shear testing and electrical continuity monitoring.

The effect of using different thicknesses of stencil during the manufacture of lead-free assemblies was found to be quite limited. Thicker stencils did produce joints with higher shear strengths for chip resistors, but during thermal cycle testing of joints made using the thinner stencils, there was no evidence of increased crack propagation or failures. No electrical failures were noted for SOIC components up to 2000 cycles. There was some evidence that using thinner stencils resulted in BGA joints of poorer reliability, with twice as many BGAs joints made using the 100µm thick stencil failing after 2000 cycles, as compared with those from the thicker stencils.

The pad design also showed only a limited effect on the reliability of lead-free chip resistor joints after thermal cycling. Having a shorter pad did produce more electrical test failures, but only for the joints made using the thinner stencils, suggesting that this combination produced a narrower fillet, and thus a shorter time to electrical failure.

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1 INTRODUCTION

European legislation will eliminate lead-containing solders from mainstream electronics manufacture, by 1st July 2006. The currently 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 that of the established SnPb solder alloys, necessitates a corresponding increase in processing temperature for both reflow and wave soldering. These new alloys have not been extensively used in electronics manufacture, so currently considerable work is being undertaken world-wide to generate reliability data. (NB. There are 60 years of reliability experience with SnPb based alloys).

In previous work at the National Physical Laboratory [Reference 1], the best stencil thickness and pad design were identified for surface mount chip resistors reflow soldered using SnPb solder paste. This report covers work aimed at extending the previous work to cover the SAC solder alloys. The effect of stencil thickness on the joint reliability of lead-free SOIC and BGA components is also explored.

2 EXPERIMENTAL

2.1 TEST VEHICLE DESIGN

The test vehicle contained four component types: two sizes of chip resistors, 1206 and 0603 (tin finish), a SOIC16 (tin finish), and a PBGA256 (SAC finish). The substrates were fabricated from double-sided FR4, thickness 1.6 mm, copper thickness of 35 μm (copper plating 1 oz/sq.ft) and immersion gold over electroless nickel (ENIG) pad finish. The test assembly is shown in Figure 1.

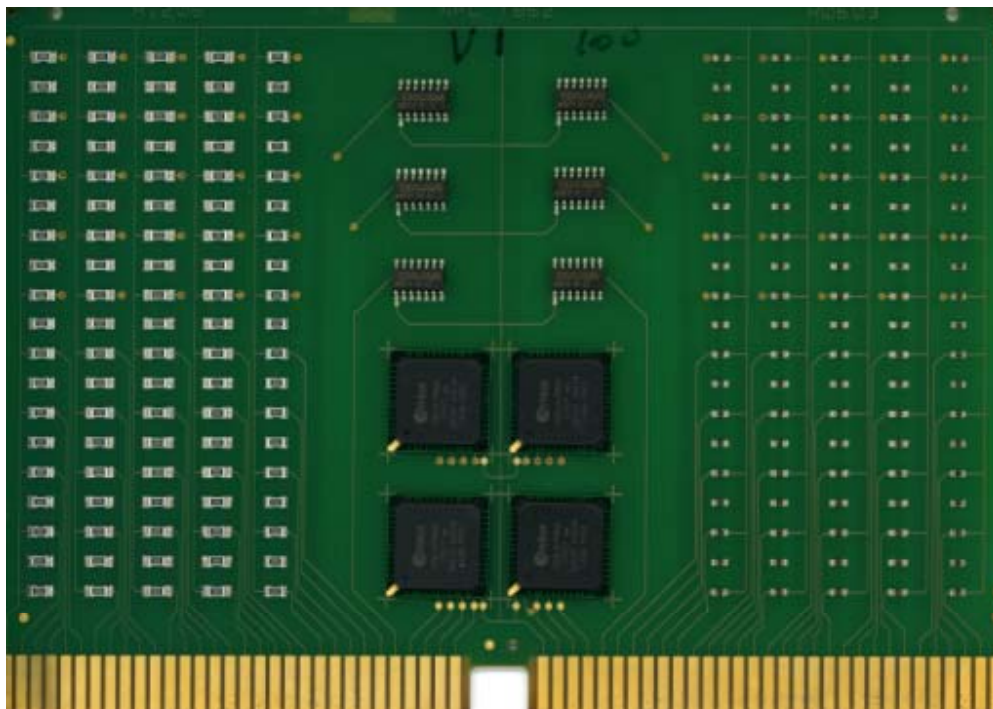


Figure 1. Test assembly

The details of the pad designs for the 1206-type and the 0603-type resistors are listed in Table 1. The pad dimension modifications were based on the IPC-SM-782 revision A - August 1993. While the recommended pad sizes from the IPC standard are A and F, designs encompassing increasing gap between the pads were also included as B and C, G and H. The impact of pad length on forming the fillet was assessed using designs D and E, and I and J. Whilst Figure 2 identifies the dimensions altered on the pad designs, Figure 3 illustrates the relative pad designs on the PCB. Figure 4 shows the position of the test pads on the test vehicle.

Table 1. Dimensions (mm) for various pad designs

R1206	IPC (A)	IPC+gap (B)	IPC+gap 2 (C)	Long pad (D)	Short pad (E)
Pad gap	1.20	1.60	2.00	1.20	1.20
Pad width	1.80	1.80	1.80	1.80	1.80
Pad length	1.60	1.60	1.60	1.92	1.28
Differences	0%	+33%(gap)	+67%(gap)	+20%(length)	-20%(length)
R0603	IPC (F)	IPC+gap (G)	IPC+gap 2 (H)	Long pad (I)	Short pad (J)
Pad gap	0.60	0.76	0.92	0.60	0.60
Pad width	1.00	1.00	1.00	1.00	1.00
Pad length	1.10	1.10	1.10	1.32	0.88
Differences	0%	+27%(gap)	+53%(gap)	+20%(length)	-20%(length)

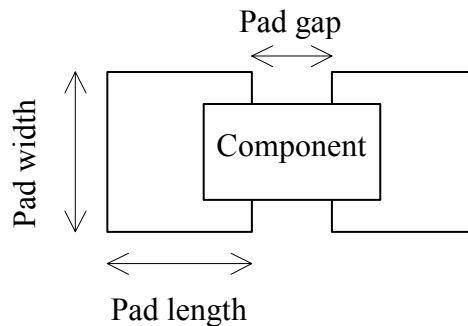


Figure 2. Orientation of pad dimensions

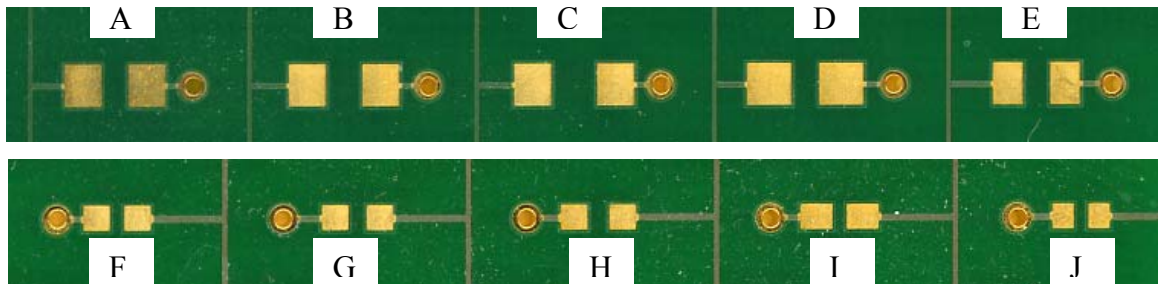


Figure 3. All variations of pad designs for 1206-type (top row) and 0603-type resistors (bottom row)

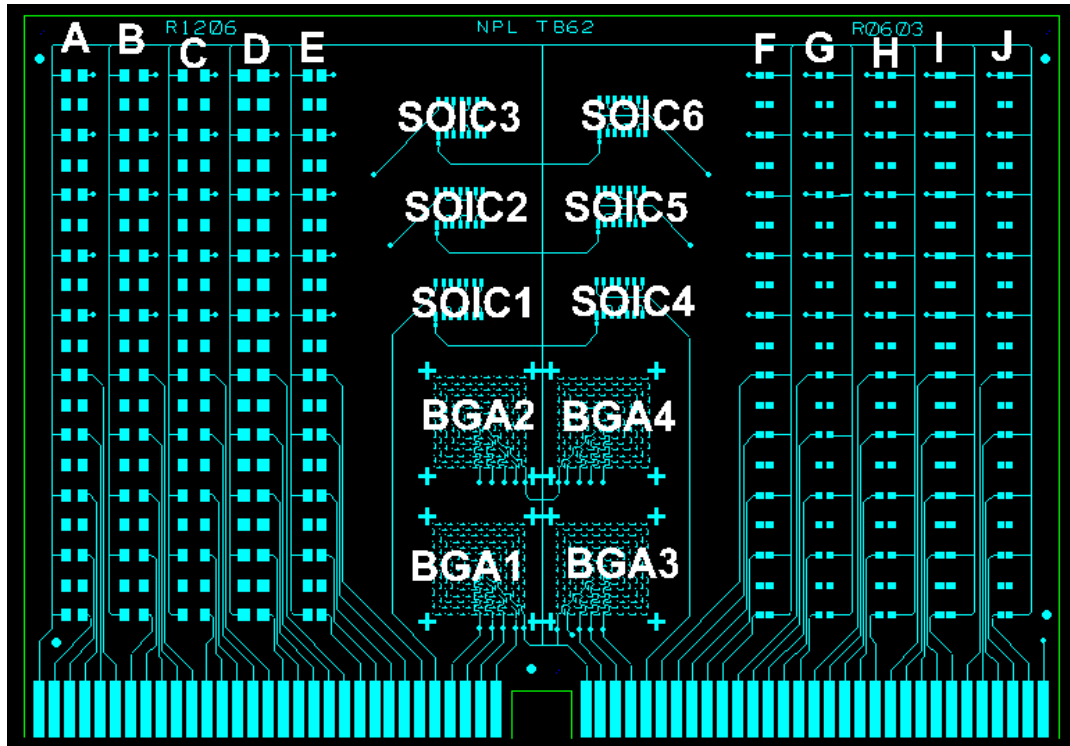


Figure 4. PCB design: from left to right 1206-type resistors, SOICs, BGAs and 0603-type resistors

Typical images of the 0603-type resistors, after the reflow process, are presented in Figure 5. It should be noted that the pad gap in the H design is equivalent to the gap between the component terminations. A similar situation existed with pad design C for the R1206-type components.

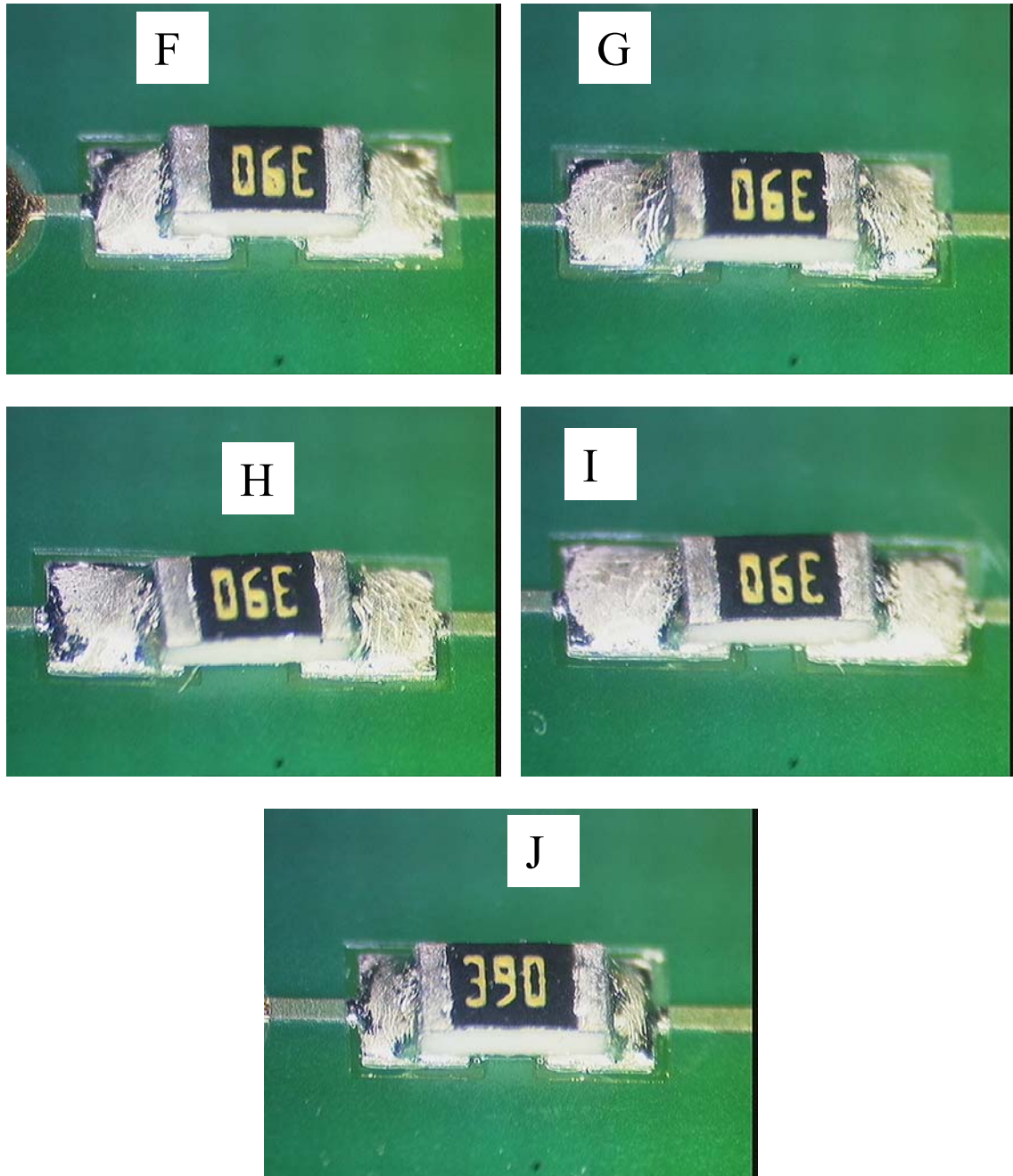


Figure 5. Images of 0603-type resistors with 5 different pad designs

All components were interconnected to gold-plated edge fingers on the PCB for insertion into an edge connector. Components were internally daisy-chained and were of low resistance, thus enabling periodic electrical resistance measurements of components to determine whether or not electrical failures had occurred. For the electrical continuity measurements, each BGA had four separate, concentric interconnected rings, as shown in Figure 6.

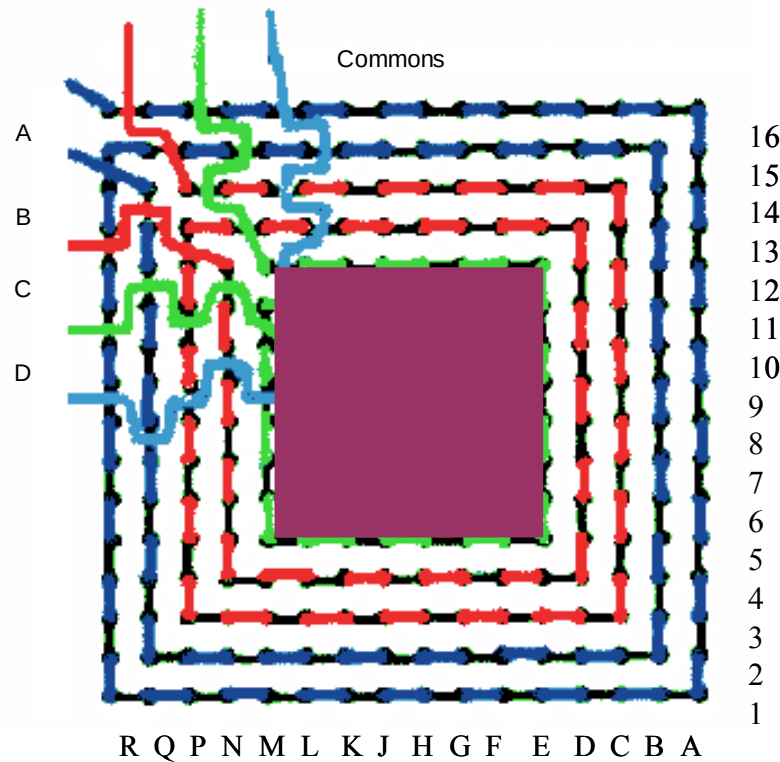


Figure 6. Diagram of daisy-chaining within BGAs showing four concentric interconnected rings (A, B, C and D). The central shaded area indicates the location of the silicon die

2.2 SUBSTRATE MANUFACTURE

Substrates were stencil printed with solder paste using three stainless steel stencils with thicknesses of 100, 150 and 200 μm . The solder paste used was 95.5Sn3.8Ag0.7Cu with a no-clean type flux. Components were placed onto the substrates using an automatic placement system. These processes ensured a consistent solder joint volume. Reflow of the lead-free solder paste was achieved in a convection reflow oven. The peak temperatures reached for the hottest parts of the assembly were between 245 and 260 $^{\circ}\text{C}$, and the time above the 217 $^{\circ}\text{C}$ temperature was less than 90 seconds for all parts of the assembly.

2.3 THERMAL CYCLING

The manufactured assemblies were subjected to thermal cycling and life-time assessment, and the technique used to characterise the level of damage in the solder joints was shear testing [Reference 2].

The choice of the cycling regime used to evaluate the reliability of lead-free solder joints is crucial since the relative performance of different solder alloys can change with thermal cycling parameters such as dwell temperatures and times, and the ramp rates between the dwell temperatures. In recent years, the military and automotive sectors have preferred to use the same cycling regime (-55 $^{\circ}\text{C}$ to +125 $^{\circ}\text{C}$), and this now appears suitable for many high reliability applications. The details of the thermal cycling regime used in this study are listed in Table 2, and presented graphically in Figure 7.

One assembly made using each stencil thickness was removed after 0, 500, 1000, 1500 and 2000 thermal cycles, and 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) after 0, 500, 1000, 1250, 1500, 1750 and 2000 cycles.

Table 2. Test 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

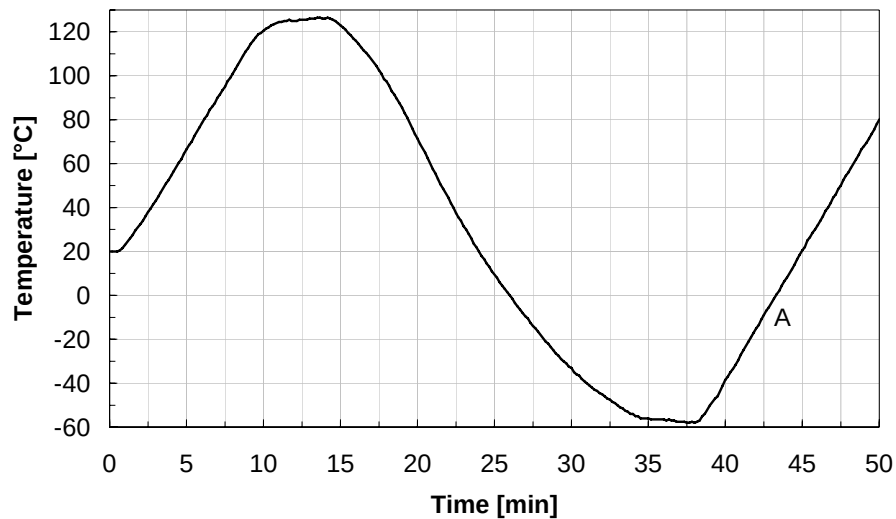


Figure 7. Temperature profile of the thermal cycle

2.4 SHEAR TESTING

The chip resistors are well suited to shear testing, having a flat edge to which a chisel tool can be easily positioned (see Figure 8). The 1206- and 0603-type 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. The stand-off height of the chisel tool above the PCB surface was 80 μm . During each test, the shear tool was moved forward at a defined speed of 200 $\mu\text{m}/\text{s}$ against the test component, and the force was monitored until the solder joint broke. The shear tester used was a Dage Series 4000 instrument, with a DS 100 Kg testing head. Ten 0603-type and 1206-type chip resistors were tested for each condition.

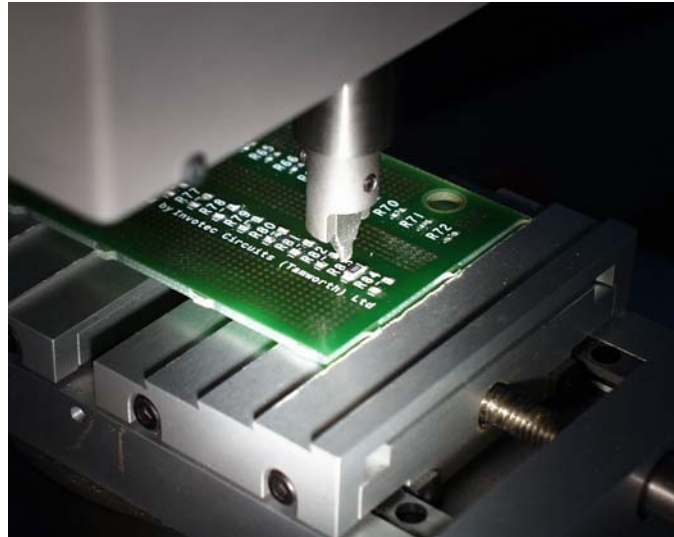


Figure 8. Shear test jig and push-off tool

3 RESULTS

3.1 ELECTRICAL TEST FAILURES

For the purposes of this work, an electrical failure was defined as an interconnect loop resistance greater than 100Ω . The electrical faults detected after 2000 thermal cycles by the automated switch system, were confirmed manually with a digital ohmmeter, and where possible, the location of failure was ascertained by probing with the ohmmeter between individual pins.

3.1.1 R0603 Electrical Test Failures

There were no electrical test failures for the R0603-type components after 2000 thermal cycles for any stencil thickness or pad design.

3.1.2 R1206 Electrical Test Failures

The electrical test failures over 2000 cycles for the R1206-type components, are listed in Table 3.

Table 3. R1206 components cumulative electrical test results

Stencil Thickness	100	150	200		Stencil Thickness	100	150	200
Pad Design A	μm	μm	μm		Pad Design D	μm	μm	μm
<i>0 cycles</i>	0	0	0		<i>0 cycles</i>	0	0	0
<i>500 cycles</i>	0	0	0		<i>500 cycles</i>	0	0	0
<i>1000 cycles</i>	0	0	0		<i>1000 cycles</i>	0	0	1
<i>1300 cycles</i>	0	0	1		<i>1300 cycles</i>	1	1	1
<i>1500 cycles</i>	1	1	1		<i>1500 cycles</i>	1	1	1
<i>1750 cycles</i>	1	2	1		<i>1750 cycles</i>	1	1	3
<i>2000 cycles</i>	1	2	2		<i>2000 cycles</i>	1	1	3
Stencil Thickness	100	150	200		Stencil Thickness	100	150	200
Pad Design B	μm	μm	μm		Pad Design E	μm	μm	μm
<i>0 cycles</i>	0	0	0		<i>0 cycles</i>	0	0	0
<i>500 cycles</i>	0	0	0		<i>500 cycles</i>	1	0	0
<i>1000 cycles</i>	0	0	0		<i>1000 cycles</i>	1	1	0
<i>1300 cycles</i>	0	0	0		<i>1300 cycles</i>	1	1	0
<i>1500 cycles</i>	0	0	1		<i>1500 cycles</i>	1	1	0
<i>1750 cycles</i>	0	0	1		<i>1750 cycles</i>	1	1	0
<i>2000 cycles</i>	1	0	2		<i>2000 cycles</i>	4	2	2
Stencil Thickness	100	150	200					
Pad Design C	μm	μm	μm					
<i>0 cycles</i>	0	0	0					
<i>500 cycles</i>	0	0	0					
<i>1000 cycles</i>	0	0	0					
<i>1300 cycles</i>	0	0	0					
<i>1500 cycles</i>	0	0	0					
<i>1750 cycles</i>	0	0	0					
<i>2000 cycles</i>	1	0	1					

3.1.3 SOIC Electrical Test Failures

There were no SOIC electrical test failures after 2000 thermal cycles.

3.1.4 BGA Electrical Test Failures

The numbers of BGA C-ring electrical test failures over 2000 cycles are listed in Table 4. There were no electrical test failures within the BGA A, B and D rings after 2000 cycles.

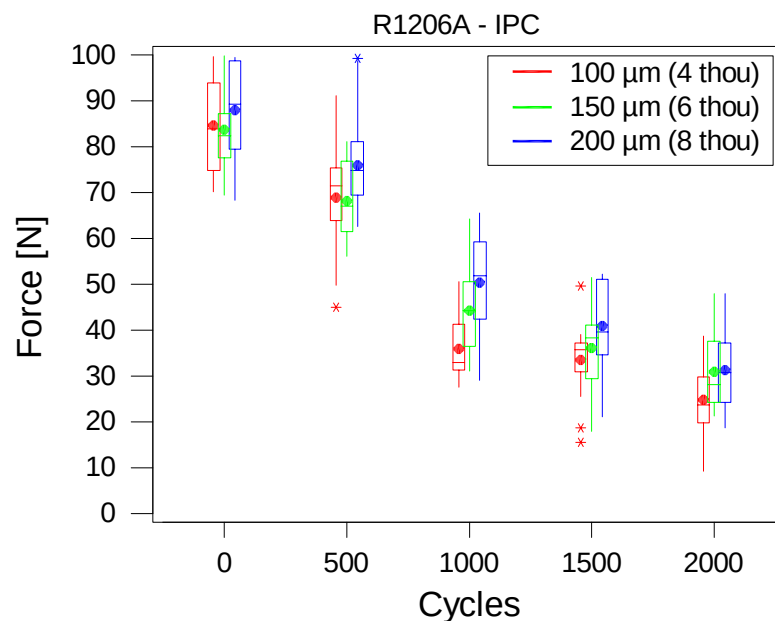
Table 4. BGA C-ring cumulative electrical test results

Stencil Thickness	100	150	200
BGA C-ring	μm	μm	μm
<i>0 cycles</i>	0	0	0
<i>500 cycles</i>	0	0	0
<i>1000 cycles</i>	0	0	0
<i>1300 cycles</i>	0	0	0
<i>1500 cycles</i>	1	0	0
<i>1750 cycles</i>	2	1	1
<i>2000 cycles</i>	5	1	2

3.2 SHEAR TEST RESULTS

3.2.1 R1206 Shear Test Results – Stencil Thickness

The shear test results for the IPC pad layout (A) and the R1206 components, assembled using stencils of three thicknesses, are summarised in Figure 9.

**Figure 9.** Shear test results for R1206 components and IPC standard pad (A)

3.2.2 R0603 Shear Test Results – Stencil Thickness

The shear test results for the IPC pad layout (F) and the R0603 components, assembled using stencils of three thicknesses, are summarised in Figure 10.

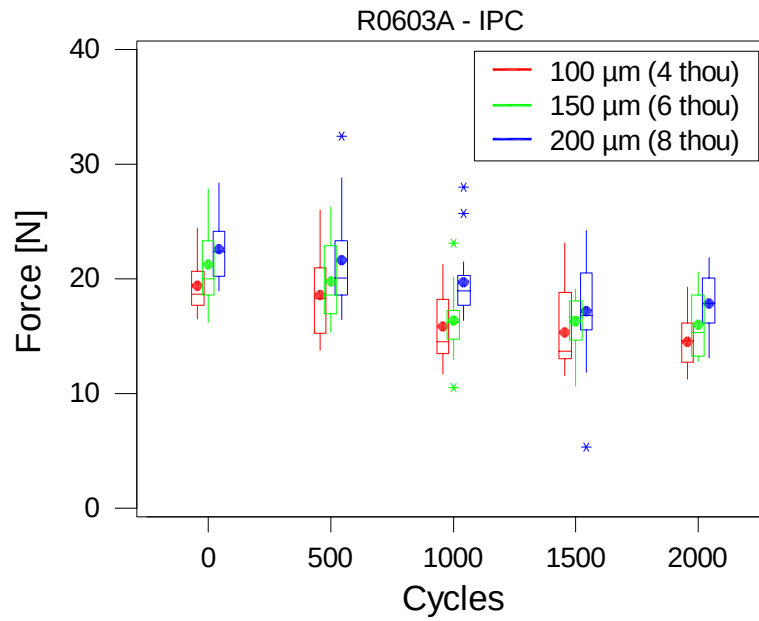


Figure 10. Shear test results for R0603 components and IPC standard pad (F)

3.2.3 R1206 Shear Test Results – Pad Design

The shear test results for the different pad layouts (A to E) and the R1206 components, assembled using stencils of three thicknesses, are presented in Figures 11 to 13.

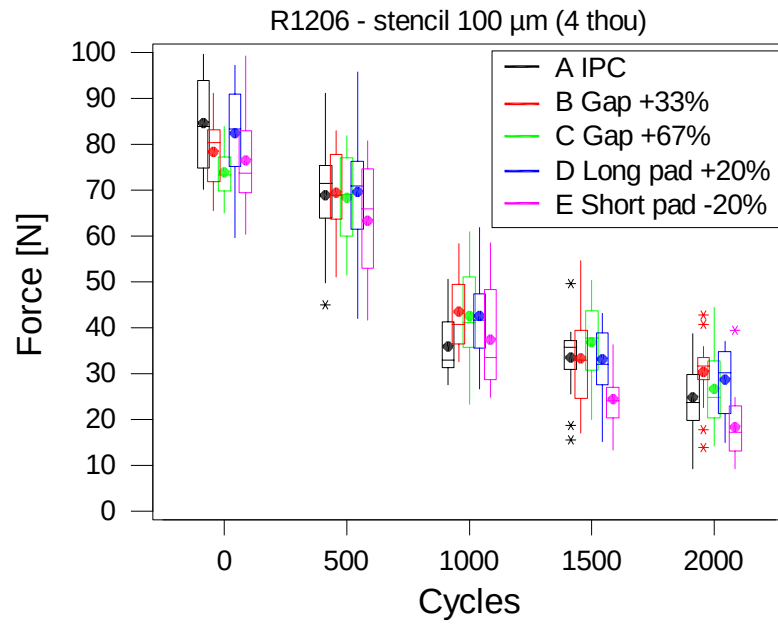


Figure 11. Shear test results for R1206 components (100 μm thick stencil)

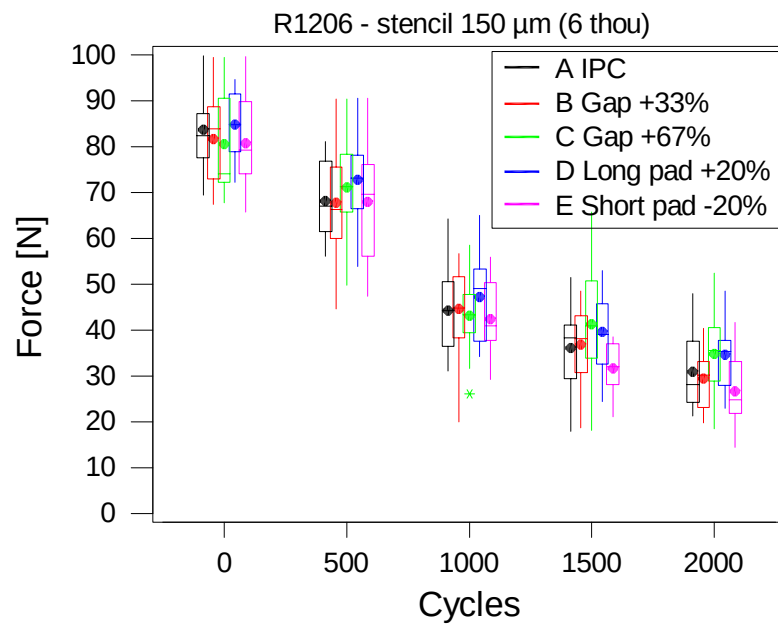


Figure 12. Shear test results for R1206 components (150 μm thick stencil)

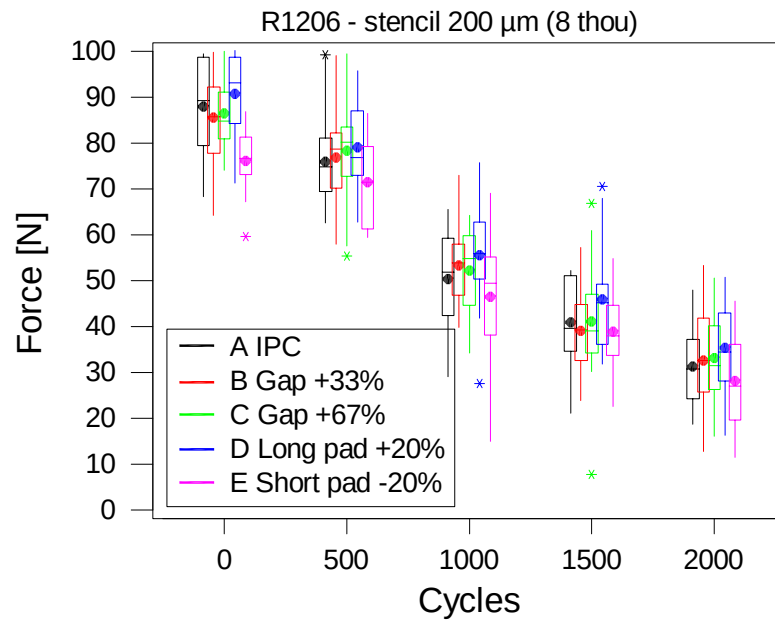


Figure 13. Shear test results for R1206 components (200 μm thick stencil)

3.2.4 R0603 Shear Test Results – Pad Design

The shear test results for the different pad layouts (F to J) and the R0603 components, assembled using stencils of three thicknesses, are presented in Figures 14 to 16.

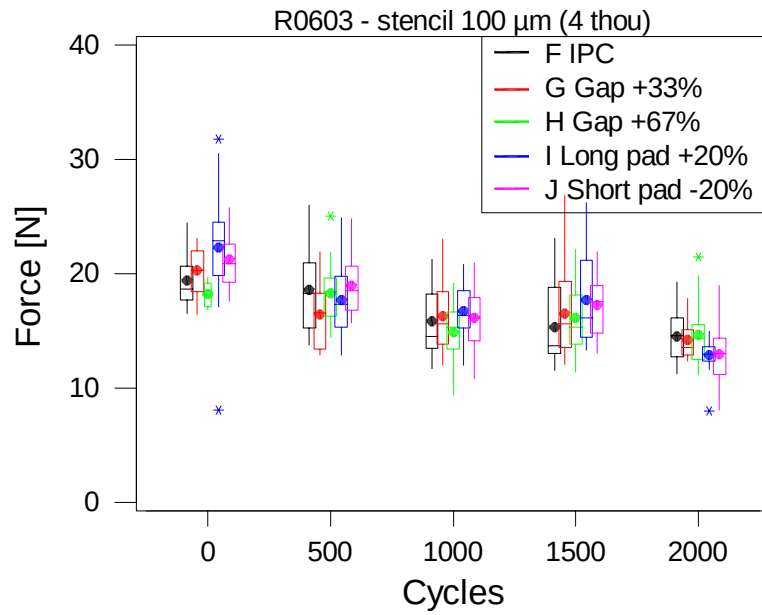


Figure 14. Shear test results for R0603 components (100 μm thick stencil)

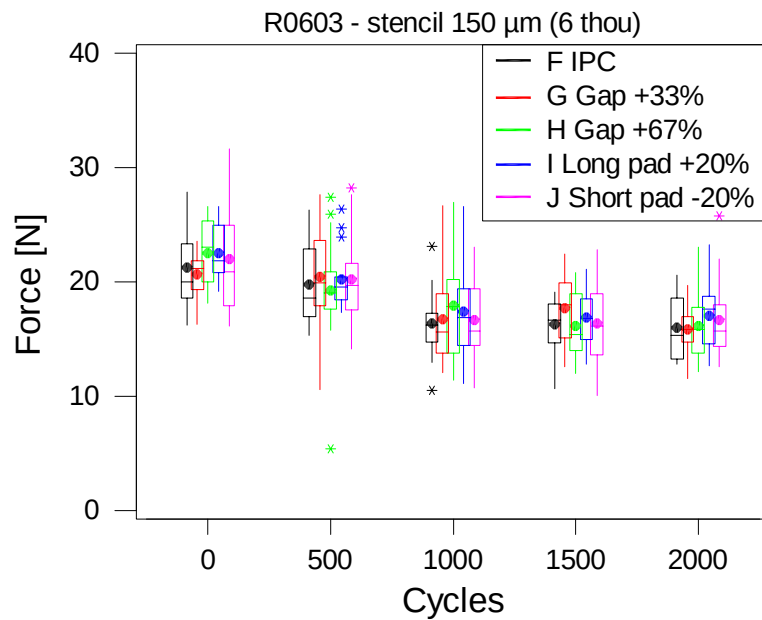


Figure 15. Shear test results for R0603 components (150 μm thick stencil)

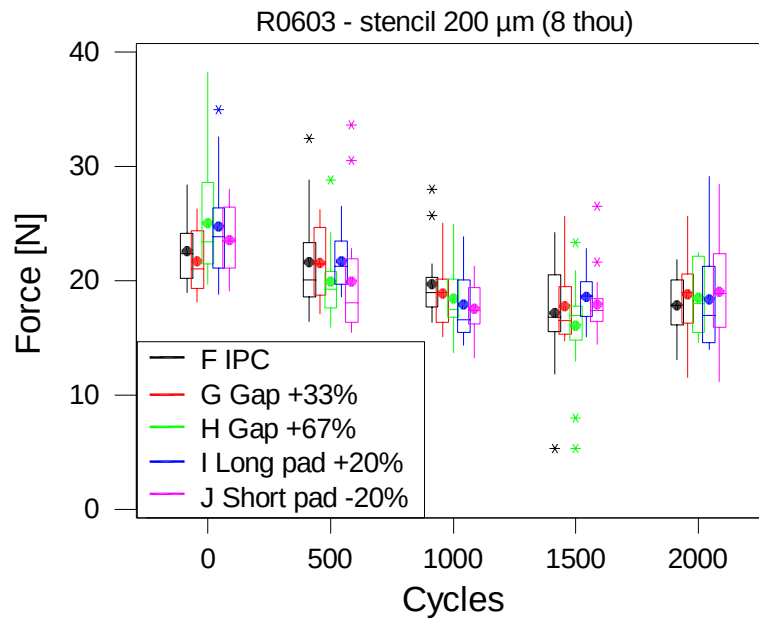


Figure 16. Shear test results for R0603 components (200 µm thick stencil)

4 DISCUSSION

4.1 EFFECT OF STENCIL THICKNESS

The results for the chip resistor and SOIC components, indicate that the stencil thickness had little effect on joint reliability, with very few electrical failures registered after 2000 cycles. There were also few differences in the shear test results for the chip resistors. In addition, rates of shear strength degradation were similar, indicating that crack propagation rates in the joints were comparable. Micro-sections of typical R1206 joints are shown in Figures 17 to 19, highlighting similar crack propagation levels.

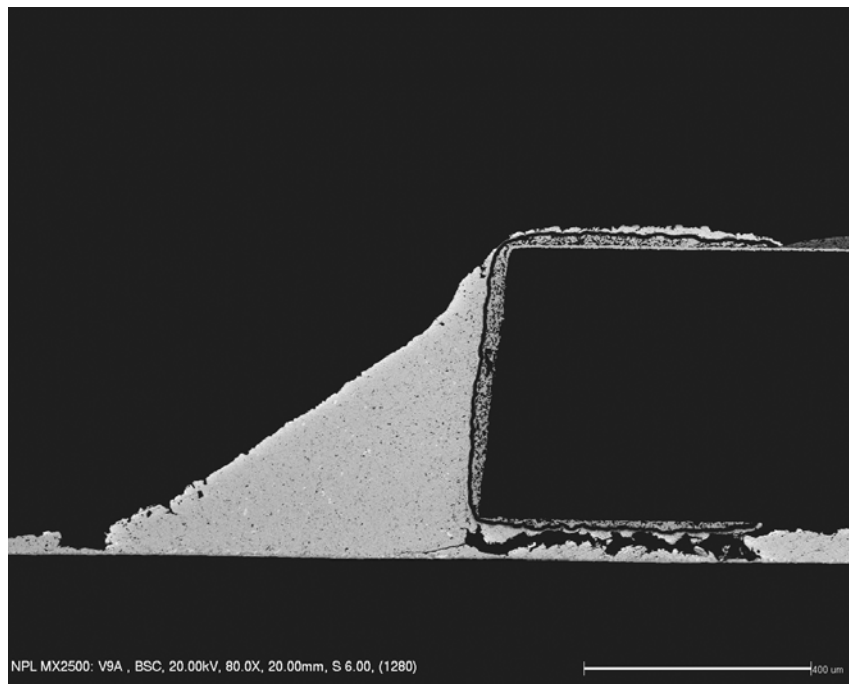


Figure 17. Typical crack propagation after 2000 thermal cycles for R1206 components (100 µm stencil; pad design A)

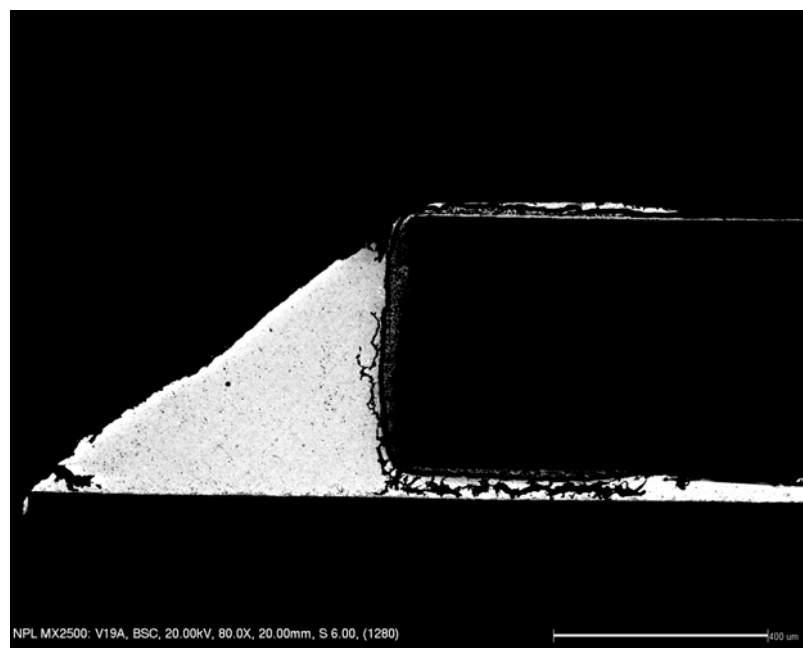


Figure 18. Typical crack propagation after 2000 thermal cycles for R1206 components (150 µm stencil; pad design A)

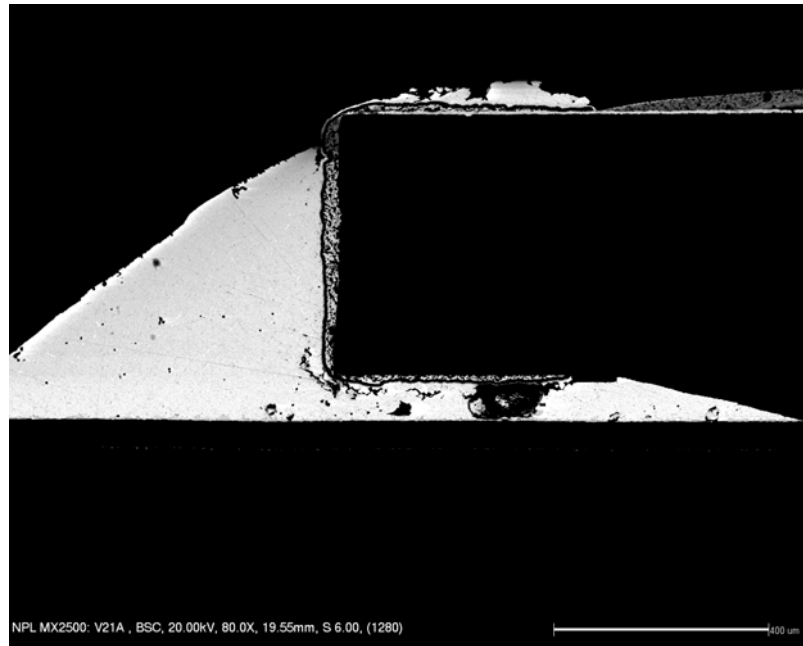


Figure 19. Typical crack propagation after 2000 thermal cycles for R1206 components (200 µm stencil; pad design A)

The shear strengths of joints assembled using the thicker stencils were highest, but this was due to the increased amount of solder in the joint. This is evident in Figures 20 to 22 which show micro-sections of the joints after manufacture. Use of the 150 µm and 200 µm stencils gave significantly larger fillets, and the 200 µm stencil produced additional solder on the upper termination of the component.

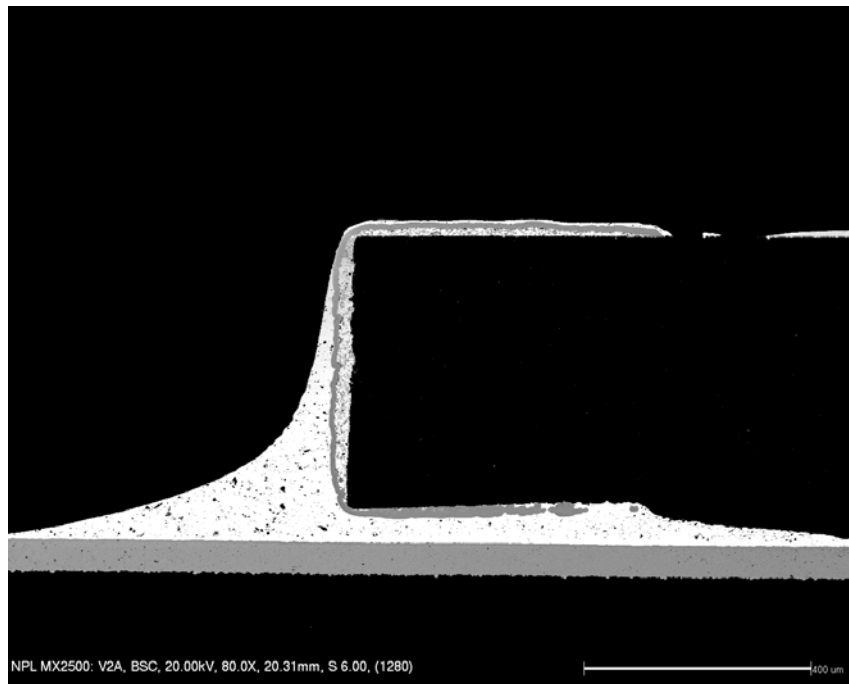


Figure 20. Micro-section of R1206 component showing typical joint after manufacture using 100µm thick stencil

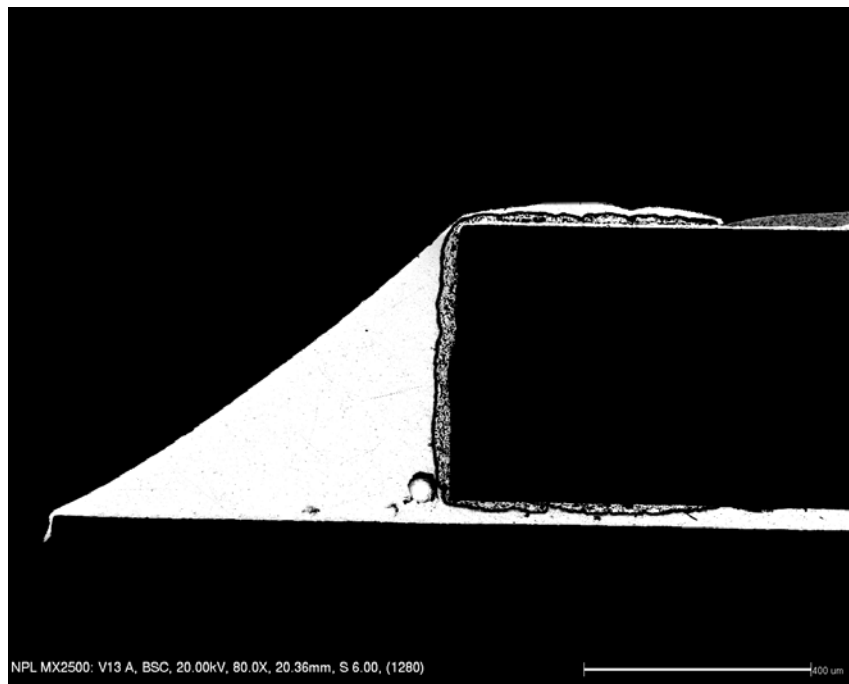


Figure 21. Micro-section of R1206 component showing typical joint after manufacture using 150 μm thick stencil

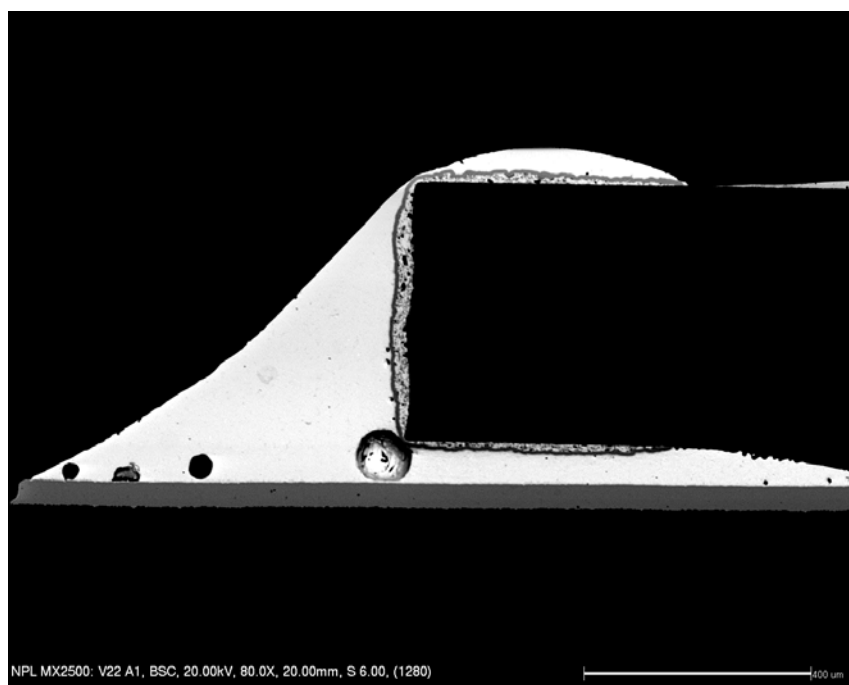


Figure 22. Micro-section of R1206 component showing typical joint after manufacture using 200 μm thick stencil

The stencil thickness did have an effect on the reliability of the BGA components, with the thinnest (100 μm) stencil producing joints having higher failure rates after 2000 cycles in comparison with those of the two thicker stencils (Figure 23). The improved performance when using the thicker stencils may be due to the increased amount of solder contributed to the joint by the thicker stencils.

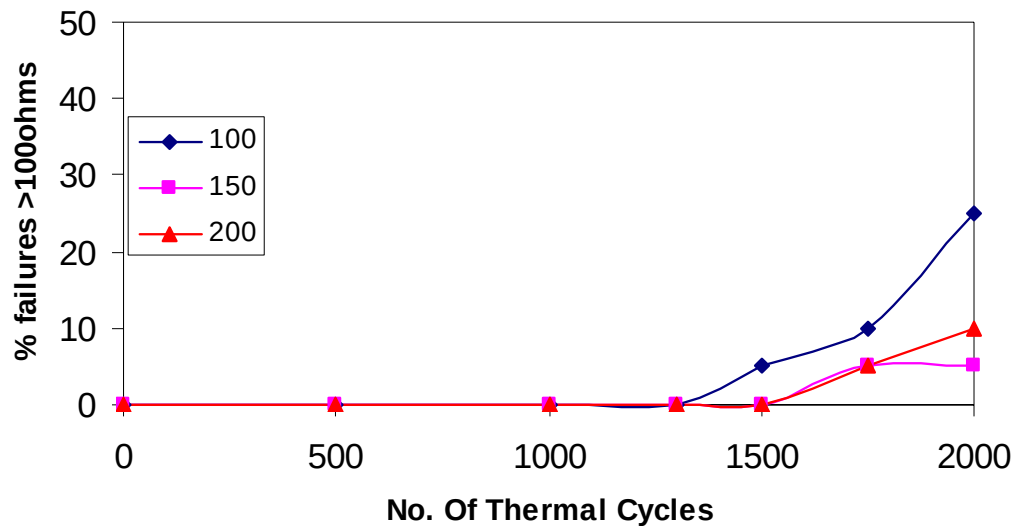


Figure 23. Generation rates of electrical failures in BGA C-rings for three different stencil thicknesses

4.2 EFFECT OF PAD DESIGN

For the R0603-type components, there were no significant differences between the results relating to the different pad designs, in terms of either the electrical test results or the shear testing.

For the R1206-type components, more electrical test failures were obtained for the E pad design (shorter pad) than for the other designs, although there was little difference in the shear test results relating to the different pad designs. Typical micro-sections of components for the five pad designs are presented in Figures 24 to 28. After 2000 cycles, there was little difference between crack propagation results.

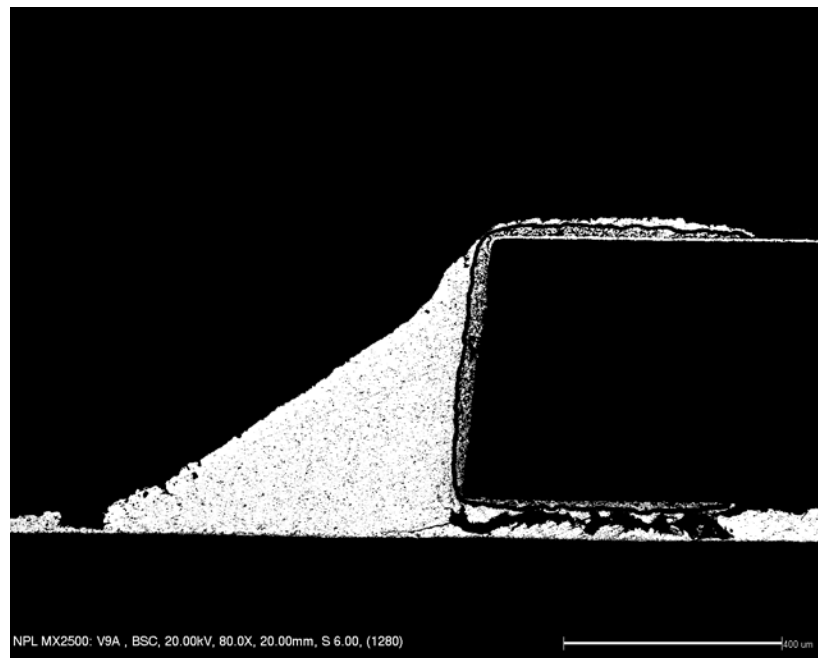


Figure 24. Micro-section of R1206 component using A-pad design after 2000 thermal cycles

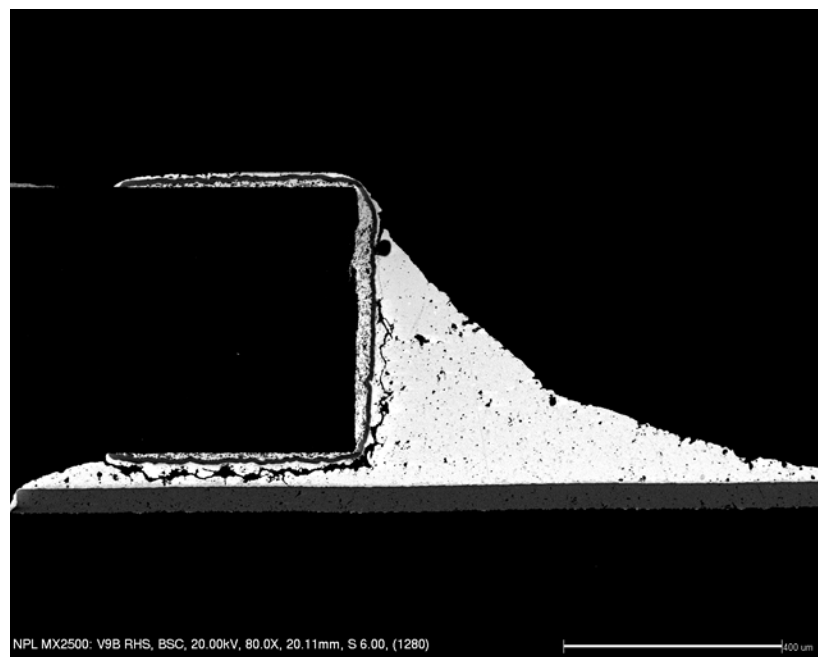


Figure 25. Micro-section of R1206 component using B-pad design after 2000 thermal cycles

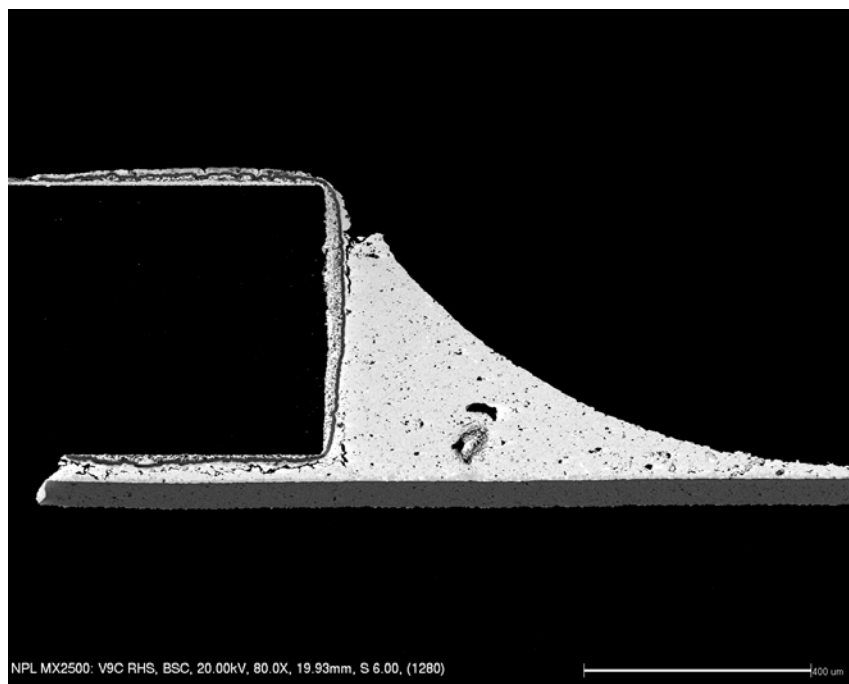


Figure 26. Micro-section of R1206 component using C-pad design after 2000 thermal cycles

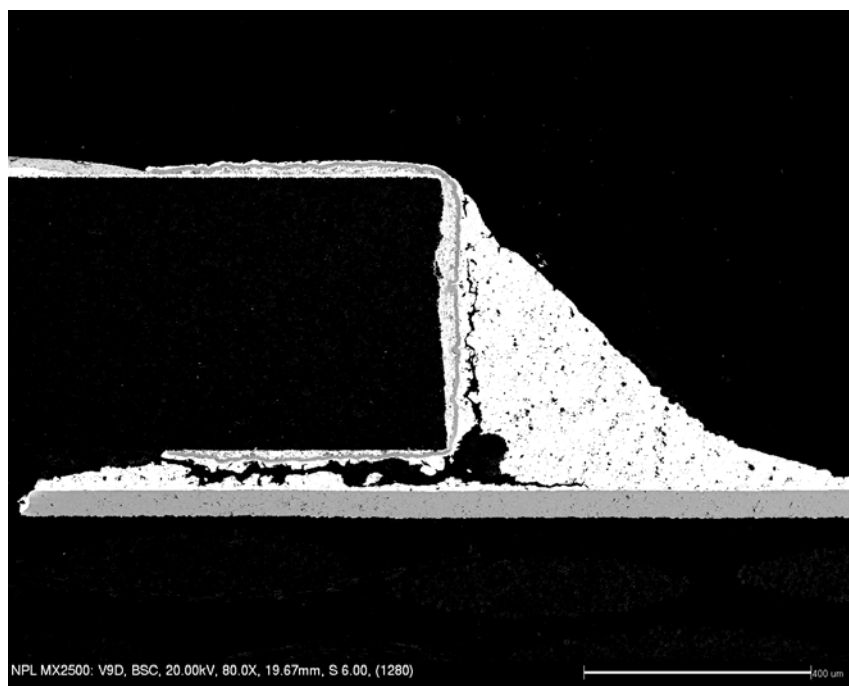


Figure 27. Micro-section of R1206 component using D-pad design after 2000 thermal cycles

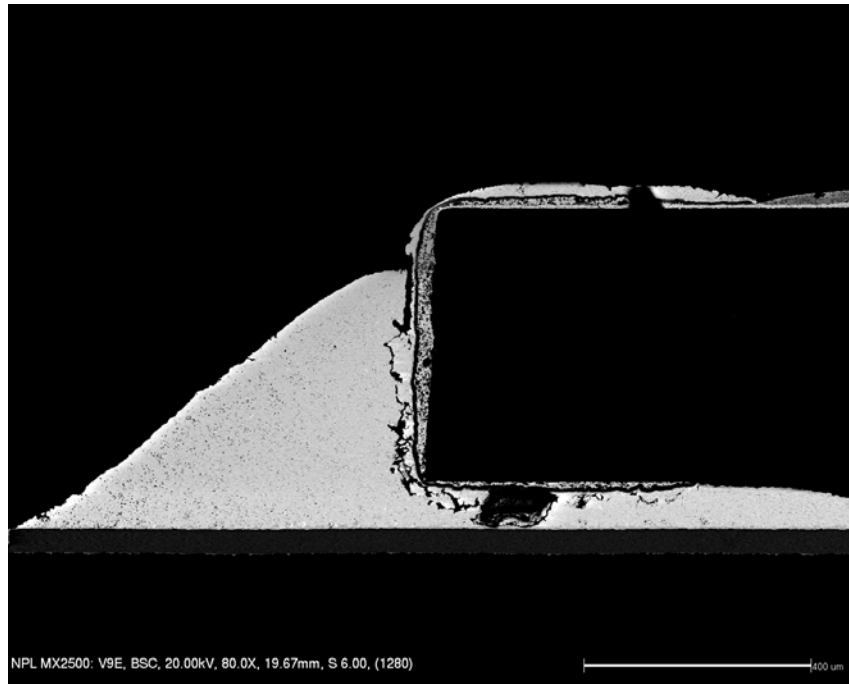


Figure 28. Micro-section of R1206 component using E-pad design after 2000 thermal cycles

5 CONCLUSION

In an attempt to ascertain the effect of pad size/design and solder joint volume on lead-free solder joint reliability, a range of test boards have been assembled using SAC solder and assessed in a matrix experiment involving four components types (R0603, R1206, SOIC and BGA), ten pad designs and three stencil thicknesses. The assemblies were thermally cycled (-55 to + 125°C) for a maximum of 2000 cycles, and the joints were studied visually, and using shear testing and electrical continuity monitoring. The salient conclusions were:

- **Stencil thickness does not have a strong effect on the joint reliability of lead-free assemblies, but there may be a slight benefit when using the thicker 200μm stencil.**
 - Thicker stencils did produce joints with higher shear strengths for chip resistors, but there was no evidence of increased crack propagation or failures before 2000 cycles for the thinner stencils.
 - Stencil thickness had no effect on reliability of the SOIC joints up to 2000 cycles.
 - The reliability of BGA joints assembled using the thinner stencils degraded more quickly, with twice as many BGA joints assembled using the 100 μm thick stencil, failing after 2000 cycles compared to those assembled using the thicker stencils.

- **Pad design is again not critical to the joint reliability of lead-free assemblies, although shortening the pad can be detrimental.**
 - Having a shorter pad did produce more electrical test failures, but only for joints made using the thinner stencils. This suggests that this combination produced a narrower fillet, which enabled the fatigue crack formed during thermal cycling, to penetrate to the joint surface resulting in electrical failure.

6 ACKNOWLEDGMENTS

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