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**DEPC MPR 038**

**Measuring the Impact of  
Component Solderability on  
Lead-Free Solder Joint  
Reliability**

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

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## Measuring the Impact of Component Solderability on Lead-Free Solder Joint Reliability

M Wickham, L Zou, M Dusek and C Hunt  
Engineering and Process Control Division

### ABSTRACT

Whilst the impact of poor component solderability on lead-containing solder systems is well understood, little information is available on the impact on the new lead-free assembly processes being introduced to conform to European legislation. Previous NPL work has demonstrated relationships for SnPb solder systems between component solderability, solder fillet rise, and process yield, and between solderability and thermal fatigue. This report summarises similar work on assembly yield and subsequent reliability of joints made using a lead-free soldering systems, employing visual inspection, micro-sectioning, electrical conductivity, and shear testing to evaluate the solder joints.

Components with lead-free finishes (R0603, R1206, SOIC and BGA) were artificially aged to produce a range of reduced solderabilities and assembled into test vehicles using lead-free solders. In the cases of the resistors and SOIC components, the reduced solderability had little effect on the process yield. The previous work with SnPb solder did show an adverse effect on the solder joint fillet, and this improvement for the lead-free assembly is attributed to the greater soldering temperatures, and/or the higher flux activity levels associated with lead-free solder pastes. In the case of the BGAs, the artificial ageing process significantly degraded the component substrate, causing warping during assembly, and reduced yield for the most severely aged components.

The reliability of the solder joints was again examined after thermal cycling. There were no electrical failures with the R0603 or SOIC components, and only a few with the R1206 components – insufficient to differentiate between the various component solderabilities. In the case of the BGAs, as thermal cycling progressed, the number of electrical failures increased for the most severely aged components, particularly in the outer rings of the BGAs. After 2000 cycles, joint cracking was present close to the component interface in samples from all ageing groups (i.e. different solderabilities). This is attributed to stress concentrations associated with solder mask definition of the pads.

The salient conclusion from this work is that, for the normal range of solderability associated with quality lead-free components likely to be experienced by end users, there should be no adverse effect on assembly yield or subsequent reliability, in a controlled lead-free assembly process.

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

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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**

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. However, these new alloys have not previously been extensively used in electronics manufacture. Consequently considerable work is currently being undertaken world-wide to generate relevant reliability data on lead-free soldering systems, in an attempt to complement the 60 years of reliability experience generated with SnPb-based alloys.

Whilst the degradation of lead-containing finishes has been researched and understood, little published work is available on the impact of poor solderability on the lead-free assembly process. Previous work at the National Physical Laboratory [1], demonstrated a relationship between component solderability, solder fillet rise and hence process yield for SnPb solder. That work also correlated solderability and yield with thermal fatigue properties. Hence for SnPb solder systems, it was demonstrated that poor solderability of component terminations led to lower fillet rises and poorer process yields. In turn, components with lower fillet rise exhibited reduced reliability when assessed via low cycle fatigue.

To determine if similar relationships exist for lead-free soldering systems, the work reported here was aimed at extending the previous NPL work to cover the lead-free SAC solder alloys.

## **2 EXPERIMENTAL**

### **2.1 TEST VEHICLE DESIGN**

The test vehicle design contained two sizes of chip resistors, 1206 and 0603 (both tin-finished), SOIC16 (tin-finished) and PBGA256 (SAC-finished) components. 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 incorporated a range of PCB pad sizes but only IPC standard pads were evaluated in this exercise. The test assembly is shown in Figure 1.

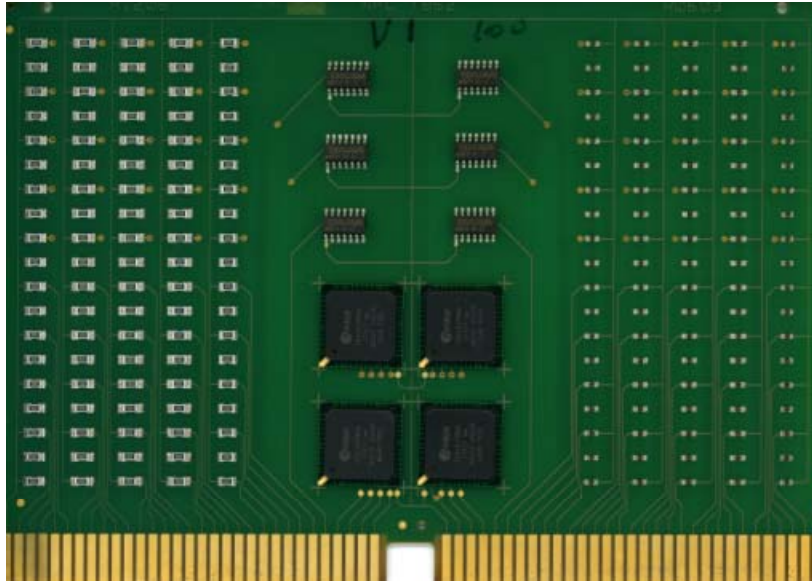


Figure 1. Test assembly

All components were interconnected to gold-plated edge fingers for insertion into an edge connector. The components were internally daisy-chained or of low resistance, enabling electrical resistance of the components to be monitored periodically to determine if any electrical failures had occurred. Each BGA had four separate, concentric interconnected rings as shown in Figure 2.

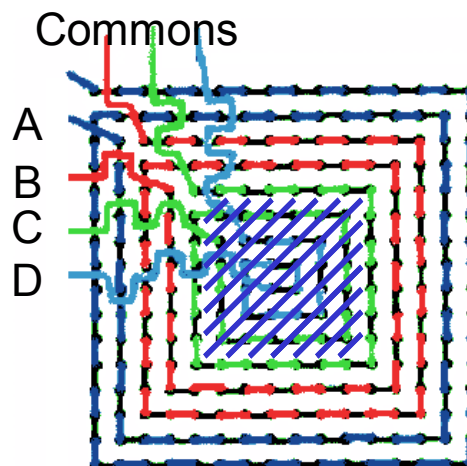


Figure 2. Diagram of daisy-chaining within BGAs showing four concentric interconnected rings (A, B, C and D), and a hatched area representing the location of the component die

## 2.2 COMPONENT AGEING

Components of each of the three types utilised were artificially aged at 155 °C for extended periods to develop three batches of each component type, each having a different solderability, and designated Age 0, Age 1 and Age 2. The three ageing periods were chosen after separate experiments on representative components of ageing followed by solderability measurements. The change in solderability with ageing time

at 155 °C is shown in Figure 3 for the R1206-type components, and in Figure 4 for SOIC components. The three levels of solderability chosen in each case are indicated by the arrows in these Figures. As the solder coatings on BGAs are comparably much thicker than for chip resistors, no significant ageing of the BGA solder balls was expected, so the BGAs were aged for the same periods as the chip resistors.

The largest reductions in measured solderability would represent a storage life of well in excess of 5 years for components of good manufactured quality (i.e. components with well plated tin finishes in excess of 5  $\mu\text{m}$  thick).

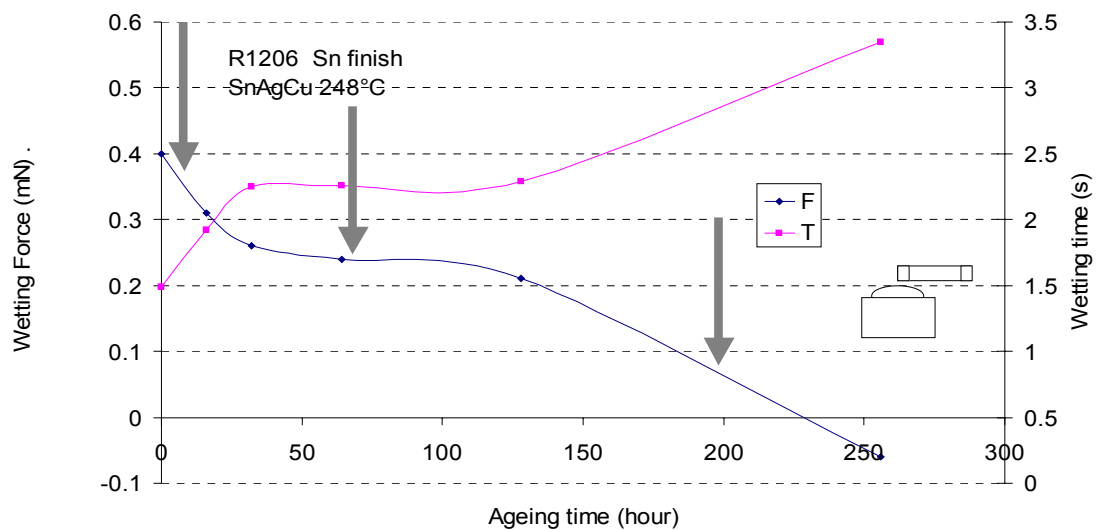


**Figure 3. Change of solderability (wetting force and wetting time) with ageing time for R1206-type components indicated**

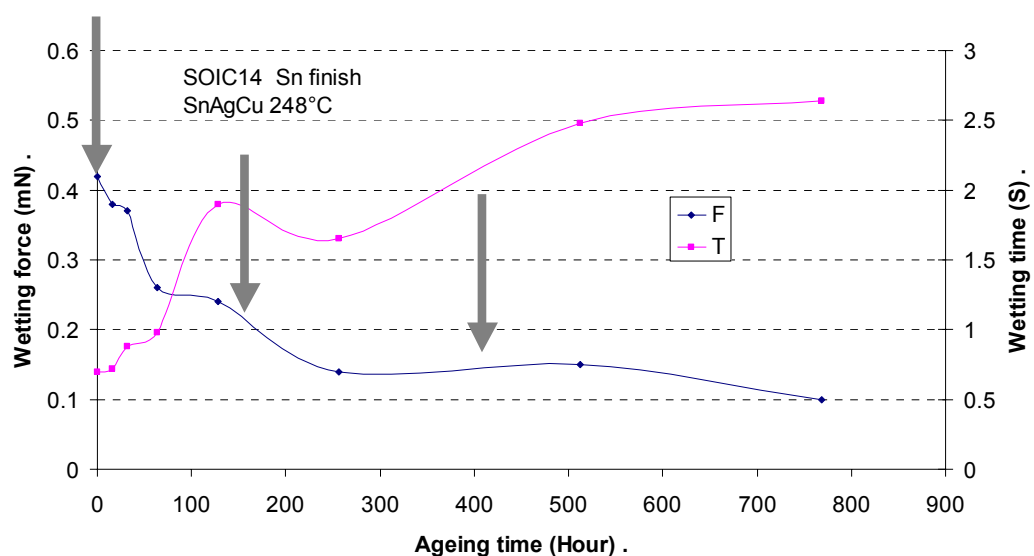


**Figure 4. Change of solderability (wetting force and wetting time) with ageing time for SOIC14 components indicated**

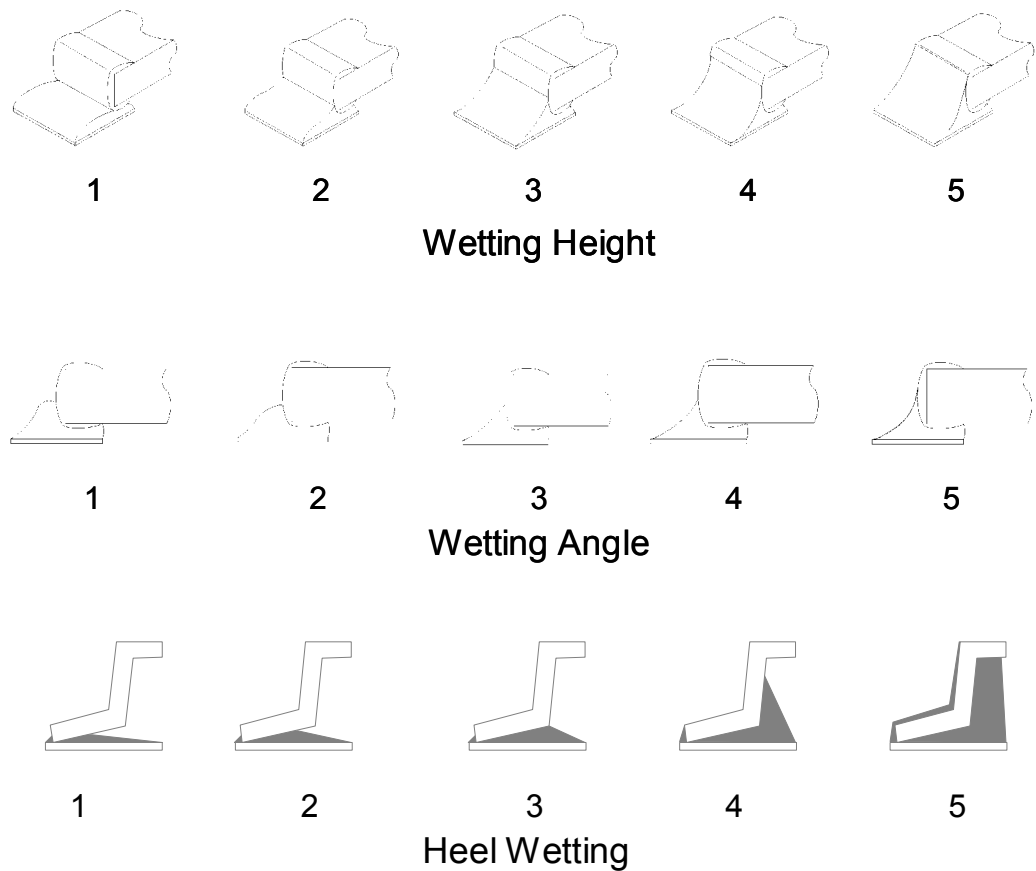
ageing time for SOIC components indicated

2.3 SUBSTRATE MANUFACTURE

Substrates were stencil printed with solder paste using a laser-cut stainless steel stencil with a thickness of 150  $\mu\text{m}$ . The solder paste used was 95.5Sn3.8Ag0.7Cu with a no-clean flux. Components were placed onto the substrates using an automatic placement system, ensuring a consistent solder joint volume. Reflow of the lead-free solder paste was achieved in a convection reflow oven. The peaks of reflow temperature profiles were between 245 and 260  $^{\circ}\text{C}$ , and the time above the 220  $^{\circ}\text{C}$  temperature was between 1 and 1.5 min.

2.4 VISUAL INSPECTION

After manufacture, every chip resistor and SOIC joint was inspected by a single operator (using a 10x to 30x binocular zoom microscope) and graded according to the following scale:



## 2.5 THERMAL CYCLING

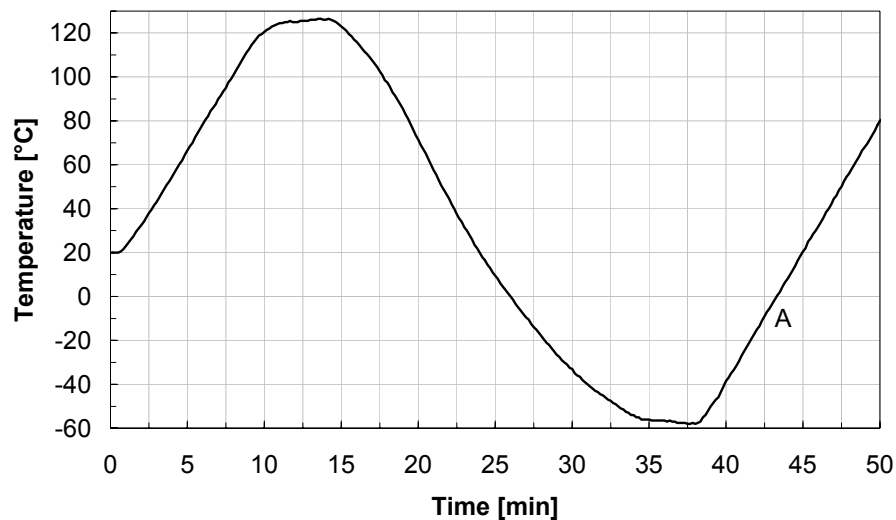
The manufactured assemblies were subjected to thermal cycling and lifetime assessment, and the technique used to characterise the level of damage in the solder joints was shear testing [2].

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 (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 °C to +125 °C), and this now appears suitable for many high reliability applications. The thermal cycling regime parameters used in this evaluation study are listed in Table 1, and presented graphically in Figure 5.

One assembly from each “aged batch” was removed after 0, 500, 1000, 1500 and 2000 thermal cycles respectively. These assemblies were then subjected to shear testing and micro-sectioning. In addition, 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.

**Table 1. Tested temperature cycling regime with  $\pm 4^{\circ}\text{C}$  temperature tolerance**

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

**Figure 5. Temperature profile of the thermal cycle**

## 2.6 SHEAR TESTING

Chip resistors are well suited to shear testing, having a flat edge to which a chisel tool can be easily positioned (see Figure 6).

The 1206 and 0603 components were tested on the board in order to determine the ultimate shear strength for the SM joints (the maximum force prior to fracture). Ten 0603 and 1206 chip resistors were tested for each condition. All testing of thermally cycled samples was undertaken at room temperature.

The stand-off height of the chisel tool above the PCB surface was  $80\text{ }\mu\text{m}$ . During each test, the shear tool was moved forward at a defined speed of  $200\text{ }\mu\text{m/s}$  against the test component, and the force was monitored until the solder joint broke. The shear tester used in this work was a Dage Series 4000 instrument, with a DS 100N testing head.

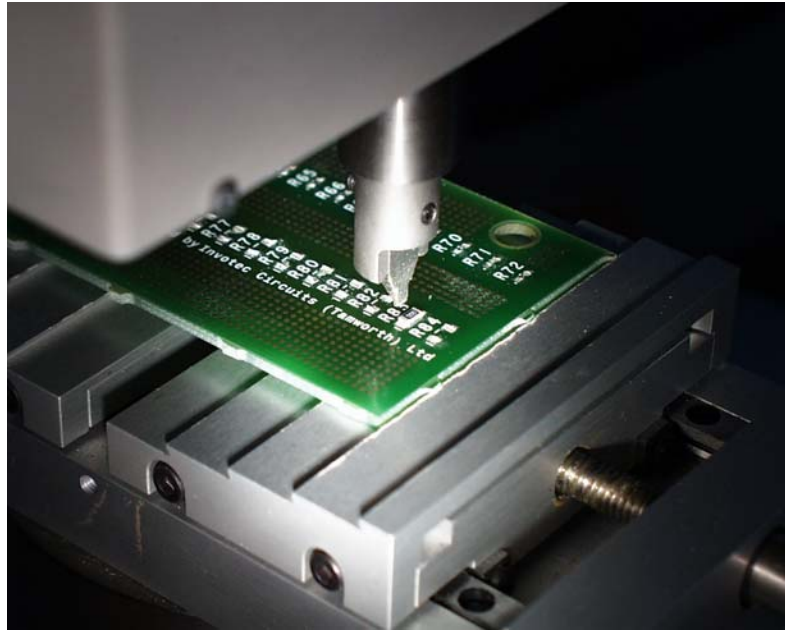


Figure 6. Shear test jig and push-off tool

### 3 RESULTS

#### 3.1 VISUAL INSPECTION SCORES

The changes in visual scores for the three component types with external, visible joints, are displayed graphically in Figure 7. It is evident that the wetting of the joints of the R0603 and SOIC components exhibited a greater deterioration with ageing than did those of the R1206 components. However, all components passed visual inspection to Class 3 of IPC visual inspection guidelines [4]. Due to their nature, no visual inspection of the BGA solder joints was possible.

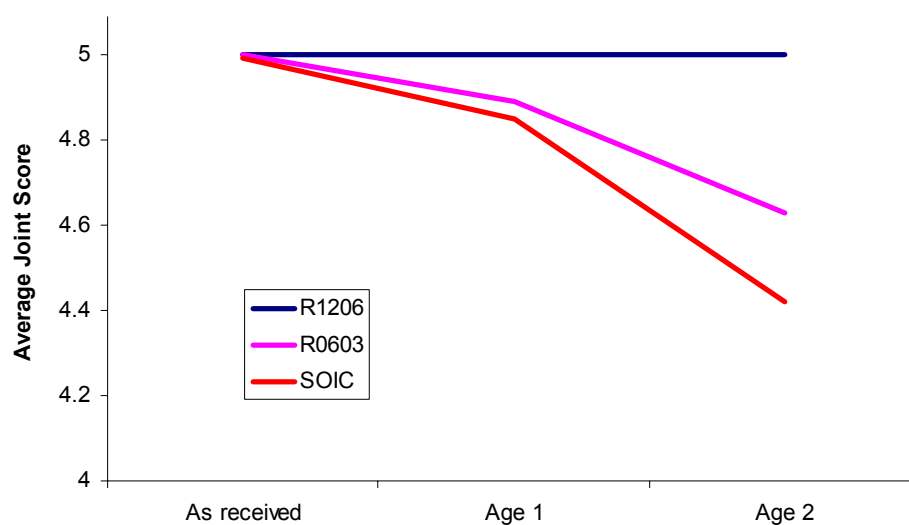


Figure 7. Visual inspection scores for R0603, R1206 and SOIC components

### 3.2 ELECTRICAL TEST FAILURES

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

#### 3.2.1 R0603 Electrical Test Failures

There were no electrical test failures on the R0603 components up to 2000 thermal cycles.

#### 3.2.2 R1206 Electrical Test Failures

The electrical test failures on R1206 components up to 2000 thermal cycles are listed in Table 2.

**Table 2. R1206 cumulative electrical test failures**

| Cycles | A/R | Age 1 | Age 2 |
|--------|-----|-------|-------|
| 0      | 0   | 0     | 0     |
| 500    | 0   | 0     | 0     |
| 1000   | 0   | 0     | 0     |
| 1300   | 0   | 0     | 0     |
| 1500   | 1   | 0     | 0     |
| 1750   | 2   | 0     | 0     |
| 2000   | 2   | 1     | 0     |

#### 3.2.3 SOIC Electrical Test Failures

There were no electrical test failures on the SOIC components up to 2000 thermal cycles.

#### 3.2.4 BGA Electrical Test Failures

The electrical test failures on BGA components up to 2000 thermal cycles are listed in Table 3.

**Table 3. BGA cumulative electrical test failures**

| Age                | A/R | Age 1 | Age 2 |
|--------------------|-----|-------|-------|
| <b>BGA A-ring</b>  |     |       |       |
| <i>0 cycles</i>    | 1   | 0     | 1     |
| <i>500 cycles</i>  | 1   | 1     | 4     |
| <i>1000 cycles</i> | 1   | 1     | 4     |
| <i>1300 cycles</i> | 1   | 1     | 5     |
| <i>1500 cycles</i> | 1   | 1     | 5     |
| <i>1750 cycles</i> | 1   | 1     | 5     |
| <i>2000 cycles</i> | 1   | 1     | 5     |
| <b>BGA B-ring</b>  |     |       |       |
| <i>0 cycles</i>    | 1   | 0     | 3     |
| <i>500 cycles</i>  | 1   | 0     | 5     |
| <i>1000 cycles</i> | 1   | 0     | 5     |
| <i>1300 cycles</i> | 1   | 0     | 5     |
| <i>1500 cycles</i> | 1   | 0     | 5     |
| <i>1750 cycles</i> | 2   | 1     | 6     |
| <i>2000 cycles</i> | 2   | 1     | 6     |
| <b>BGA C-ring</b>  |     |       |       |
| <i>0 cycles</i>    | 1   | 0     | 1     |
| <i>500 cycles</i>  | 1   | 1     | 1     |
| <i>1000 cycles</i> | 1   | 1     | 1     |
| <i>1300 cycles</i> | 1   | 1     | 1     |
| <i>1500 cycles</i> | 1   | 1     | 2     |
| <i>1750 cycles</i> | 2   | 1     | 3     |
| <i>2000 cycles</i> | 2   | 1     | 3     |
| <b>BGA D-ring</b>  |     |       |       |
| <i>0 cycles</i>    | 1   | 0     | 1     |
| <i>500 cycles</i>  | 1   | 0     | 2     |
| <i>1000 cycles</i> | 1   | 0     | 2     |
| <i>1300 cycles</i> | 1   | 0     | 2     |
| <i>1500 cycles</i> | 1   | 0     | 2     |
| <i>1750 cycles</i> | 1   | 0     | 2     |
| <i>2000 cycles</i> | 1   | 0     | 2     |

### 3.3 SHEAR TEST RESULTS

#### 3.3.1 R1206 Shear Test Results

The shear test results for the IPC pad layout (A) for the R1206 components for three levels of ageing/solderability, are presented graphically in Figure 8.

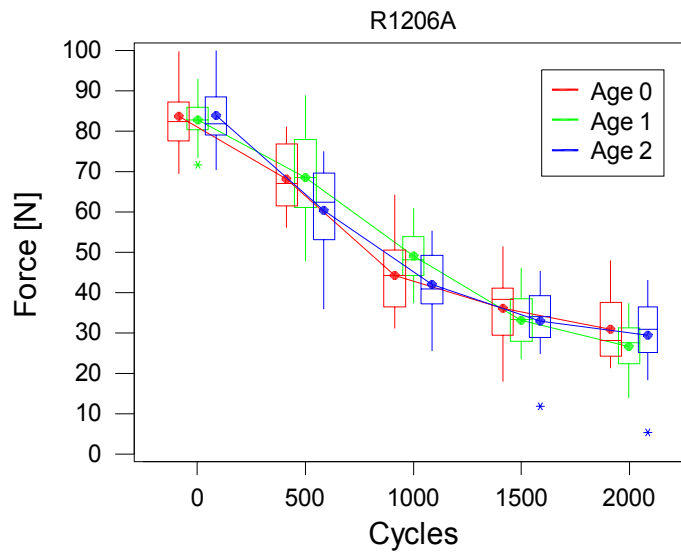


**Figure 8. Shear test measurements for R1206 components for three levels of solderability**

### 3.3.2 R0603 Shear Test Results

The shear test results for the R0603 components for the three levels of ageing/solderability, are presented graphically in Figure 9.

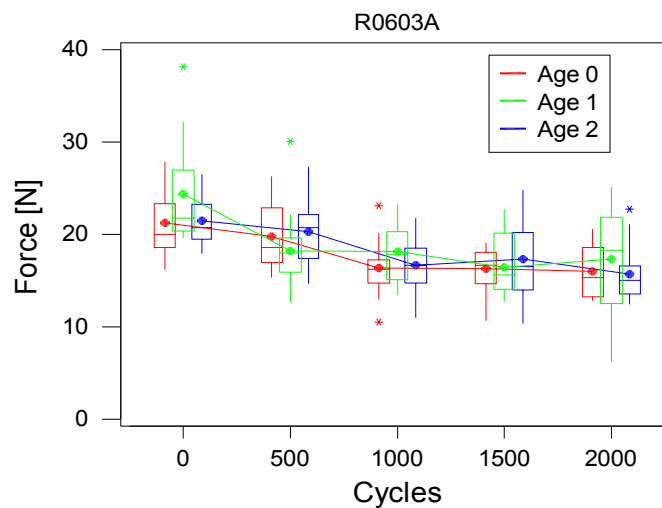


**Figure 9. Shear test measurements for R0603 components for three levels of solderability**

## 4 DISCUSSION

### 4.1 EFFECT OF COMPONENT SOLDERABILITY ON VISUAL INSPECTION AND PROCESS YIELD

Although for the R0603 and SOIC components the solder fillet rise deteriorated with ageing (see Figure 7), the change was minimal and all joints exhibited a fillet rise to the top of the resistors, or above the heel of the SOICs. Ageing the R1206 components did not affect the solder fillet rise. No joints on any component failed visual inspection or initial electrical test. Based on previous work with SnPb alloys [1], the levels of ageing chosen for the components were expected to produce a wider range of fillet heights. The better responses from the lead-free soldering process compared to SnPb systems, may be due to two factors. First, soldering temperatures are greater and this may promote better wetting of the components. Second, lead-free solder pastes are formulated with higher flux activity levels to cope with the typically hotter and longer profiles of lead-free soldering, and this could contribute to improved component soldering.

The yield for the BGA components, subjected to the Age 2 regime was poorer than that for the other ageing regimes, but perhaps not significantly greater than that for the as-received BGA components. However, micro-sections of the Age 2 BGA components indicated that the joint shape was significantly different after assembly (see Figure 10).



**Figure 10. Section of Age 2 BGA component after manufacture**

Further inspection of the as-manufactured BGA micro-sections indicated that the combination of the ageing process and lead-free assembly temperatures, resulted in significant deterioration of the component substrate (see Figure 11). The component base substrate had degraded and warped, causing the solder joints to be deformed. It is probable that this deformation had caused the reduction in the solder joint reliability, rather than any effect of the change in solderability. Whilst the ceramic chip resistor and

filled epoxy SOIC components were capable of surviving ageing at 155°C for extended periods, clearly this ageing procedure was inappropriate for the BGA components with BT resin substrates.

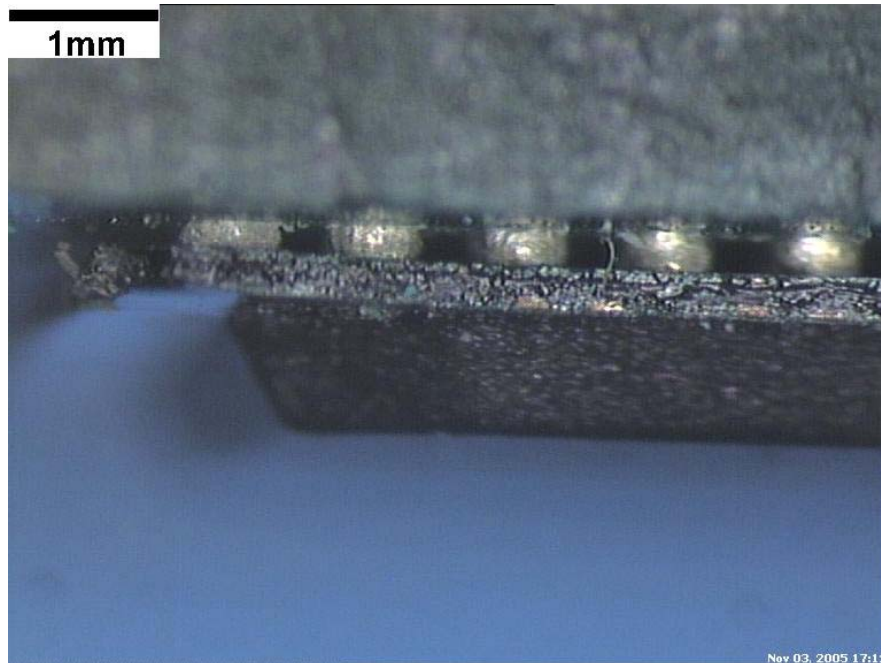


**Figure 11. Age 2 BGA component showing warped and degraded BGA substrate and deformed solder joints**

#### 4.2 EFFECT OF COMPONENT SOLDERABILITY ON RELIABILITY

Since there were no electrical failures associated with the R0603 or SOIC components, it was not possible to differentiate between the relative reliabilities of the differently aged components. The situation for R1206 components was similar: no differentiation was possible because of the low number of electrical failures obtained. However, the few failures that did occur, were concentrated in the samples with better solderability. Typical micro-sections of some of the R1206 components after 2000 thermal cycles are presented in Figures 12 to 14. The level of crack propagation within these samples is similar.

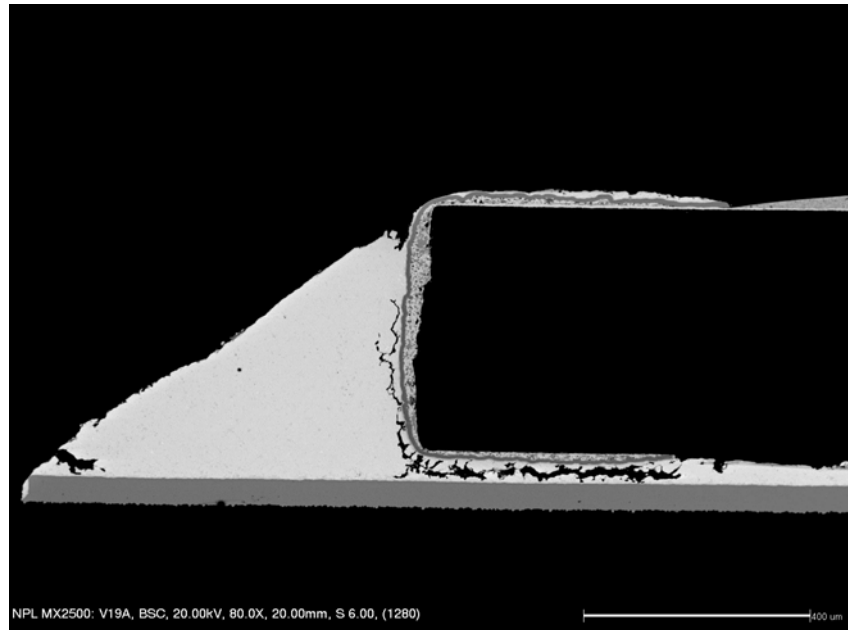


**Figure 12. Typical crack propagation after 2000 thermal cycles for  
as-received R1206 (pad design A)**

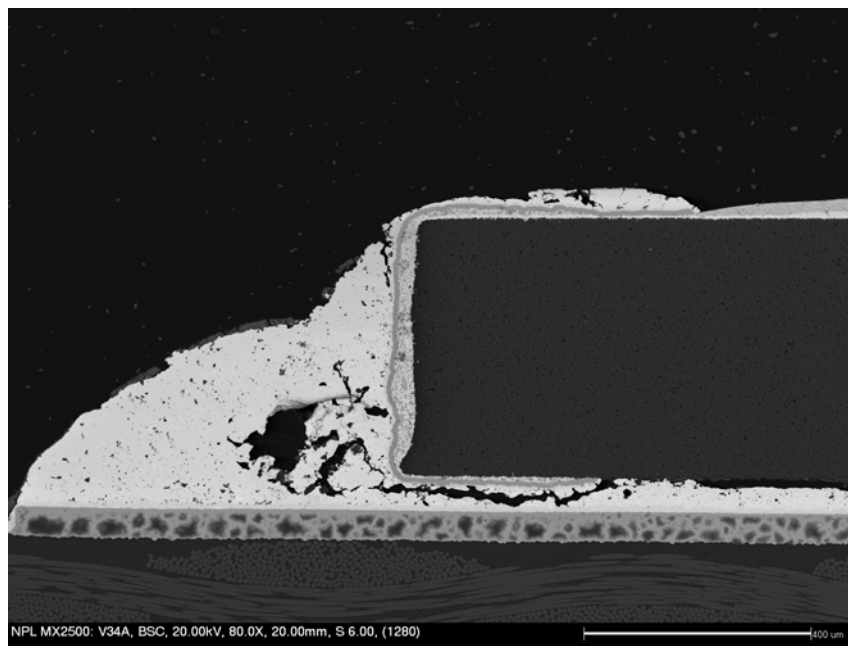


**Figure 13. Typical crack propagation after 2000 thermal cycles for  
Age 1 R1206 (pad design A)**

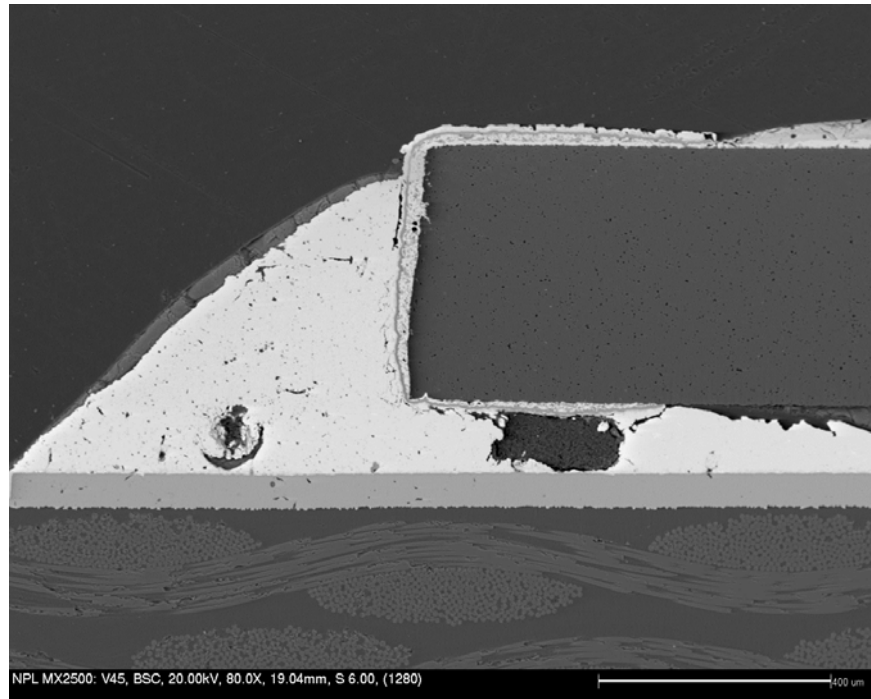


**Figure 14. Typical crack propagation after 2000 thermal cycles  
for Age 2 R1206 (pad design A)**

In the case of the BGA components, the effect of changing solderability was more noticeable. As previously discussed, there was a higher incidence of electrical failures for the Age 2 samples after manufacture, due to the damage to the component substrates.

As thermal cycling progressed, a higher incidence of electrical failures was noted in the Age 2 samples. This can be seen clearly in Figures 15 to 18, in which the development of failures in the respective BGA rings is represented graphically. These data are based on those in Table 3, but with the failures at 0 hours removed. This increased failure rate is particularly evident in the outer rings of the BGAs (rings A and B), where warping of the thermally damaged BGA component substrates, appeared to have caused the greatest joint distortion (see Figure 11).

Therefore, it is concluded that the solderability degradation levels utilised in this study, did not have a significant adverse effect on the reliability of the solder joints formed during thermal cycling to 2000 cycles.

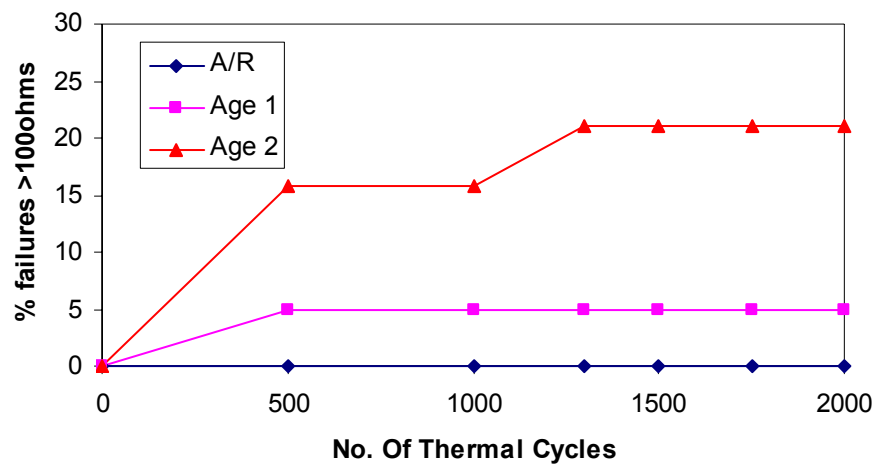


Figure 15. Cumulative failure rates in BGA A-rings for three component ageing up to 2000 thermal cycles

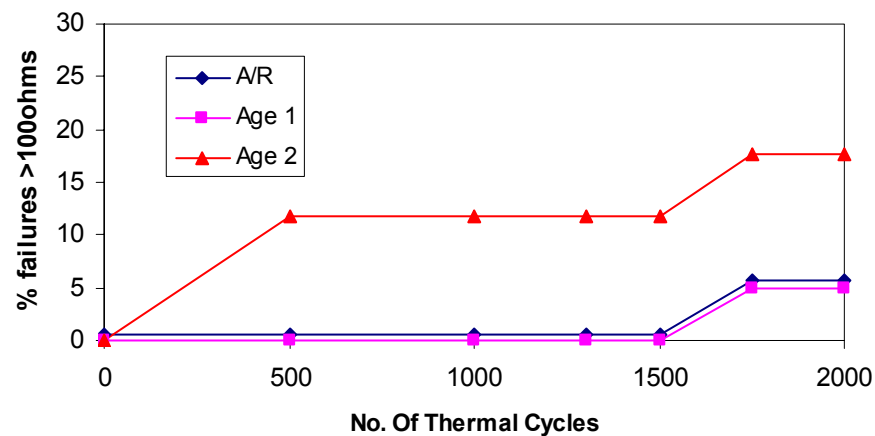


Figure 16. Cumulative failure rates in BGA B-rings for three component ageing up to 2000 thermal cycles

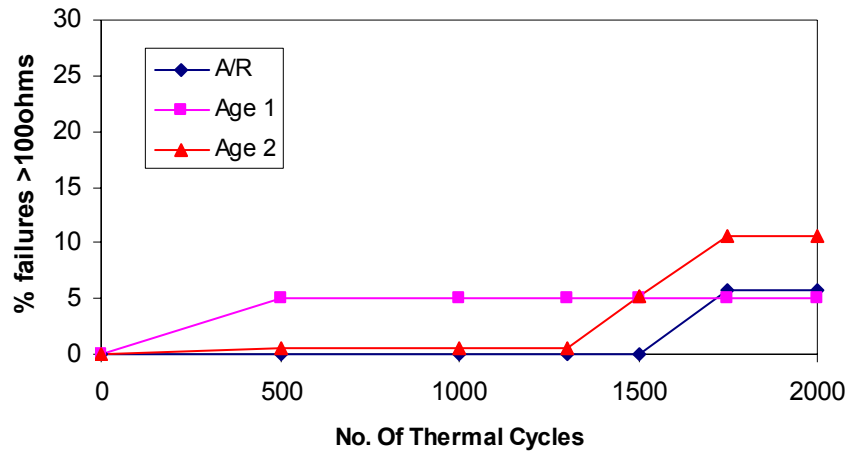


**Figure 17. Cumulative failure rates in BGA C-rings for three component ageing up to 2000 thermal cycles**

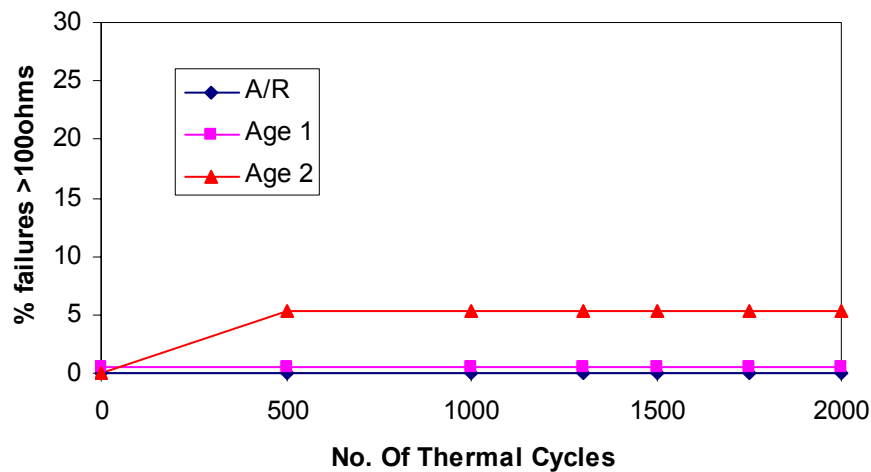


**Figure 18. Cumulative failure rates in BGA D-rings for three component ageing up to 2000 thermal cycles**

Micro-sections of thermally cycled BGA components of each of the three ageing regimes highlighted cracking of joints adjacent to the component interface (Figures 19 to 21). That this cracking occurs is not surprising, since the component pads were solder mask defined, causing a stress concentration close to the component pad. Clearly, the degradation of the Age 2 components had at least contributed to the lower reliability of these devices. Hence it is not possible to draw any conclusions as to the effect of component solderability on the reliability performance of BGA components.

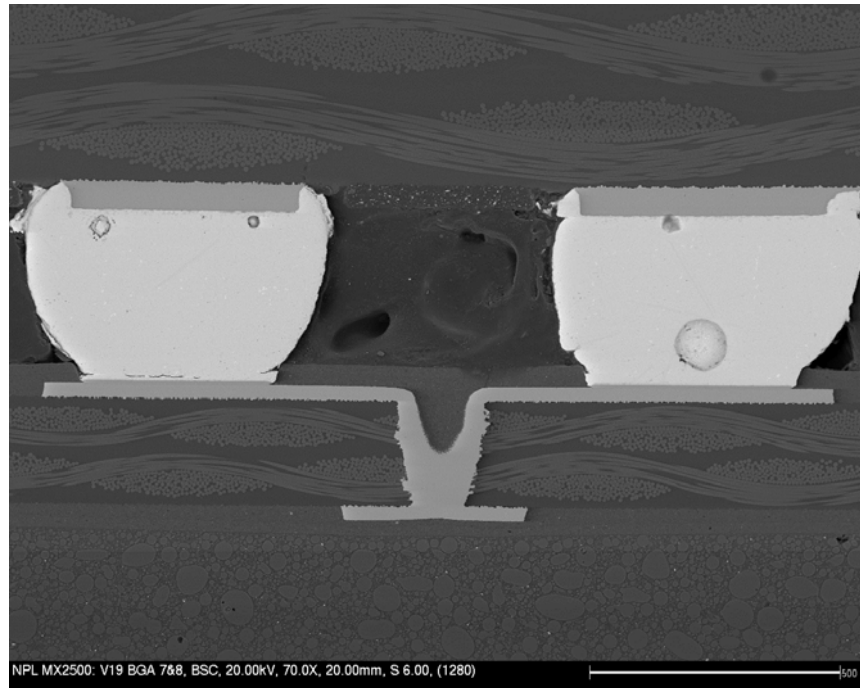


**Figure 19. Micro-section of as-received BGA component after  
2000 thermal cycles (PCB uppermost)**

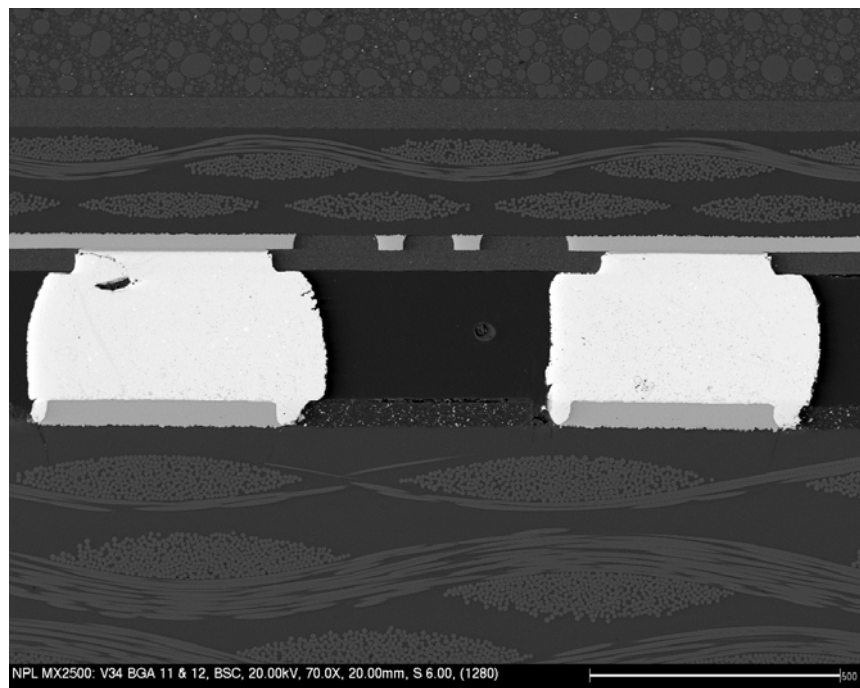


**Figure 20. Micro-section of Age 1 BGA component after  
2000 thermal cycles (component uppermost)**

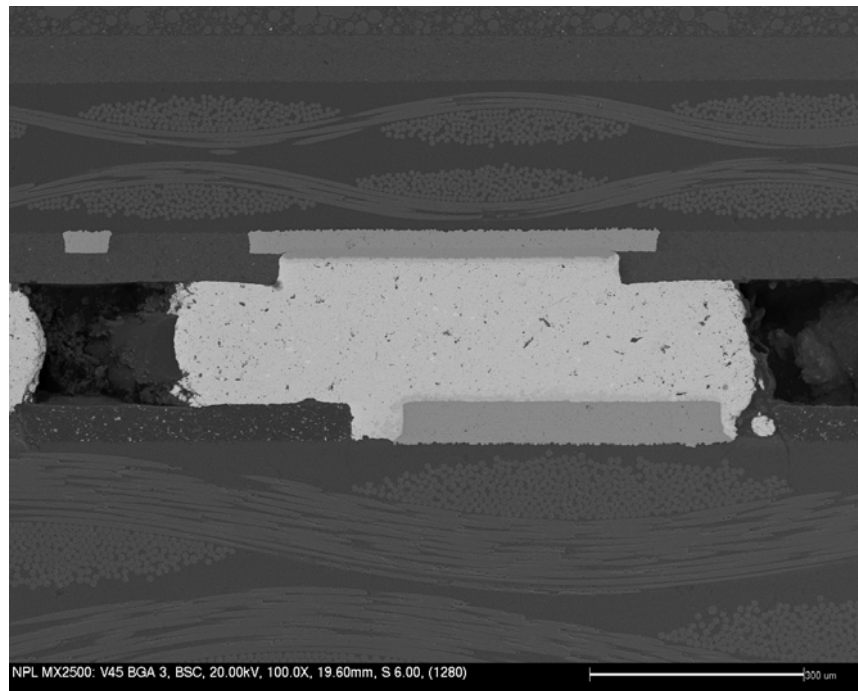


**Figure 21. Micro-section of Age 2 BGA component after  
2000 thermal cycles (component uppermost)**

## **5 CONCLUSIONS**

Lead-free finished components (resistors, SOICs and BGAs) were artificially aged at 155°C to produce three finishes of different solderabilities. These components were then assembled to test vehicles. For the R0603, R1206 and SOIC components, the reduced solderability had little effect on the yield of the process, with no defective joints produced. Previous NPL work with SnPb solder and SnPb components similarly aged, showed a much greater effect on solder joint fillet rise. This improvement for lead-free assembly may be a result of two factors. First, soldering temperatures are greater and this may promote better wetting of the components. Second, lead-free solder pastes are formulated with higher flux activity levels to cope with the typical hotter and longer profiles of lead-free soldering, and this could contribute to improved component soldering.

For the BGA components, the artificial ageing process significantly adversely affected the components, causing degradation and warping of the component substrate. The resultant electrical test yield for the Age 2 components was poorer than that for the other component ages, but perhaps not significantly greater than that for the as-received components. However, micro-sections of the Age 2 BGA components indicated that the joint shape was significantly different after assembly, with the joints compressed.

The assemblies were subsequently thermally cycled to 2000 cycles. For the R0603 or SOIC components, there were no electrical failures in any of the three test groups, so it was not possible to differentiate between the relative reliabilities of the joints from the differently ages of components. Moreover, there were few electrical failures for the

R1206 components, so again no differentiation was possible between the reliability of the three groups of aged components. Micro-sections of R1206 components after 2000 thermal cycles exhibited similar levels of crack propagation, again providing little differentiation between the components of different solderability.

For the BGAs, the effect of changing solderability was more noticeable. As thermal cycling progressed, a higher incidence of electrical failures was noted in the damaged Age 2 samples. This increased failure rate was particularly evident in the outer rings of the BGAs (rings A and B), where warping of the BGA component substrates associated with the ageing process, had caused the greatest distortion. Micro-sections of BGA joints after 2000 cycles highlighted joint cracking in samples of all three ages, close to the component interface. This is not surprising, since the component pads were solder mask defined, causing a stress concentration close to the component pad.

*It is concluded from this work that, the range of typical solderabilities experienced by end users on good quality surface mount components, should not represent a problem in manufacturing yields (or subsequent reliability) in a well controlled lead-free process.*

## 6 ACKNOWLEDGMENTS

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 would like to thank Madeleine Peck for her assistance with micro-sectioning and SEM imaging, and Loctite Multicore for supply of solder paste.

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