

Compatibility of Lead-free Solders with PCB Materials

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ABSTRACT:

This report presents the results of an evaluation of the compatibility of some lead-free alloys with other materials currently used in pcb assembly (flux systems, lead-tin solder, board and component finishes), and the consequential effects on the joint reliability. Three techniques have been used in these investigations: electrical continuity measurements, shear testing, and observations of microstructural changes. Test boards were generated under a matrix of assembly conditions (three component termination styles, five board finishes, and three solders), and subsequently comparative data were acquired following thermal exposure of the boards (-55 to +125°C for up to 2200 cycles). The work has benefited from the use of a new accelerated test method to obtain failure data in timescales much less than those traditionally experienced.

The electrical continuity findings indicated that for the larger components (2512-type resistors) the larger strain range can be better accommodated using traditional SnPb solder than using the new lead-free alloys. By contrast, when the strain range was smaller (e.g. with 0603-type resistors or SOIC devices) the lead-free solders were as good as, or better than, the traditional SnPb solder. There appears to be a benefit of adding Bi to the SnAgCu solder. The shear strength tests demonstrated that, over all the test cycle regimes used, the joints made using lead-free solders were stronger than those made using traditional SnPb solder. In the as-formed condition the ultimate shear forces required to break lead-free joints were significantly higher than those required to break lead-containing joints.

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ISSN 1473 2734

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head, Materials Centre

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1 INTRODUCTION

There is general agreement that whatever the drivers, be they legislative, technological or commercial, lead-free soldering will become the industrial norm in the next few years. However, one of the key concerns in embracing lead-free soldering technologies is the lack of data relating to (a) the compatibility of the lead-free solders with the other materials used in the assembly, and (b) the reliability of such solder joints under the various service conditions throughout a range of industrial applications. Such data are critical, not only in the understanding of the underpinning science, but also in being able to assess potential service performance, and/or predict life via modelling. Hence there is increased industrial interest in acquiring such compatibility and reliability data for these new soldering systems.

Traditionally, reliability data have been generated using accelerated test regimes (often temperature cycling), and a convenient test method such as electrical continuity testing. However, the latter does have a significant drawback in that it depends on a complete electrical failure (an open) before any defect is registered, and this is often after a large number of cycles. In practice the strength of the joint can be seriously compromised by any defect (especially cracking) long before it affects its electrical performance; such prolonged cycling is therefore wasteful in both time and effort.

The objectives of this work were therefore

- to generate credible data on the compatibility of some lead-free solders with the materials used in pcb assembly
- to generate some associated reliability data
- to recommend a new test method by which credible data can be acquired in timescales shorter than those traditionally experienced.

Both the data themselves, and the method of acquiring them, would hold potential benefits for those who use modelling to predict service performance and life. Such a move towards a greater use of modelling is also being spurred by the increasing cost of practical experiments, the wide choice of lead-free solders, the variability of joint geometries, and the increased capability of modelling and the reduced cost of computing time (see References 1-3).

Electronics assemblies are manufactured from a range of materials with different coefficients of thermal expansion (CTEs) – see Figure 1. As these assemblies experience temperature/power changes during use (power consumption; switching product on/off; day/night temperature changes) the CTE mismatches place shear strains on the various components in the assembly, which can result in joint failure and hence compromise the reliability of the product. Temperature cycling can therefore be used to accelerate the stresses in the solder joint, which to some extent are relieved by strain creep in the joint.

A traditional method for assessing reliability is to use electrical continuity measurements, which provide a technique in which a large number of joints can be monitored. However, the technique is dependent on a complete electrical failure occurring before any defect is registered, which can be a severe disadvantage when more than 2000 cycles may be required

to reach a failure. A complementary technique is the measurement of the solder joint strength, which is based on shear testing of solder joints to evaluate assemblies that have been through accelerated thermal cycling, has recently been used for reliability assessment and lifetime prediction (1). This approach is based on the premise that the solder joint strength is a complex function of microstructural damage, and specifically the degree of crack propagation. In order to enhance the failure rate, and obtain data in the shortest timescales, known “weak links” are usually selected for the tests. These “weak links” are components in which the CTE mismatch is high, and in which early joint failures might be expected, and for which failures have been reported in commercial product. Typical examples are ceramic resistors (in which the mismatch increases with size from 0603-type to 2512-type), BGAs, flip-chips and TH connectors, and these components have been used in the present study.

As the assembly is used in service creep stresses accumulate in the solder joint as a direct result of the CTE mismatches. When the value of creep stress exceeds that of stress relaxation, micro-cracks are initiated, usually in the region of the solder-termination interface under the component. As the shear strain is increased still further, more micro-cracks arise, and propagate through the solder towards the outer surface of the solder fillet. This micro-crack growth and propagation are followed by changes in the mechanical and electrical properties of the joint.

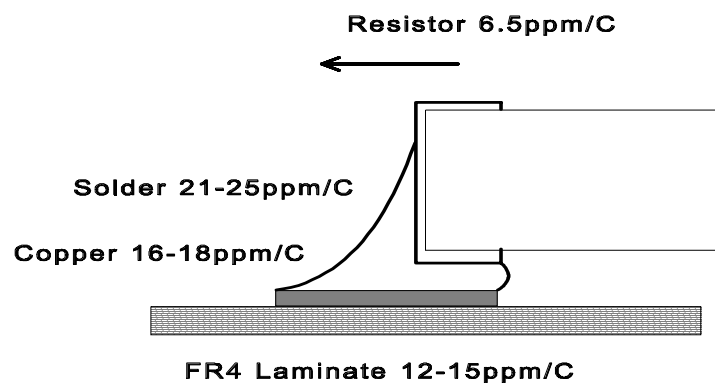


Figure 1. X-axis CTE mismatches in SM assemblies

2 EXPERIMENTAL

2.1 Assembly and materials

The material experiment matrix is shown in Table 1.

Table 1. Test board matrix and number of boards assembled.

Number of manufactured boards		Board finishes					Process
		Cu OSP	HASL	Immersion Sn	Immersion Ag	AuNi	
Alloys	Sn63Pb37	10	7	7	5	6	Reflow
	Sn95.5Ag3.8Cu0.7	11	6	5	6	5	Reflow
	Sn93.5Ag3.8Bi2Cu0.7	8	7	8	5	5	Reflow
	Sn95.5Ag4Cu0.5	11	5	5	7	7	Wave

The test pcb was a double-sided FR4 substrate (with a photo-imagable resist) and of dimensions 122 x 113 x 1.6 mm. The board layout is shown in Figure 2. The thickness of the conductive copper foil was 35 μ m, and five different board/pad finishes were employed – HASL (SnPb), AuNi, Ag, Sn and Cu (OSP). Reflow soldering was carried out using two lead-free solders benchmarked against SnPb, and one lead-free solder was used for the wave soldering exercise.

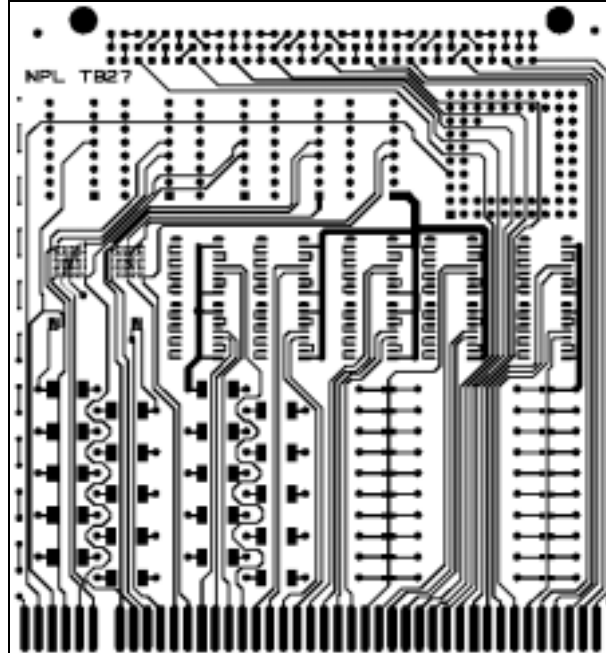


Figure 2. Test board layout, size 152 x 152 x 1.6 mm

Photographs of assembled boards are shown in **Appendix A**. Each assembled board incorporated 20 off 2512-type resistors, 20 off 0603-type resistors, 40 off TH resistors, 2 off BGAs (ball grid arrays), 2 off CSP (chip scale package) devices, 10 off SOICs, 20 off DIPs (dual-in-line package), one PGA (pin grid array) and one 3x32 pin connector. All the

components were connected to the edge connector to enable electrical continuity measurements. This pcb and other designs are available from www.npl.co.uk/npl/ei.
Printing process

The stencil used in the solder paste printing process was made from stainless steel, generally 100µm thick, but in the connector area the thickness was increased to 200µm using an additional nickel foil glued to the stencil. The solder pastes were printed using an automatic printing machine in a temperature/humidity controlled chamber, with constant temperature (22°C) and humidity (40%RH). The stencil design is shown in Figure 3, in which the three alignment fiducials allowing precision alignment, are clearly indicated.

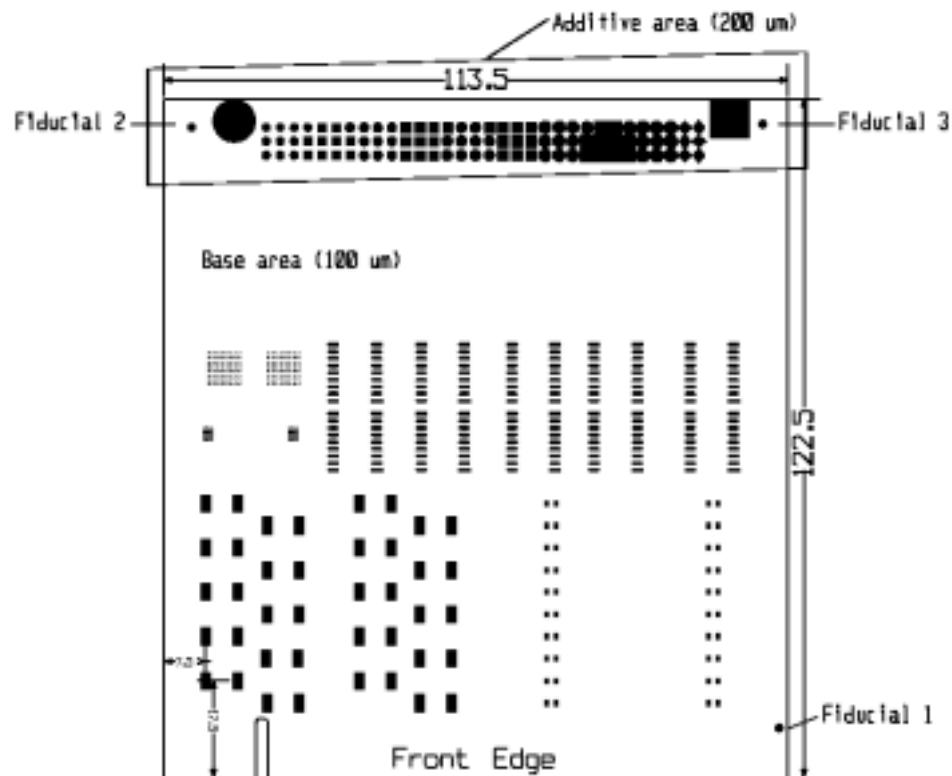


Figure 3. Stencil design for test board

Component assembly

The BGA and CSP components were pre-baked in a laboratory oven for approximately one hour at 125°C to prevent “pop-corning” and/or blistering from entrapped moisture. All the SM components were placed using an automatic pick & place system. The through-hole components such as resistors, PGAs, DIPs and connectors were placed manually. In addition, the components to be wave soldered were attached to the boards using a surface mount adhesive (SMA), which was dispensed from an automatic dispenser. The curing process was carried out in a laboratory oven at 150°C for 90 minutes.

2.2 Reflow soldering trials

Two lead-free solder pastes (Sn95.5Ag3.8Cu0.7 and Sn93.5Ag3.8Bi2Cu0.7) were used in the reflow soldering exercise, benchmarked against traditional tin-lead (Sn63Pb37). All the solder pastes were described as no-clean flux based. A summary of the components used in this study is presented in Table 2. The boards were soldered in a convection reflow oven with five temperature zones, and the relevant temperature profiles are shown in Figures 4 and 5.

Table 2. Summary of the components used in the reflow soldering trials (75 pcbs)

<i>Components</i>	<i>Components per board</i>	<i>Detection channels per components</i>	<i>Finish alloy</i>	<i>Quantity per experiment</i>
PBGA 64 (8 x 8 mm)	1	4	SnPb	75
PBGA 64 (8x8mm) Pb-free	1	4	SnAgCu	75
Connector 3 x 32 intrusive	1	10	Sn	75
SOIC resistor network	10	2	SnPb	750
2512 resistor	20	1	SnPb	1500
0603 resistor	20	1	SnPb	1500
CSP (2x2.5 mm)	2	1	SnPb	150
Total number of components	55			4125

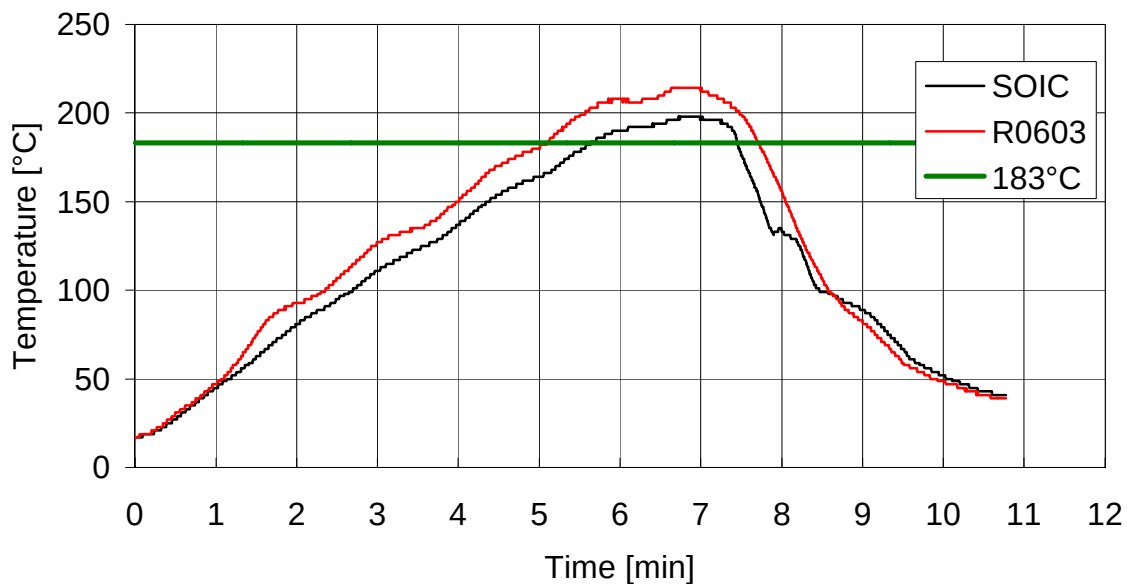


Figure 4. The reflow temperature profile used for the SnPb solder alloy

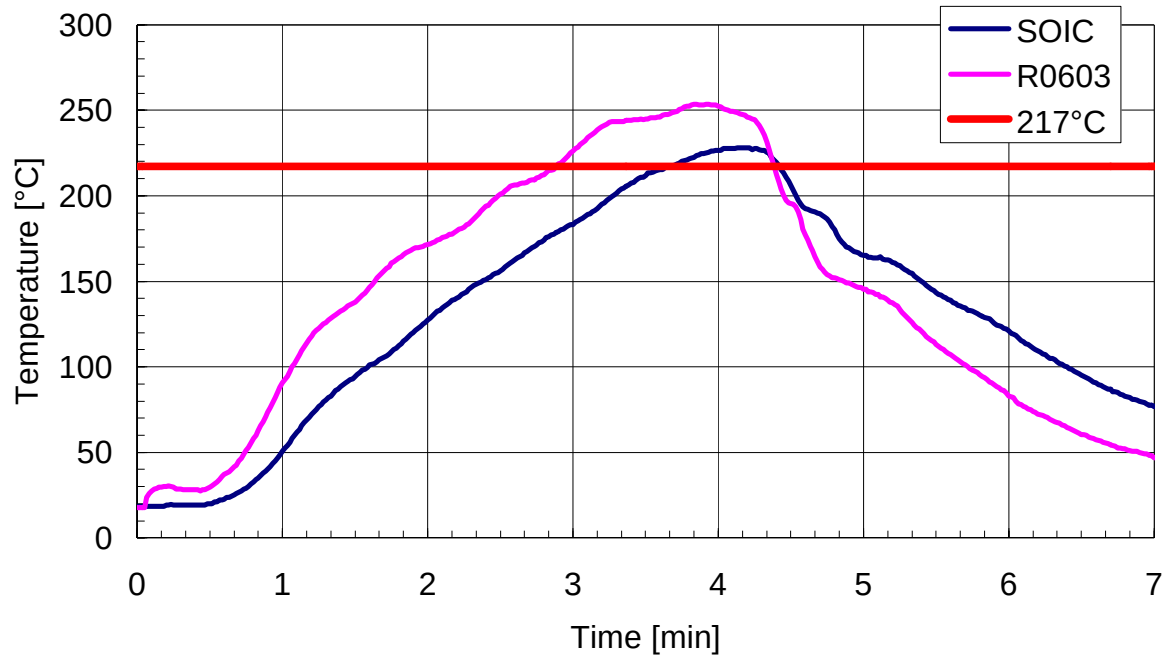


Figure 5. The reflow temperature profile used for lead-free solder alloys

The profiles labelled SOIC were the temperature profiles for the “coolest” place on the boards (board centre), as indicated by a measurement thermocouple attached to an SOIC component lead. The profiles labelled R0603 were the temperature profiles for the “hottest” location on the board (board edges), as indicated by a thermocouple attached to an R0603 component termination. The horizontal lines marked 183°C (SnPb) and 217°C (SnAgCu) refer to the melting points of the respective solder alloys.

2.3 Wave soldering trials

One lead-free solder alloy, Sn95.5Ag4Cu0.5, was used in the wave soldering trials. The speed of the conveyor was 1.2m/min, with a soldering temperature of 250°C, i.e. a superheat of around 35 degrees depending on the lead-free solder under test. To ensure good wetting of the joined surfaces rosin free flux (RF 800T) was applied by spraying across the board and solder wave. A summary of the components used in this study is presented in Table 3.

Table 3. Summary of the components used in wave soldering trials (25 pcbs)

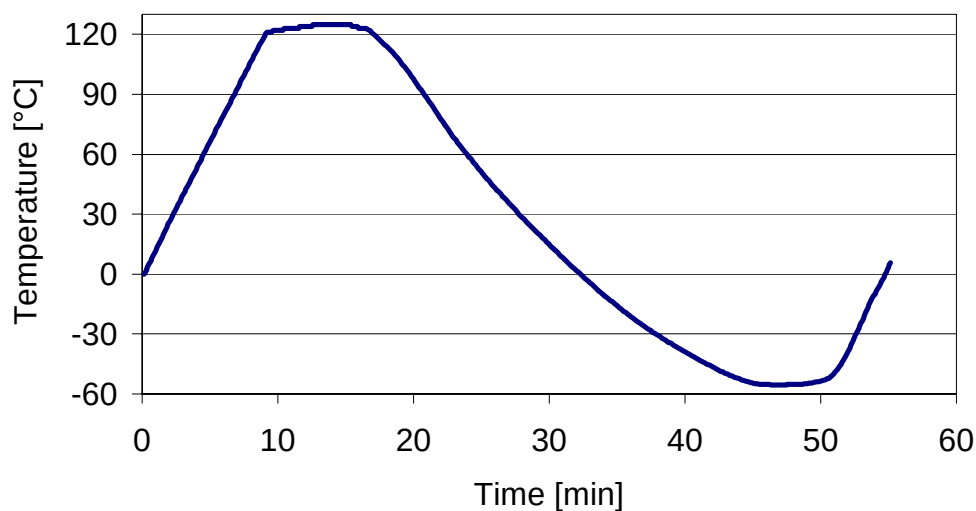
<i>Components</i>	<i>Components per board</i>	<i>Detection channels per components</i>	<i>Finish alloy</i>	<i>Quantity per experiment</i>
SOIC resistor network	10	2	SnPb	250
DIP resistor network	5	2	NiPd/Sn	125
2512 resistor	20	0.5	SnPb	500
0603 resistor	20	0.5	SnPb/Sn	500
PGA	1	1	AgCu	25
TH resistor	40	0.5	SnPb	1000
Total number of components	96			2400

3 TEST METHODS AND RESULTS

Three techniques were employed to assess the performance of the solder joints using a thermal cycling experiment in which the thermo-mechanical fatigue properties of the solders were evaluated:

- Electrical continuity measurements
- Shear testing
- Microsectioning, and microstructural analysis

The boards were thermally cycled employing the profile presented in Figure 6. This was selected on the basis of being widely used throughout industry, particularly within the military and automotive sectors. There were two temperature dwell points, -55°C and 125°C, with a five minute dwell duration, the latter being defined as the time during which the temperature in the oven was within $\pm 5^\circ\text{C}$ of the set value.

**Figure 6. Temperature cycling regime used**

3.1 Electrical continuity measurement

Electrical continuity measurement is a well established DC method used for assessing solder joint reliability for many years. Although this method has the advantage that a large number of joints can be monitored, it is dependent on a complete electrical open circuit occurring before any failure is registered. It does not give any indication of a weakened joint. There are two basic methods of carrying out the test, viz:

- static (periodic) monitoring
- dynamic (continual) monitoring

Each method has specific advantages and disadvantages in terms of the data generated. In the **static monitoring** mode multiple boards can be tested sequentially using only one measuring connector, thus allowing a large number of specimens to be assessed. However, it has the disadvantage that there is a low confidence level in detecting the first failure, and hence the recorded number of cycles to failure will be higher, the actual level depending on the measurement frequency.

The advantage of **dynamic monitoring** is the high probability of capturing a failure. The limitations of this approach are related to the monitoring capacity, which is restricted by the number of monitored channels, and hence the number of boards in the tests. Another possible issue is the integrity of the board connections in the test chamber, which are also exposed to the thermal cycling regime.

In this study the static (periodic) monitoring was implemented using a measurement period of 100-200 cycles with measurements at room temperature. Each board was connected through an 80-way switch bridge to a multimeter, and the measuring current was kept below 1mA since a higher current could partially melt any fractured solder joint. To limit the current, a resistor R_s was used. Additionally, to restrict the time of measurement, another resistor R_p ($\geq 1M\Omega$) was connected in parallel across the measured device (DUT) as shown schematically in Figure 7.

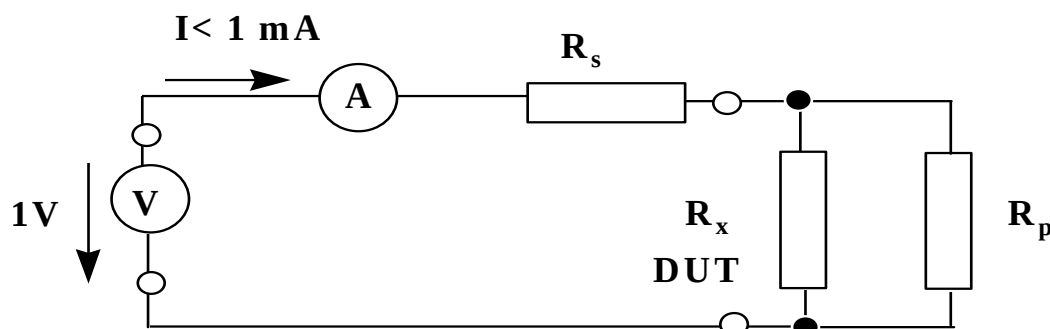


Figure 7. Schematic circuit used for electrical continuity testing (R_s - serial resistor, R_p -parallel resistor, DUT - device under test)

A pragmatic approach was taken in defining the pass/fail criterion. A failure was assumed (and recorded) when a channel resistance increased by 5% above its nominal value. In practice, when failure occurs the resistance increases by several orders of magnitude over a very short

time. To maximise the usefulness of the data, it is appropriate to fit a Weibull distribution to the data for each component, a procedure that was carried out in this study. Three common ranking factors for Weibull distributions were used as appropriate metrics i.e. $N_{f,50\%}$, the median number of cycles (50 % cumulative failures), $N_{f,62.3\%}$, the characteristic number of cycles (62.3 % cumulative failures), and shape factor β - see References 4-7. Typical results are presented in Appendix B.

A schematic of the apparatus used for the electrical continuity testing is given in Figure 8. The measurements were computer controlled using LabVIEW® software. The computing multimeter SI 7151 was used either for monitoring board temperatures while thermal cycling was in progress, or for electrical continuity measurements for the 100-200 cycles periods. A switch system Keithley 7011 allowed selection of the proper measurement channel. Both instruments were connected to a computer using IEEE-488.2 communication protocol and controlled by LabVIEW® applications. Data generated from both measurements were stored as ASCII files ready for later analysis.

Some of the boards were removed from the cycling experiments for microsectioning and shear testing.

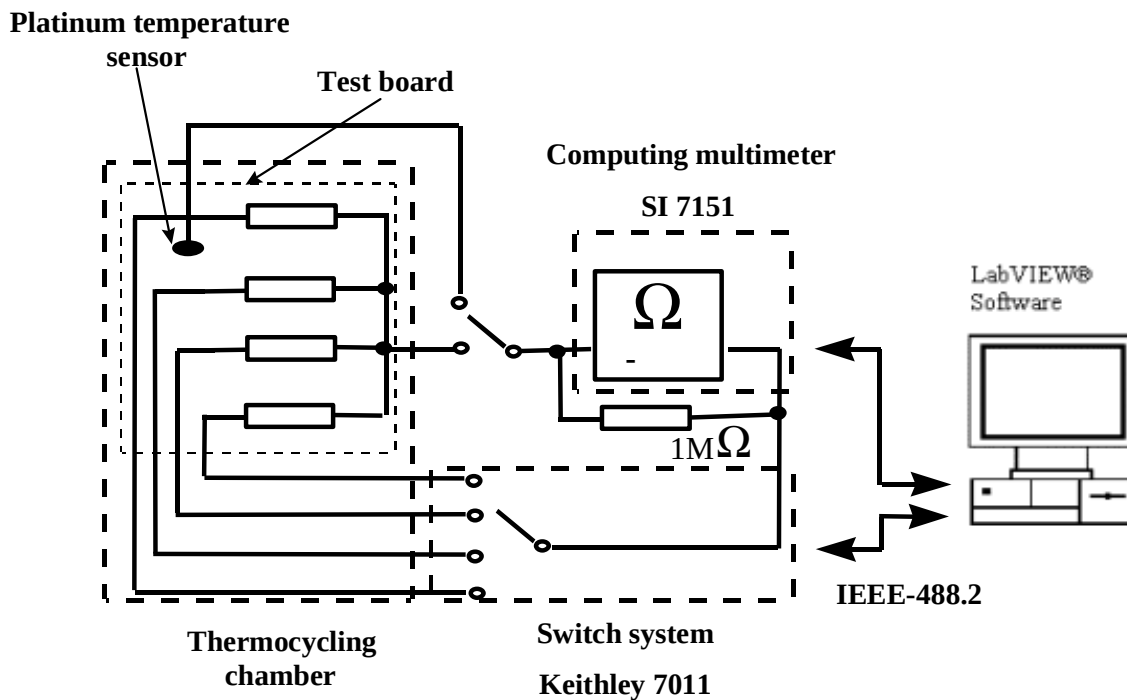
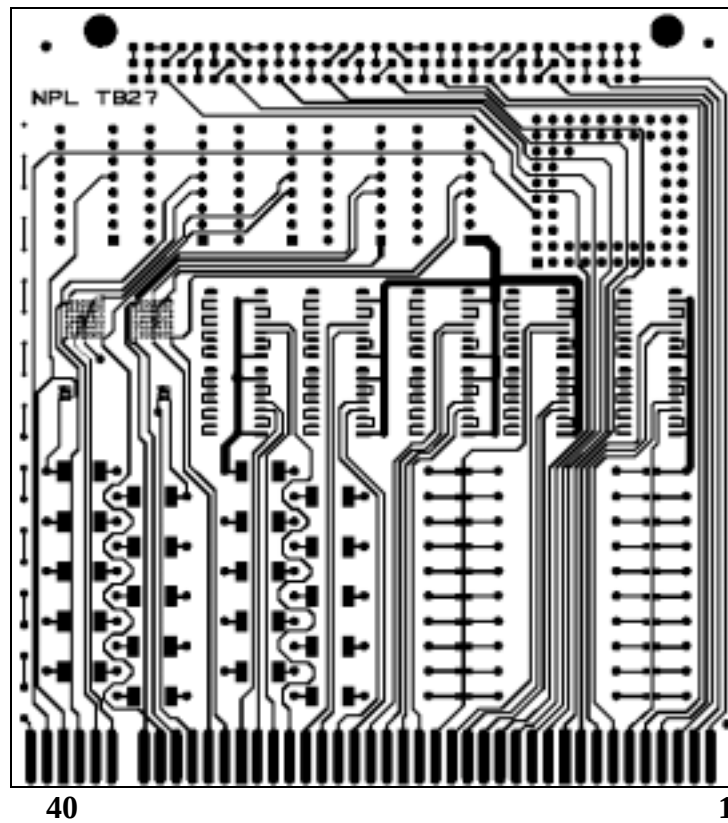


Figure 8. Schematic of electrical continuity testing apparatus

Table 4. Component - channel assignment

Component	Channel
R2512/TH resistor	1-20
R0603/TH resistor	21-40
CSP1/DIP1	41
BGA/DIP 2	42,43
BGA/DIP 3	44,45
BGAf/DIP 4	46,47
CSP 2	48
BGAf/DIP 5	49,50
SOIC1	51,52
SOIC2	53,54
SOIC3	55,56
SOIC4	57,58
SOIC5	59,60
SOIC6	61,62
SOIC7	63,64
SOIC8	65,66
Connector	67-71
SOIC9	72,73
SOIC10	74,75
Connector	76-80



3.1.1 2512-type resistors results

The electrical continuity results give a clear indication of the differences in performance of the tested solder alloys when combined with different pcb finishes. For ease of presentation and to illustrate the effect of **board finish on reliability** (i.e. cumulative failures), the results in Figure 9 are averaged over the three solder alloys used in the reflow trials (i.e. Sn95.5Ag3.8Cu0.7; Sn93.5Ag3.8Bi2Cu0.7; Sn63Pb37). It is evident that boards with an OSP finish showed significantly higher cumulative failures compared with the other finishes, and this difference became apparent after only approximately 400 cycles. The other finishes performed considerably better than the OSP finish, exhibiting similar behaviours up to approximately 1500 cycles. Thereafter there was a demonstrable difference, with AuNi and HASL finishes being the most reliable. It is interesting to note that the same behaviour was observed with the wave soldering trials although the cumulative numbers of failures were, not surprisingly, much lower in all cases. (NB. In the case of the wave soldering trials there was only one lead-free solder used – hence the data are not averaged in the way they were for the reflow trials – Figure 10).

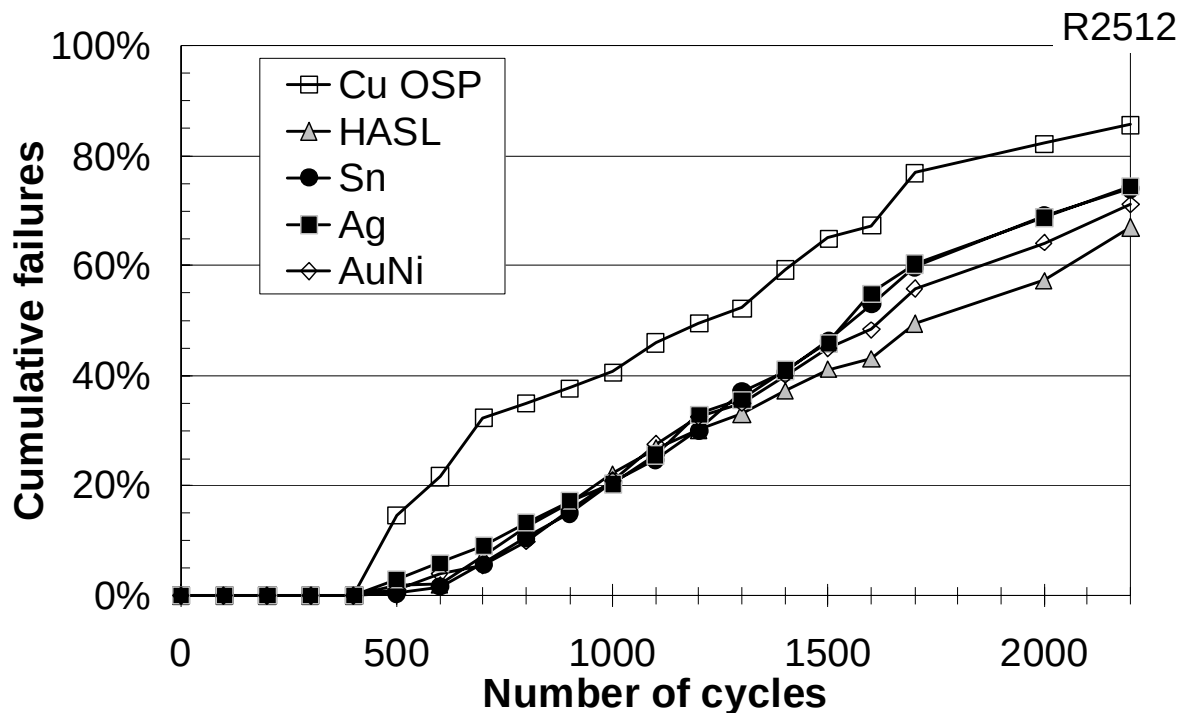


Figure 9. Cumulative failures for 2512-type resistors from reflow soldering trials (data averaged over 3 solder alloys)

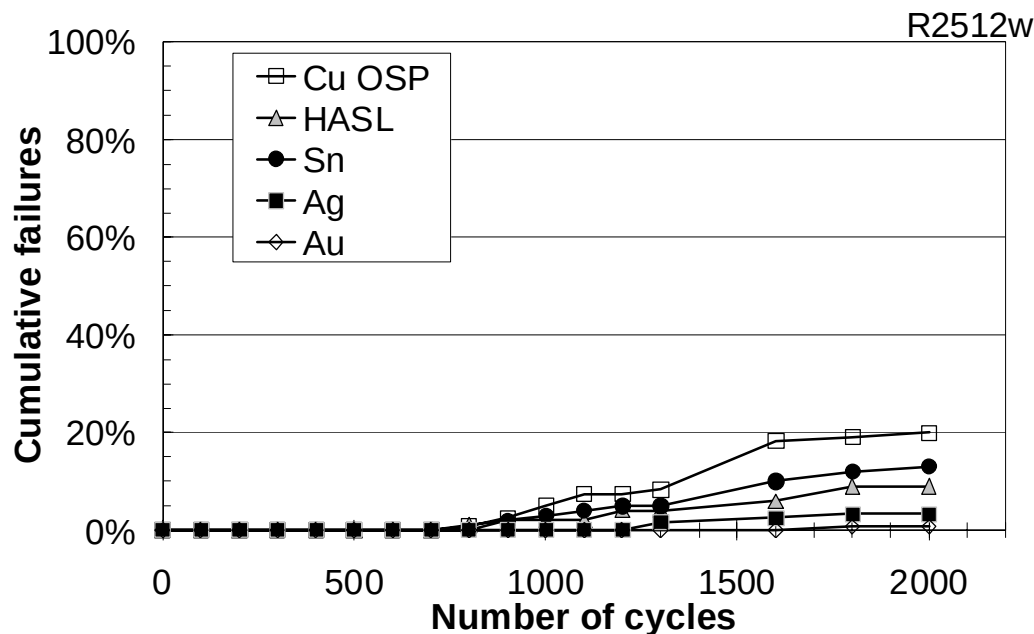


Figure 10. Cumulative failures for 2512-type resistors from wave soldering trials (data not averaged)

For ease of presentation and to illustrate the *effect of solder alloy on reliability* (i.e. cumulative failures) for the 2512-type resistors, the results in Figure 11 are averaged over the five board finishes used in the reflow trials. Again the electrical continuity results give a clear indication of the differences in performance of the solder alloys when combined with different pcb finishes, and that these differences were apparent after only 400 cycles. The results clearly demonstrated that SnPb performed the best and that SnAgCu performed the worst. The SnAgBiCu solder exhibited intermediate performance, the improvement over SnAgCu being attributable to the addition of the bismuth.

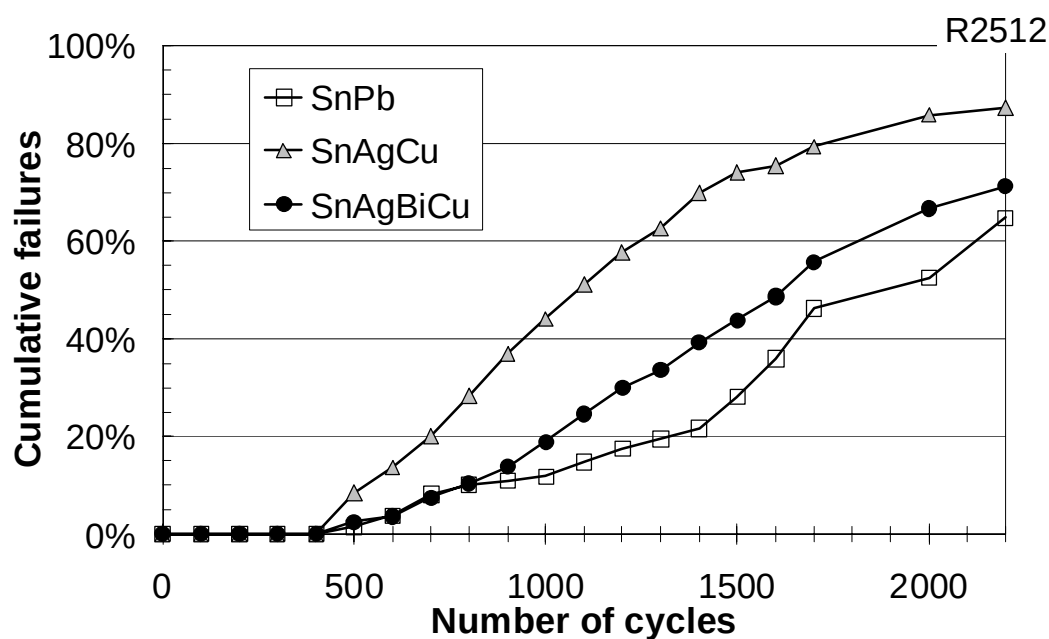


Figure 11. Cumulative failures for 2512-type resistors from reflow soldering trials (data averaged over 5 board finishes)

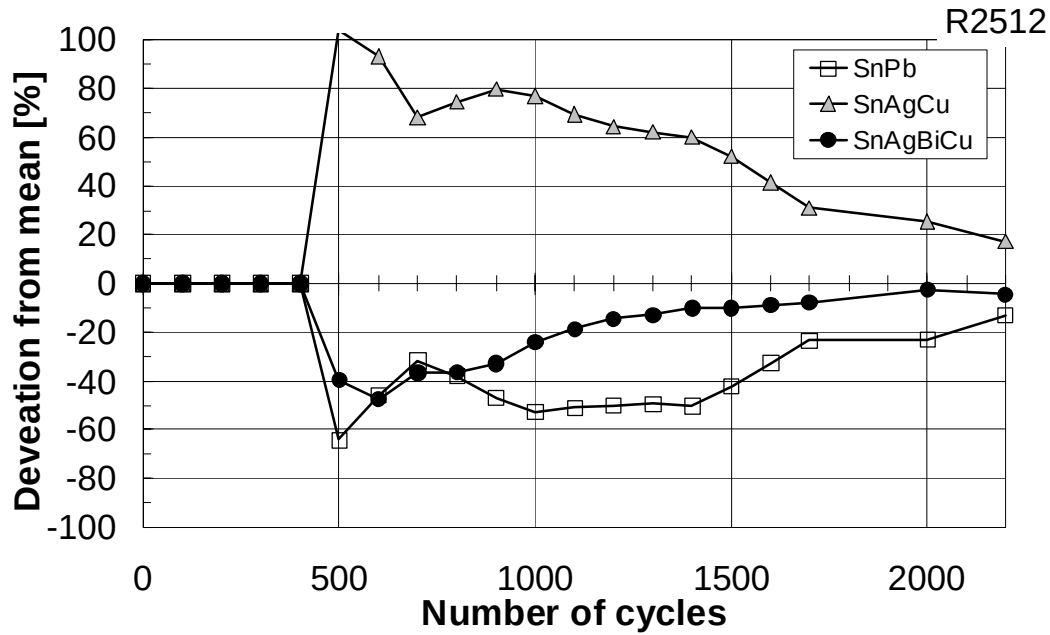


Figure 12. Deviation from mean of accumulative failures for 2512-type resistors from reflow soldering trials (data averaged over 5 board finishes)

Another useful way of highlighting the differences in performance between the various solder alloys, is to examine how each deviates from the mean of the cumulative results. In Figure 12 the relative deviations from the mean of all three alloys are plotted for the three solder alloys, with the results for individual board finishes again being averaged. A positive deviation indicates a poorer performance than the mean of all three alloys, and a negative deviation indicates a better performance. It is clear that the SnAgCu alloy shows the poorest performance, and SnPb the best, over all the 2200 cycles of this investigation.

The results of a Weibull fit are presented in Figure 13 and show the distribution of $N_{f,62.3\%}$ -characteristic life time, and ratio $(N_{f,62.3\%} / \beta)$ — for all combinations of soldering alloys and board finishes. β is the shape parameter from the Weibull fit, and indicates the range over which failures occur. A low value of β indicates failures over a wide range, whereas a high value indicates failure occurring over a short range, or nearly all at once. It is possible to infer from this that if β is high there is a single mode of failure, but with low β more than one failure mechanism may be occurring. For example, multiple modes may include failure of the solder joint, and failure of the bond between the component termination finish and body. Using β on its own while useful, does not give a good view of failure performance, whereas $(N_{f,62.3\%} / \beta)$ indicates when failure occurs and the range over which it occurs. Hence plotting $(N_{f,62.3\%} / \beta)$ against N_f reveals when failure occurs and the various modes and range over which failure happens. The best performance conditions occur when $(N_{f,62.3\%} / \beta)$ ratio is in the range of 600-800 and $N_{f,62.3\%}$ is a maximum. Under these conditions the performance of solder joints does not change too rapidly (β), while characteristic lifetime is high (N_f). In this case it is evident that the combinations of Au, Ag and Sn finishes with SnPb and SnAgBiCu solders exhibited the most promising optimal performance. It is interesting to note that the data for the SnAgCu solder alloy are clustered together with low $(N_{f,62.3\%} / \beta)$ values. This indicates failure occur over a smaller range. The SnAgBiCu alloy has significantly higher N_f and values the SnAgCu alloy, indicating the benefit of adding Bi to this alloy in this assembly and reliability test.

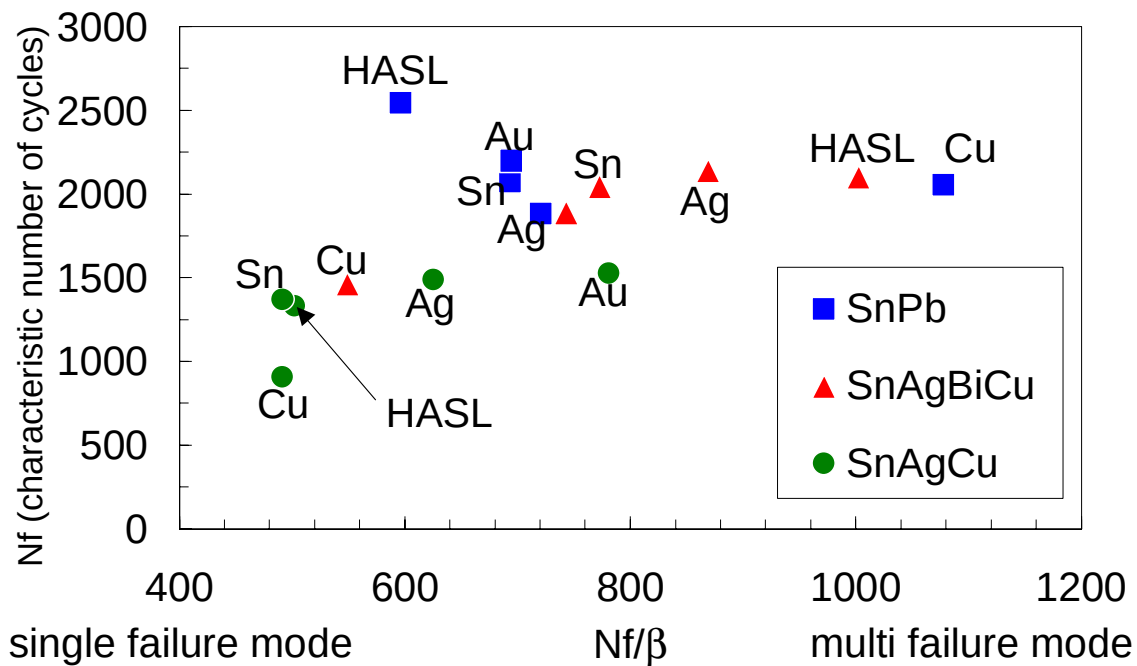


Figure 13. Weibull parameters for 2512-type resistors for reflow trials

3.1.2 0603-type resistor results

For ease of presentation and to illustrate the effect of **board finish on reliability** (i.e. cumulative failures), the results in Figure 14 are averaged over the three solder alloys used in the reflow trials. The results for the reflowed solder joints on 0603-type resistors displayed similar trends to those obtained on the 2512-type resistors. In particular, the joints associated with the OSP finish gave the poorest performance (i.e. had higher cumulative failures – Figure 14) than those associated with the other finishes. However, the level of cumulative failures was much lower (at ~25% after 2200 cycles) than that for the 2512-type resistors (at ~85% after 2200 cycles – see Figure 9), and was comparable to that obtained in the wave soldering trials (see Figures 10 and 15). The OSP finish in both reflow and wave trials the performance was the poorest.

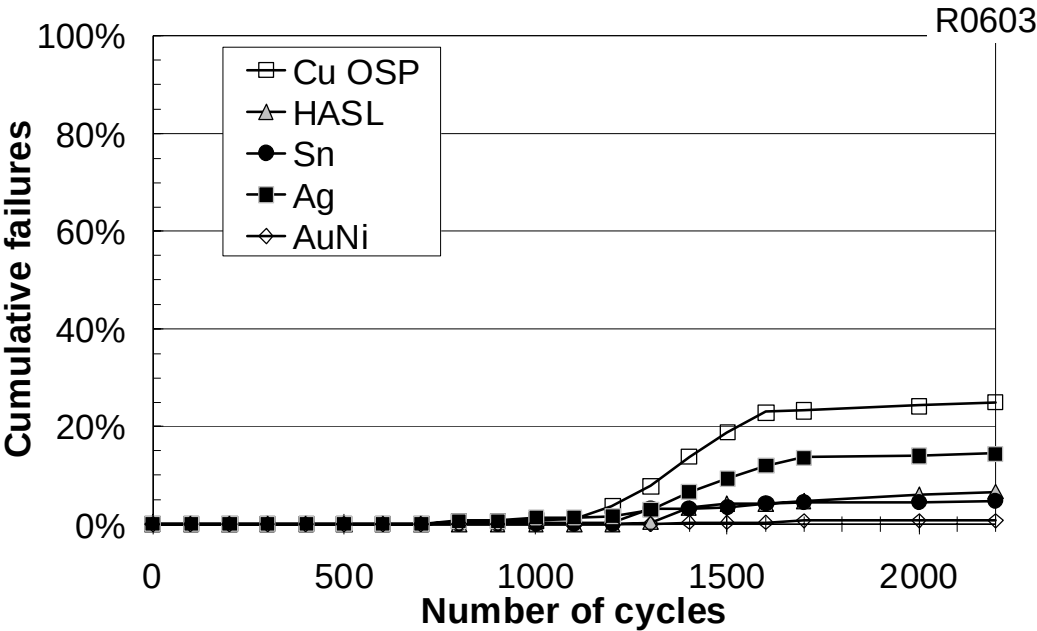


Figure 14. Cumulative failures for 0603-type resistors from reflow soldering trials (data averaged over 3 solder alloys)

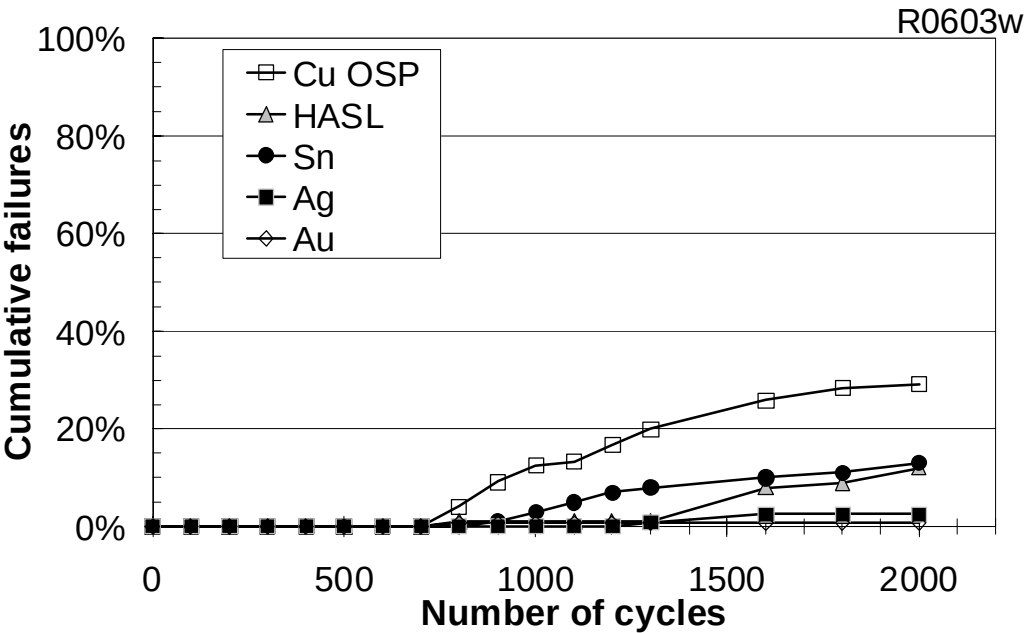


Figure 15. Cumulative failures for 0603-type resistors from wave soldering trials (data not averaged)

For ease of presentation and to illustrate the *effect of solder alloy on reliability* (i.e. cumulative failures) for the 0603-type resistors, the results in Figure 16 were averaged over the five board finishes used in the reflow trials. Once again the electrical continuity results highlighted a clear difference in performance between the three solder alloys, the difference becoming apparent after ~1300 cycles. Whilst the SnAgCuBi solder behaved in a comparable manner to the traditional SnPb solder, the SnAgCu solder alloy generated about twice the number of failures (see Figure 16).

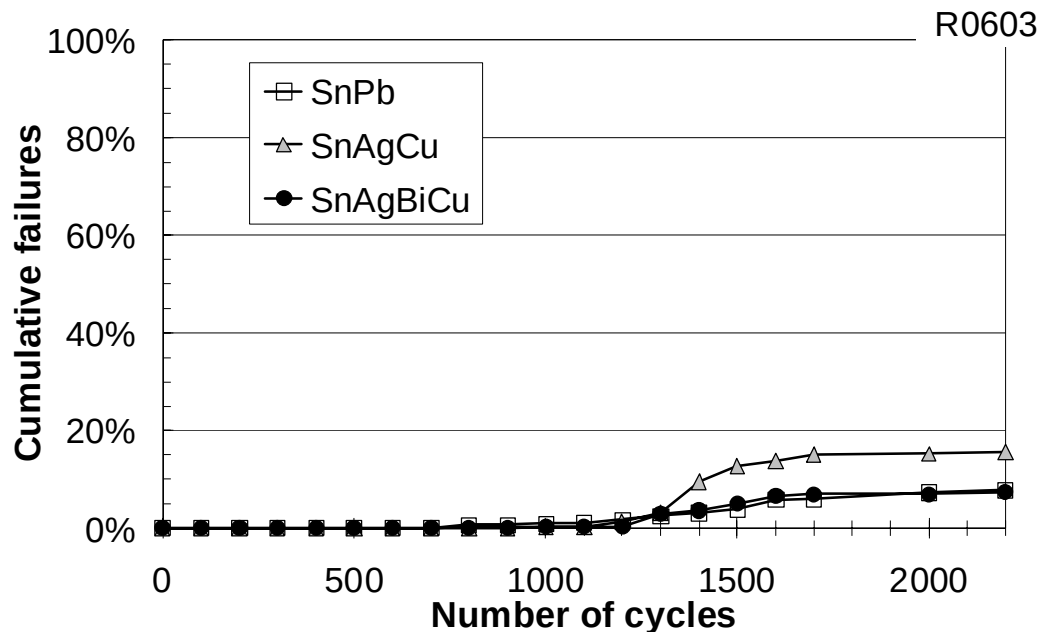


Figure 16. Cumulative failures for 0603-type resistors from reflow soldering trials (data averaged over 5 board finishes)

This behavioural difference was detected much earlier (at around 700 cycles) when the deviation from the mean of the cumulative failures was plotted against the number of cycles (see Figure 17) for each solder alloy. A positive deviation indicates a poorer performance, whilst a negative deviation indicates better performance than mean of all three alloys. In these results the SnPb showed poor performance from 700 to 1300 cycles, where after the SnAgCu alloy had the poorest performance.

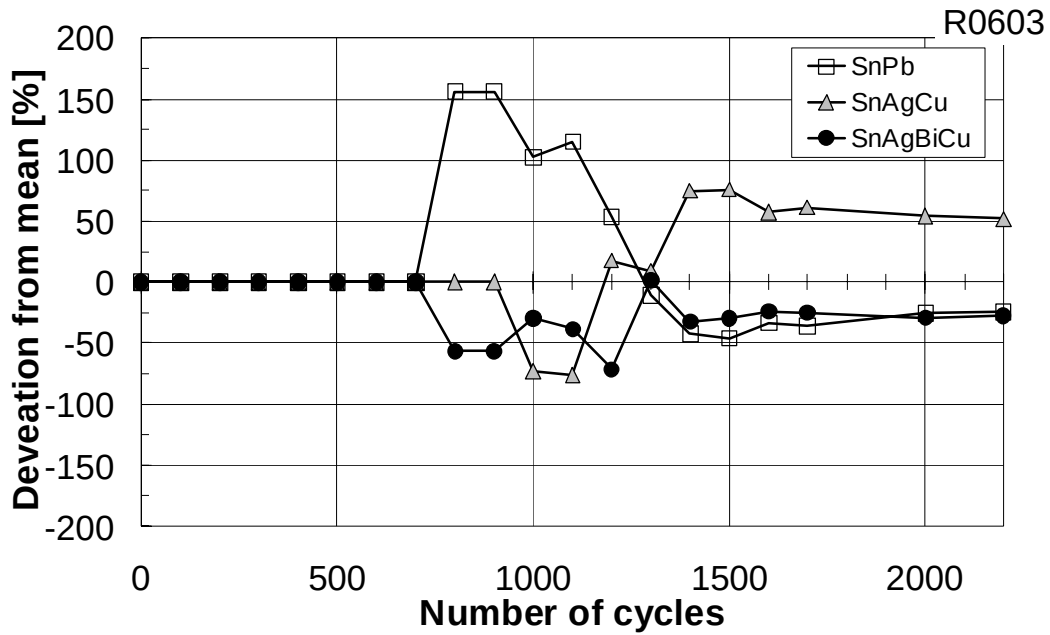


Figure 17. Deviation from mean of accumulative failures for 0603-type resistors from reflow soldering trials (data averaged over 5 board finishes)

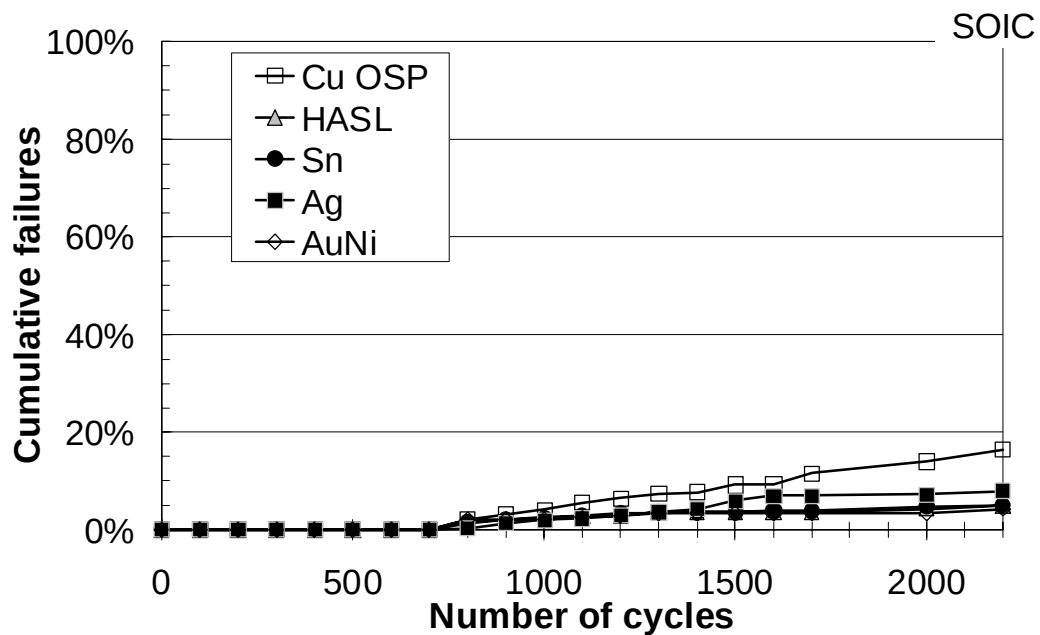


Figure 18. Cumulative failures for SOIC devices from reflow trials (data averaged over 3 solder alloys)

3.1.3 SOIC device results

As for results discussed in Sections 3.1.1 and 3.1.2, for ease of presentation and to illustrate the effect of board finish on reliability (i.e. cumulative failures), the results in Figure 18 are

averaged over the three solder alloys used in the reflow trials. The electrical continuity test again highlighted the poorer performance of the OSP finished boards. The latter generated failures after ~700 cycles, at least twice the rate of the boards with the other finishes, with failures approaching 20% after 2200 cycles. A similar behaviour was observed with wave soldered joints (see Figure 19) but in this case the boards with the tin finish performed as poorly as those with the OSP finish, with cumulated failures of around 20%.

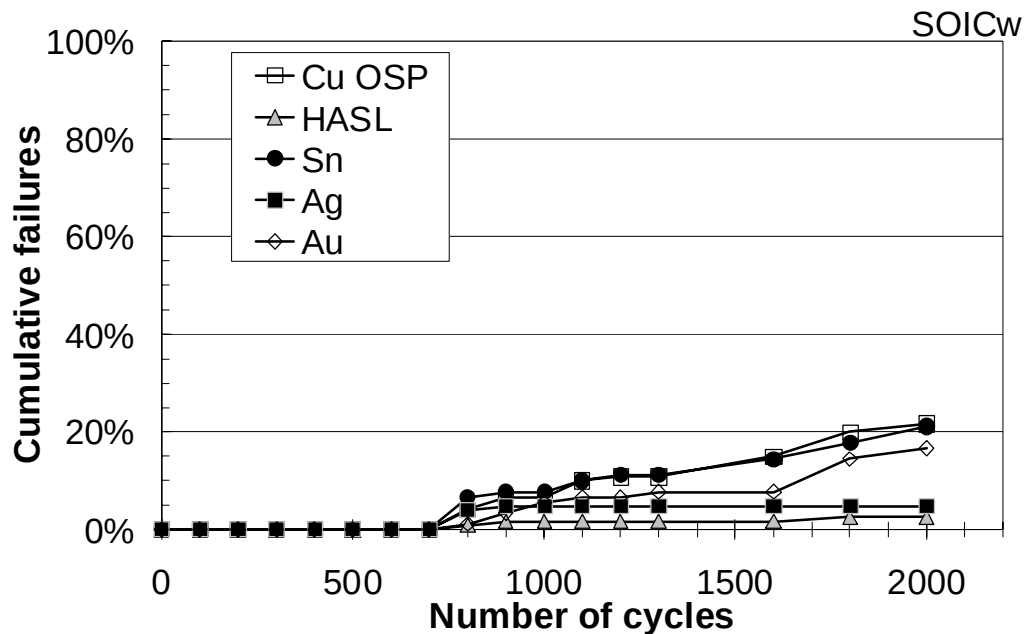


Figure 19: Cumulative failures for SOIC devices from wave soldering trials (data not averaged)

As with the earlier results, for ease of presentation and to illustrate **the effect of solder alloy on reliability** (i.e. cumulative failures) for the SOIC devices, the results in Figure 20 were averaged over the five board finishes used in the reflow trials. The results indicated that in terms of solder alloy performance the traditional SnPb alloy was out-performed by the lead-free alloys (see Figures 10 and 21) with half the number of generated failures.

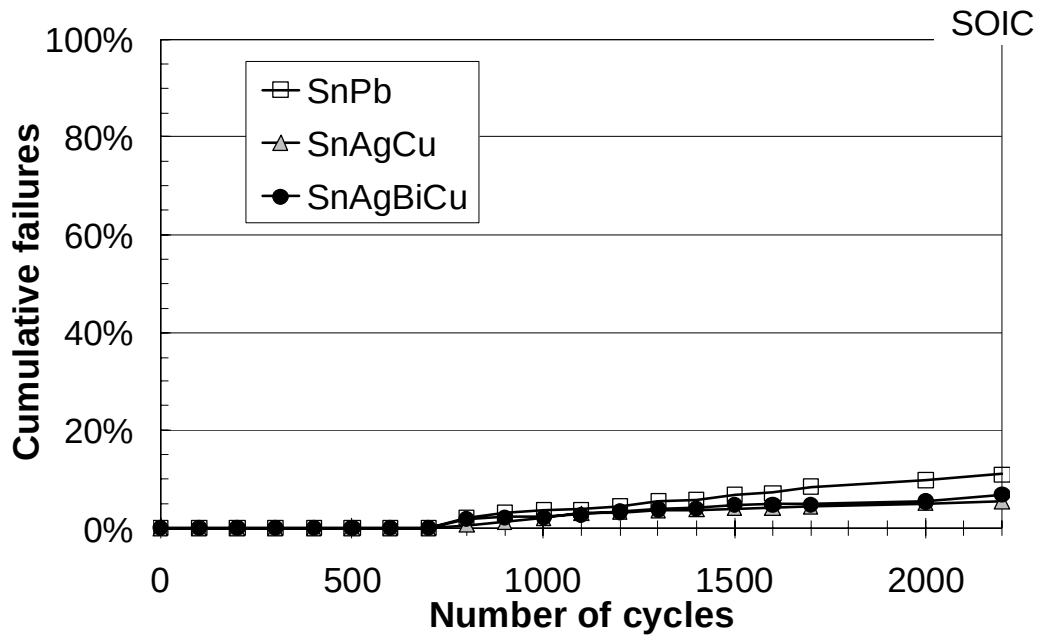


Figure 20: Cumulative failures for SOIC devices from reflow soldering trials (data averaged over 5 board finishes)

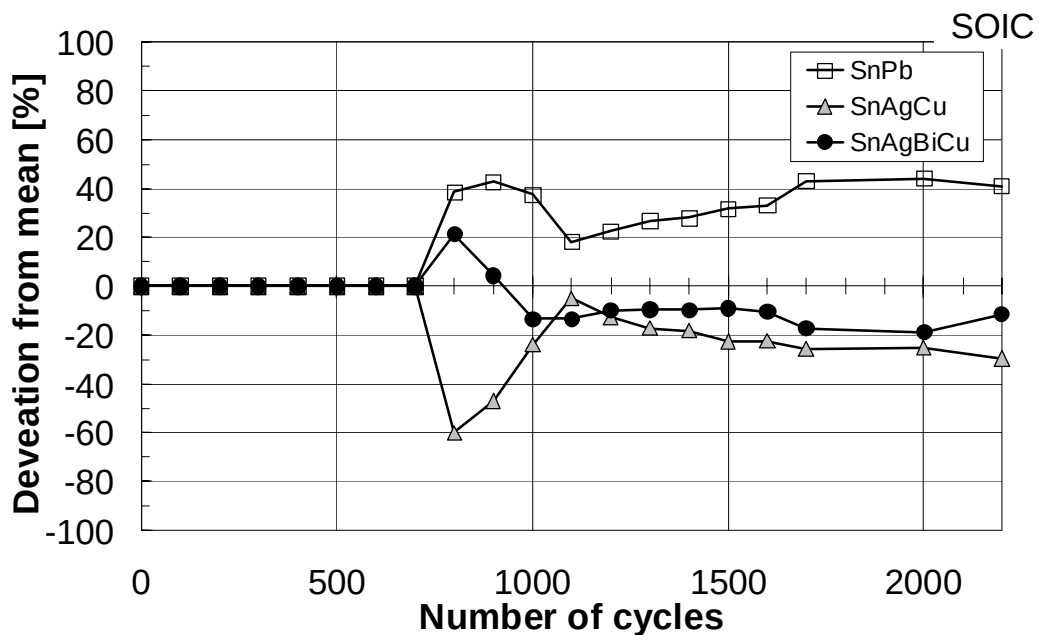


Figure 21: Deviation from mean of accumulative failures for SOIC devices from reflow soldering trials (data averaged over 5 board finishes)

3.1.4 Through hole connector results

The electrical continuity measurements indicated that there were no failures of the solder joints on the connectors even after 2200 thermal cycles. This is attributed to the robustness of the compliant pins, which allow stress relief, and the mechanical keying effect of the pins in the

through holes. These results also indicated the consistency of the intrusive reflow soldering method used to assemble the connectors onto the boards. The intrusive reflow design details are listed in Appendix C.

3.2 Shear testing

Shear testing is an established destructive method for evaluating not only the degree of crack propagation and damage to the solder joint, but also the general strength of the solder joint. 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 influence the strength of a joint. Hence a correlation will exist between the strength of the solder joint and the failure rate. A schematic of the shear test is shown in Figure 22.

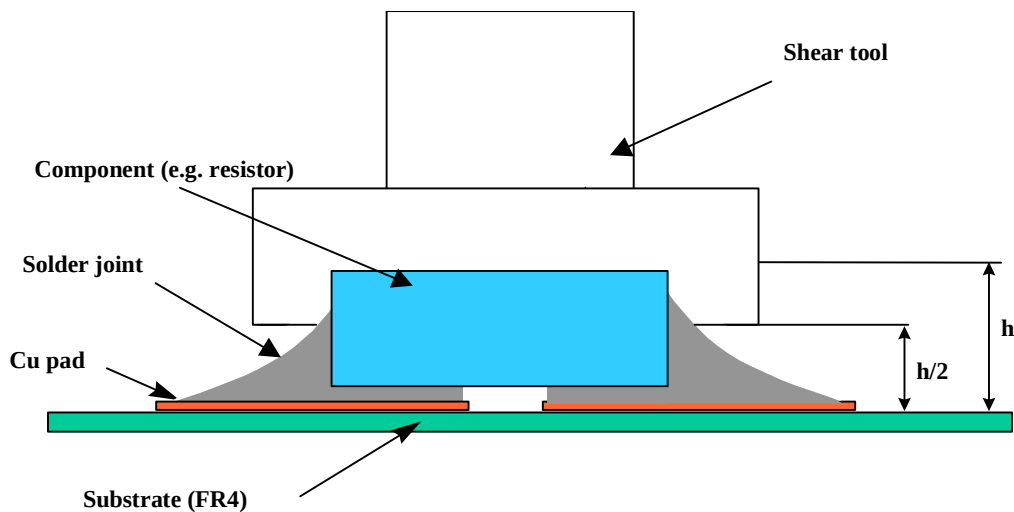


Figure 22. Tooling and test sample location for shear test (front view)

There are three essential steps in carrying out the shear tests. First, the board (substrate), either whole or cut to size, needs to be properly fixed in the shear test equipment. Second, the necessary test conditions have to be set. Of these, the most important is the stand-off height = $h/2$, between the edge of the shear tool and board surface, which is required to provide the proper shear component, see Figure 22. Finally, during each test, the shear tool is moved forward against the test component, and the applied force increased until the attachment is broken.

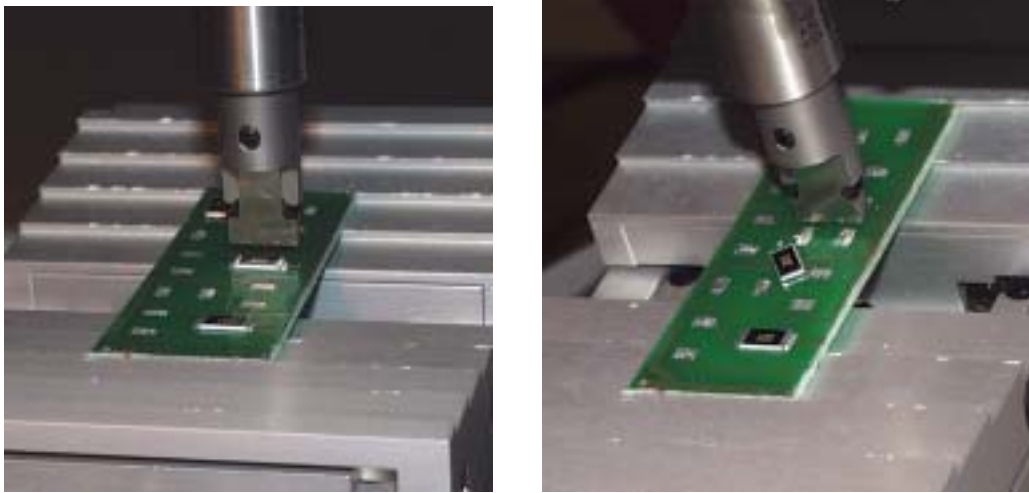


Figure 23. Shear test jig and push-off tool before and after test

Figure 23 shows the experimental arrangement of the board placed within the jig ready for testing, and the corresponding board after the test. Mounting the jig on a movable X-Y table enabled the shear test tool to be positioned directly behind the component (as shown). For each test the push-off tool was set at a pre-determined height (centre of component) of $80\text{ }\mu\text{m}$, and was moved at a defined speed of $200\text{ }\mu\text{m/s}$. The data obtained in the test can readily be plotted and analysed in terms of the ultimate shear force required to rupture the solder joint as a function of the number of thermal cycles to which it had been subjected. However, a disadvantage of the technique is that since sample boards are destroyed during the testing, the planned removal of sample boards should ideally be at the cycle of interest i.e. when failure occurs. Hence some prior knowledge of the failure range is required. A typical post-shear joint, and details of the fracture surface are shown in Figure 24.

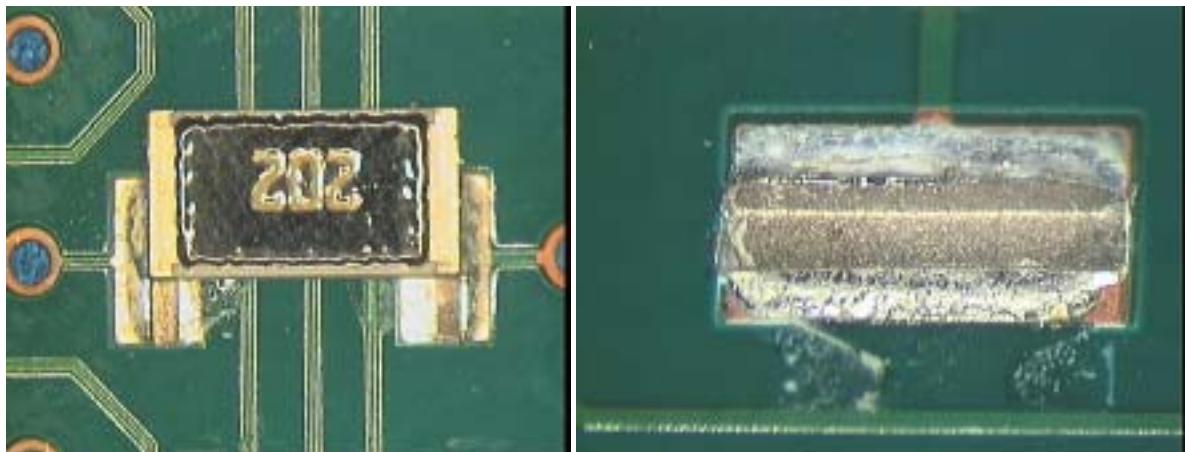


Figure 24. Solder joint after shear test and detail of fractured surface

The components studied were the 2512-type resistors on boards with an OSP finish, and they were tested after 0, 400, and 1000 thermal cycles.

For each board 19 resistors were tested in order to produce a sensible average of the joint strengths. The results (see Figure 25) show that the strongest joint strengths were obtained using the lead-free solders, SnAgCu and SnAgBiCu, for all the cycling regimes explored. The traditional lead-containing solder, SnPb, had a significantly lower pre-cycling strength of around 100 N (cf ~160N for the lead-free solders), but its strength decreased less sharply with cycling than did those of its lead-free counterparts. After 1000 cycles the strengths of the joints from SnPb and SnAgCu were similar, but inferior to that of the SnAgCuBi soldered joints. All the shear results show the general trend in reduction of joint strength with cycling.

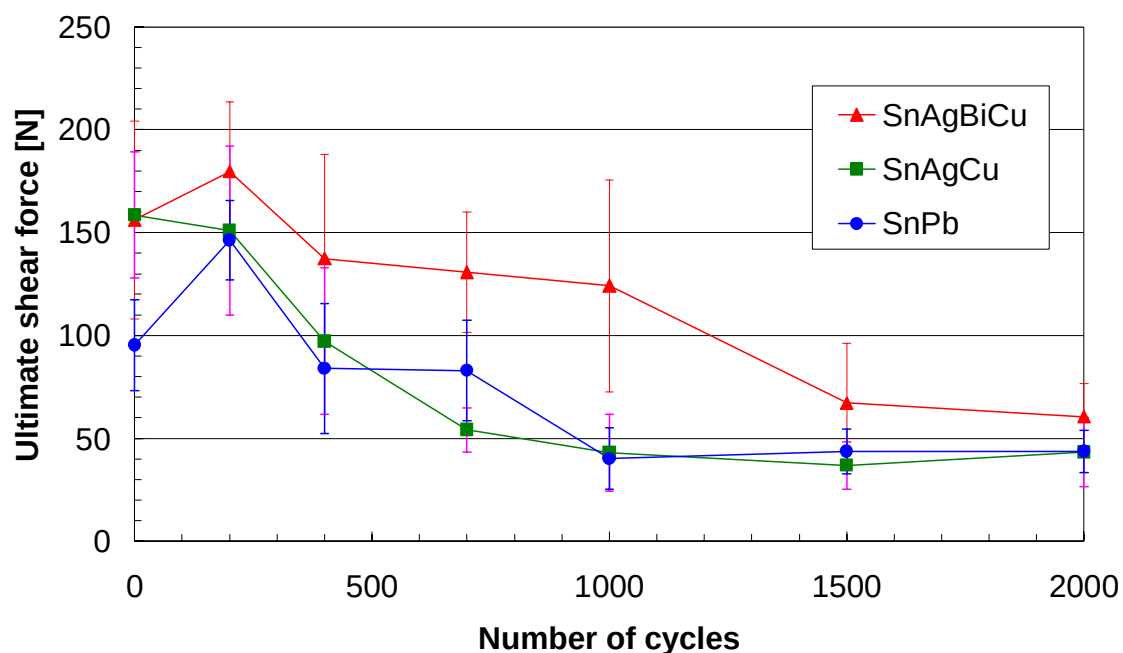


Figure 25. Shear testing results for 2512-type resistors on Cu OSP board finish

3.3 Microsectioning

Metallographic microsectioning is another widely used destructive method for understanding the behaviour of solder joints. The method is particularly useful for investigating the evolution of microstructure with thermal cycling and the subsequent development of the micro-cracks. Although no failure data can be obtained, qualitative information on how the solder joint fails can be obtained from the micrographs. Since the method involves cutting the board into sections and subsequently grinding and polishing the cross-sections, it is important to remember that any heat generated in any of these processes, whether cutting, mounting or polishing, should be minimised to avoid possible and unwanted microstructural changes.

The components chosen for this investigation were the 2512-type resistors, and samples were taken from the cycling chamber after 0, 200, 400, 700, 1000, 1500 and 2000 thermal cycles. They were cut out individually from the boards using a liquid-cooled conventional diamond

saw to ensure that the soldered joints did not heat to a level that would have affected the joint microstructure. Once cut, the components were cleaned using IPA (iso-propyl alcohol) to ensure that any residues present from the cutting stage had been removed from the joint region. The samples were then mounted in a cold curing epoxy.

The results suggested that the microstructure of the solder joints underwent significant changes as the thermal exposure was increased from 0 to 2200 cycles. In particular, after 2200 thermal cycles the joints exhibited regions in which physical continuity was completely disrupted by the presence of cracks that started in, and traversed through, the whole of the solder fillet. Grain coarsening and intermetallic growth also occurred during cycling, a phenomenon which would be expected to modify the physical properties of the joint. Additionally, the high local stress resulted in crack formation and ultimately joint failure. This coarsening effect increased with thermal cycling.

Although there were significant microstructural differences between the joints made with lead-containing and lead-free alloys, the failure mechanism appeared to be similar. Indeed, all the joints from all the alloys failed in a similar way, with crack initiation and the greatest microstructural changes occurring under the resistor.

Typical micrographs of solder joint fillets for different alloy compositions, board finishes and number of cycles experienced are presented in Figures 26-29 and in Appendix D. In Figure 26 a comparison is made between a good quality solder joint fillet and one containing voids and exhibiting the **fillet lifting phenomenon**. Appendix D shows variety of thought hole joints where fillet lifting can be observed especially with SnAgBiCu alloy. The micrographs of fillets are accompanied by microsections of intermetallic layers inside plated through hole taken at higher magnification.

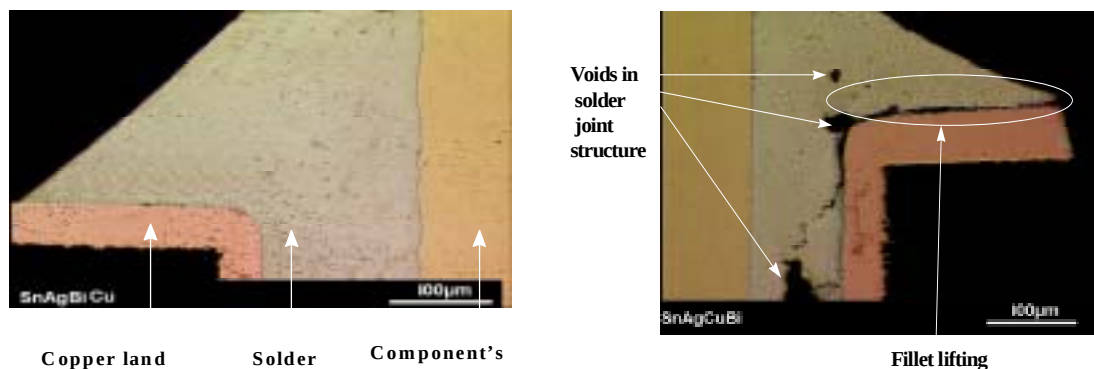
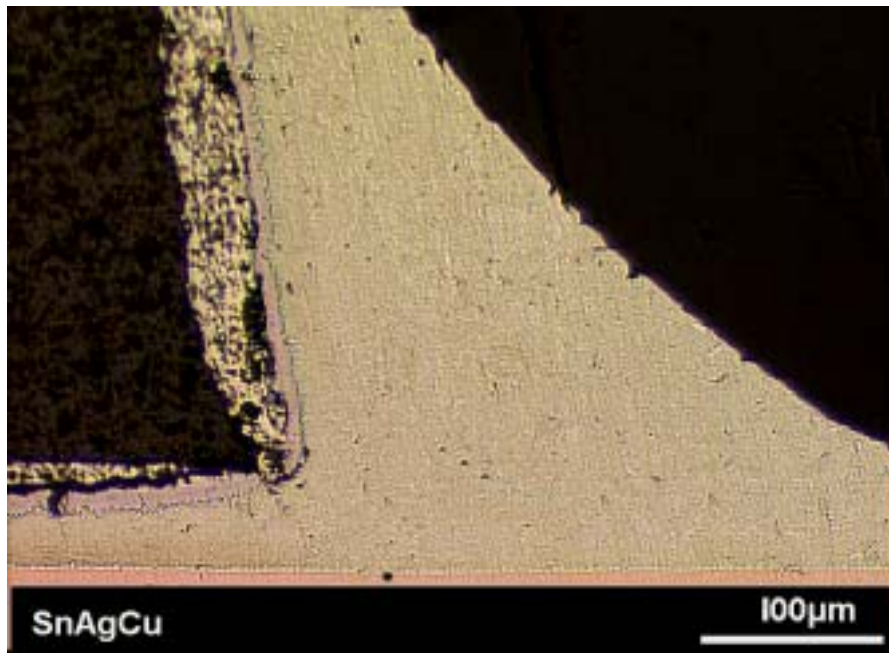


Figure 26. Solder joint fillets with and without void

Figures 27-29 illustrate how the microstructure changed as the number of thermal cycles was increased. The microstructure coarsened, the grain size grew, and cracks appeared, as the cycling was increased to 1000 cycles. The component (chip resistor) termination layers are also evident in the micrographs.



27. Microsection of joint formed using SnAgCu alloy and a Ag board finish (before cycling)

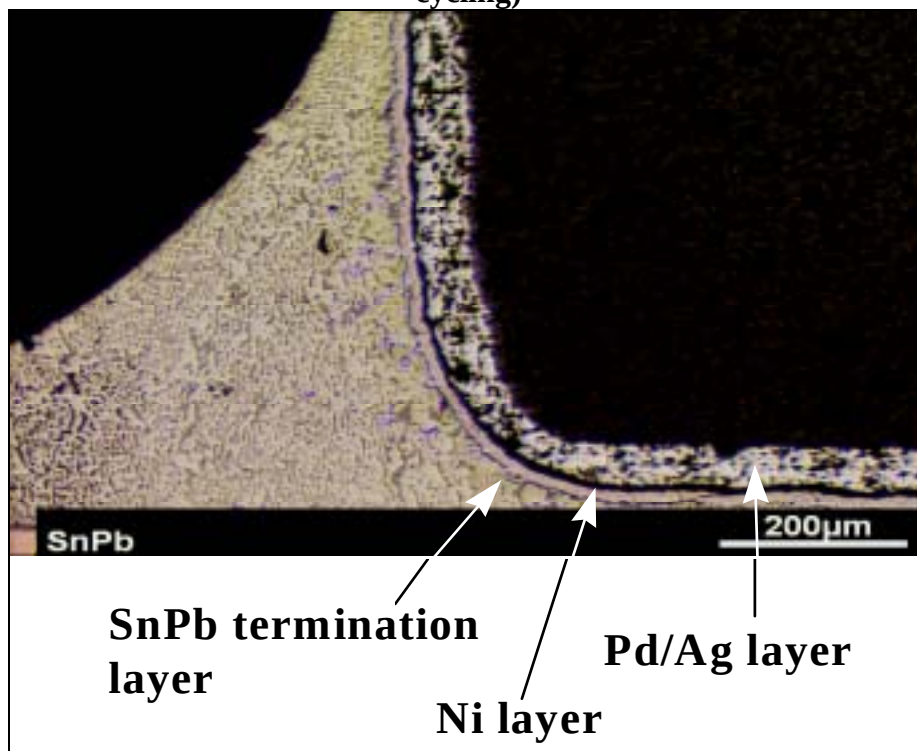


Figure 28. Microsection of joint formed using SnPb solder and a Cu/OSP board finish (after 400 cycles)

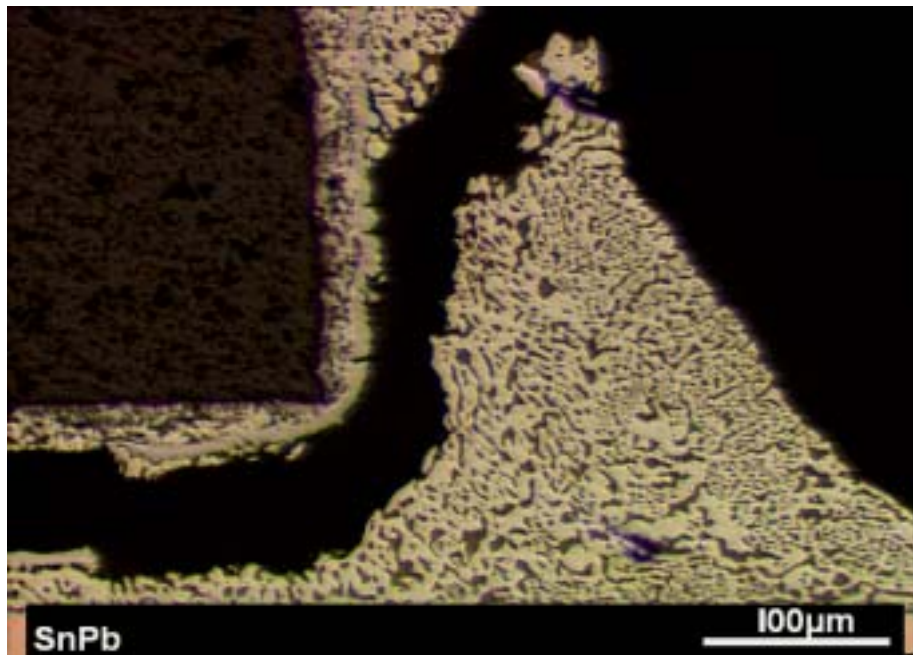


Figure 29. Microsection of joint formed using SnPb solder and a Cu/OSP board finish, (after 1000 cycles)

4 CONCLUSIONS

The compatibility of some new lead-free solders with various board pad finishes has been studied using ceramic chip capacitors and SOIC devices, three solders and five board finishes. The assessment of solder joint reliability has centred on the use of electrical conductivity measurements and shear strength data, complemented with microstructural observations. The work has benefited from the use of a new approach to the accelerated test method to obtain failure data in timescales much less than those traditionally experienced. The salient findings were:

4.1 Electrical Continuity Tests

2512-type resistors

- in terms of board finish, differences were apparent after only 400 cycles; after 2200 cycles the failures ranged from ~65 to 85%. The HASL finish outperformed the other finishes, with the Cu/OSP finish giving the worst performance
- in terms of solder alloy the performance of the traditional SnPb solder was significantly better than those of its two lead-free counterparts. The behaviour of the SnAgCu solder was improved by adding Bi.

0603-type resistors

- in terms of board finish, differences were apparent after 700 cycles; after 2200 cycles the maximum failure rate approached 25%. The AuNi finish outperformed the other finishes, with the Cu/OSP finish giving the worst performance.
- in terms of solder alloy the performances of both the SnAgBiCu and SnPb solders were better than the SnAgCu solder

SOIC devices

- in terms of board finish, differences were apparent after only 700 cycles; after 2200 cycles the number of failures ranged up to ~15%. The HASL finish outperformed the other finishes, with the Cu/OSP finish again exhibiting the worst behaviour.
- in terms of solder alloy the lead-free solder outperformed the traditional SnPb solder

For the larger components i.e. 2512-type resistors, there is a larger strain range to be accommodated by the solder joints which is better achieved with the traditional SnPb solder than with the new SnAgCu alloy. On the other hand when the strain range is smaller (i.e. with 0603-type resistors or SOICs) the lead-free alloys can perform as good as, or better than, the traditional SnPb solder. There appears to be a benefit from adding Bi to the SnAgCu solder. The presence of the bismuth in strengthening the lead-free solder joints arises via solid solution hardening (for <1% Bi, it is present at interstitial sites), and via precipitation of intermetallic particles (for >1% Bi)

4.2 Shear Strength Tests

Over all the test cycles used in this study (1000 cycles), the strengths of the joints made using lead-free were greater than those made using traditional SnPb solder. In the as-formed (i.e.

pre-cycled) condition the ultimate shear forces required to break the lead-free joints (~160N) were significantly higher than those required to break lead-containing joints (<100N). Not surprisingly, as the number of cycles was increased the strengths of all the joints decreased as the grain structures coarsened. However, the rate of strength reduction of joints made using SnAgBiCu solder was much less than observed for the other two solders. It was observed that the lead-free alloys produced brittle ruptures in comparison to the ductile splits observed with the lead-containing solder.

5 REFERENCES

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- [2] Dušek, M. Hunt, C. *The Impact of Solderability on Reliability and Yield of Surface Mount Assembly*. NPL Report CMMT(A) 214. Teddington, September 1999
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- [6] Dušek, M. Nottay, J. Hunt, C. *A Test Method for Assessing Lead-free Solder Joint reliability*. NPL Report CMMT(A) 273. Teddington, July 2000
- [7] Dušek, M. Hunt, C. *The Use of Shear Testing and Thermal Cycling for Assessment of Solder Joint Reliability*. NPL Report CMMT(A) 268. Teddington, June 2000

6 ACKNOWLEDGEMENTS

The authors are grateful for the support of the DTI as part of its Measurement for the Processability of Materials (MPM) programme, DEK Printing Machines, Alpha Metals and Multicore Solders. The authors are also grateful to Martin Wickham for many useful discussions throughout the course of the work.

7 APPENDIX A. Assembled Test Boards



Wave soldered PCB



PCB with placed components for reflow soldering

8 APPENDIX B. Electrical Continuity Test Data

R2512 SnPb Solder alloy / finish	β	Nf (50%)	Nf (62.3%)
SnPb/Cu	1.9	1695	2054
SnPb/HASL	4.3	2334	2544
SnPb/Sn	3.0	1833	2073
SnPb/Ag	2.6	1636	1883
SnPb/Au	3.2	1957	2197
SnAgCu/Cu	1.8	743	906
SnAgCu/HASL	2.7	1159	1330
SnAgCu/Sn	2.8	1201	1370
SnAgCu/Ag	2.4	1275	1487
SnAgCu/Au	2.0	1265	1526
SnAgBiCu/Cu	2.7	1271	1459
SnAgBiCu/HASL	2.1	1762	2099
SnAgBiCu/Sn	2.6	1779	2043
SnAgBiCu/Ag	2.5	1841	2137
SnAgBiCu/Au	2.5	1634	1887

R0603 SnPb Solder alloy / finish	β	Nf (50%)	Nf (62.3%)	Rem
SnPb/Cu	2.0	4888	5883	
SnPb/HASL	7.4	3087	3244	*
SnPb/Sn	2.7	4974	5689	
SnPb/Ag	2.2	3718	4390	
SnPb/Au	-	-	-	*
SnAgCu/Cu	2.7	2098	2399	
SnAgCu/HASL	1.0	13474	19154	*
SnAgCu/Sn	-	-	-	*
SnAgCu/Ag	2.8	2976	3395	
SnAgCu/Au	-	-	-	*
SnAgBiCu/Cu	2.7	3068	3512	
SnAgBiCu/HASL	5.5	4267	4559	*
SnAgBiCu/Sn	1.9	5778	7019	
SnAgBiCu/Ag	2.4	5784	6753	
SnAgBiCu/Au	6.7	3430	3623	*
* Low number of failures, Weibull fit is inaccurate				

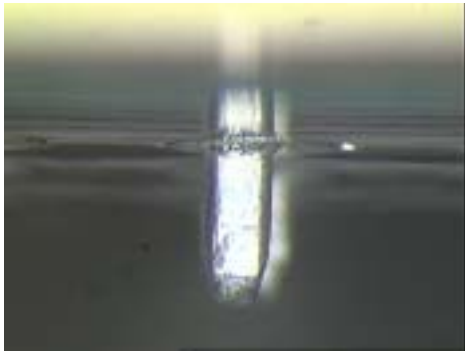
SOIC SnPb Solder alloy/finish	β	Nf (50%)	Nf (62.3%)	Rem
SnPb/Cu	2.1	3480	4152	
SnPb/HASL	1.1	18204	25147	*
SnPb/Sn	1.3	8288	11070	*
SnPb/Ag	2.6	4066	4690	
SnPb/Au	1.4	13828	17900	*
SnAgCu/Cu	1.5	4710	5970	
SnAgCu/HASL	1.6	13474	16987	*
SnAgCu/Sn	10.0	2999	3111	*
SnAgCu/Ag	1.5	15102	19250	*
SnAgCu/Au	10.9	3000	3102	*
SnAgBiCu/Cu	3.8	3581	3940	
SnAgBiCu/HASL	1.4	11766	15325	*
SnAgBiCu/Sn	3.2	5778	6480	
SnAgBiCu/Ag	1.7	5784	7153	
SnAgBiCu/Au	1.0	18396	26540	*
* Low number of failures, Weibull fit is inaccurate				

BGA SnPb Solder alloy / finish	β	Nf (50%)	Nf (62.3%)	Rem
SnPb/Cu	1.7	1636	2040	
SnPb/HASL	-	-	>2200	*
SnPb/Sn	2.2	1813	2144	
SnPb/Ag	2.2	2839	3361	
SnPb/Au	4.5	2293	2485	*
SnAgCu/Cu	2.1	1213	1444	
SnAgCu/HASL	1.7	3148	3913	
SnAgCu/Sn	-	-	>2200	*
SnAgCu/Ag	2.2	1904	2251	
SnAgCu/Au	-	-	>2200	*
SnAgBiCu/Cu	2.8	3419	3904	
SnAgBiCu/HASL	3.4	2550	2843	
SnAgBiCu/Sn	1.5	2815	3614	
SnAgBiCu/Ag	3.2	3186	3571	
SnAgBiCu/Au	1.4	4030	5286	*
* Low number of failures, Weibull fit is inaccurate				

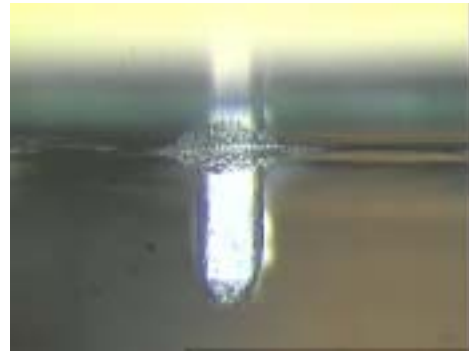
BGA SnAgCu Solder alloy / finish	β	Nf (50%)	Nf (62.3%)	Rem
SnPb/Cu	2.1	1752	2094	
SnPb/HASL	1.2	18204	24788	*
SnPb/Sn	2.8	1997	2279	
SnPb/Ag	2.0	2011	2417	
SnPb/Au	-	-	>2200	*
SnAgCu/Cu	2.1	1109	1323	
SnAgCu/HASL	2.9	2273	2576	
SnAgCu/Sn	9.2	2999	3122	*
SnAgCu/Ag	2.2	2849	3361	
SnAgCu/Au	-	-	>2200	*
SnAgBiCu/Cu	1.9	4402	5328	
SnAgBiCu/HASL	2.2	3215	3811	
SnAgBiCu/Sn	2.6	2735	3154	
SnAgBiCu/Ag	2.3	2411	2837	
SnAgBiCu/Au	1.1	18396	25593	*
* Low number of failures, Weibull fit is inaccurate				

9 APPENDIX C. Photographs of Intrusively Reflowed Joints

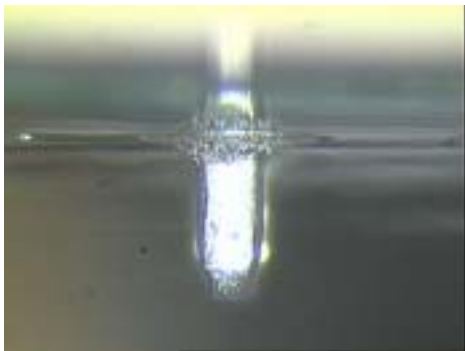
The photographs below present side views of the intrusively reflowed solder joints. The letters indicate the positions on the connector. No crack-related failures caused by accelerated thermal cycling (to 2200 cycles) were detected using electrical continuity testing.



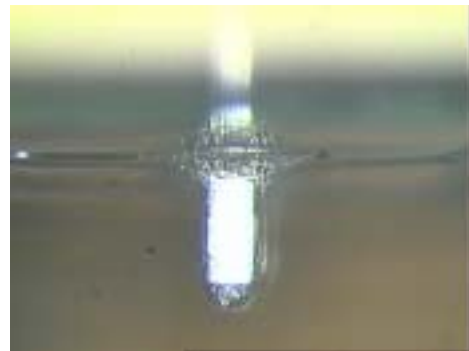
A



B



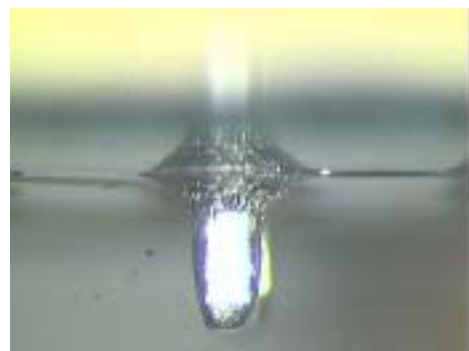
C



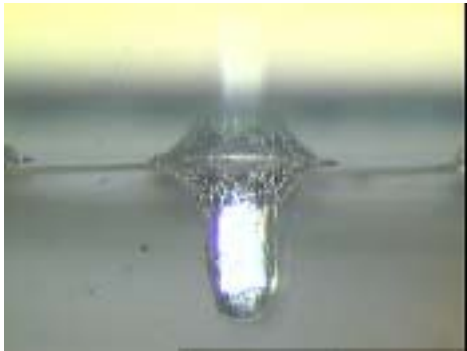
D



E



F



G



H



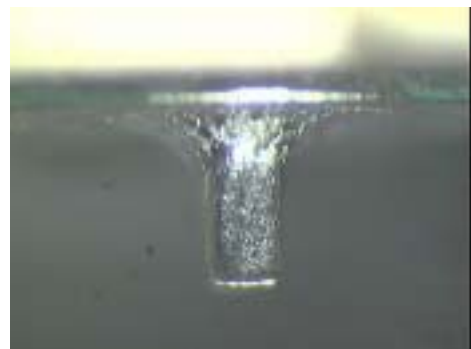
I



J



K



L

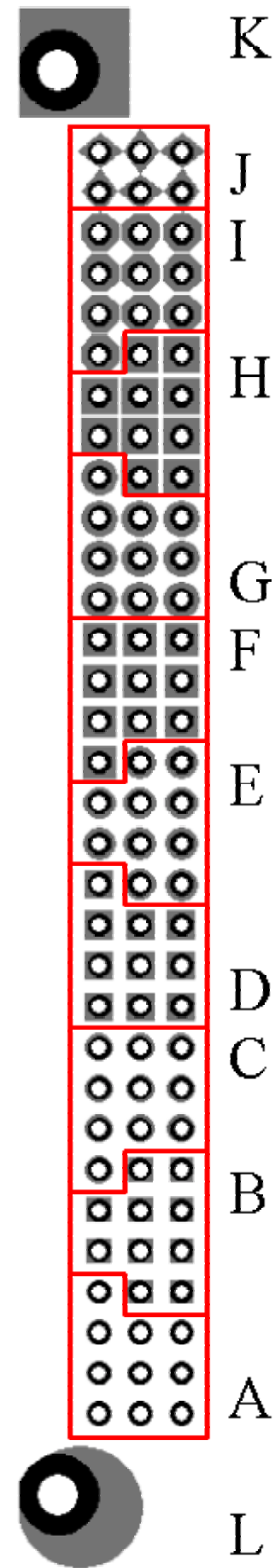
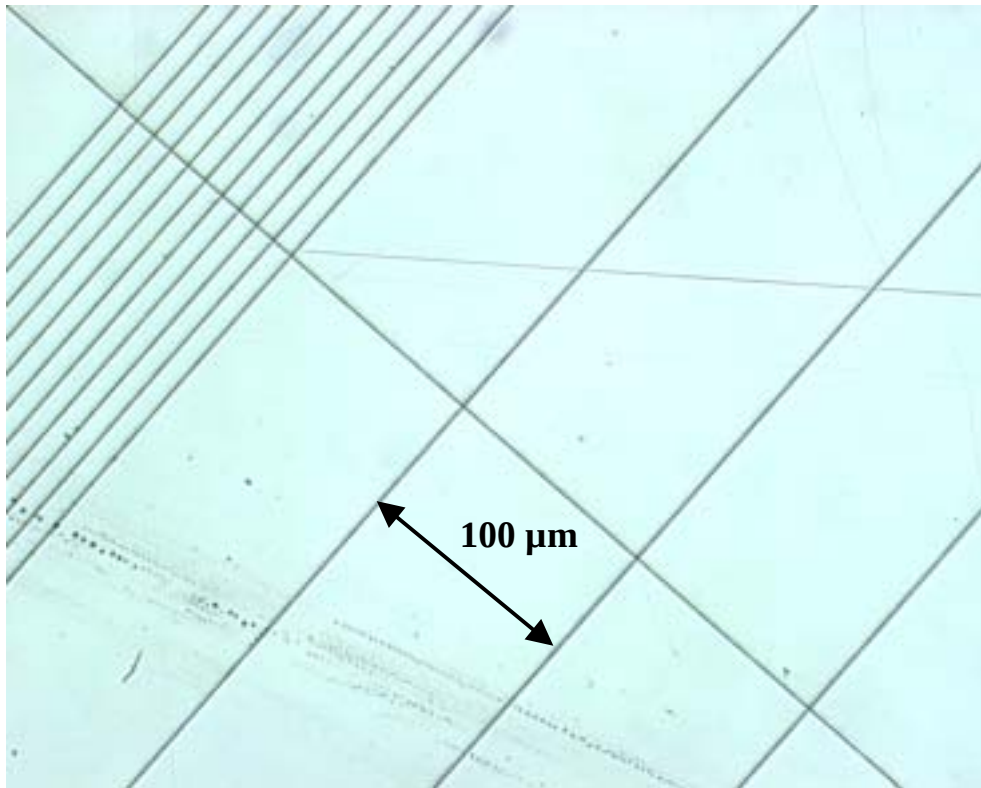


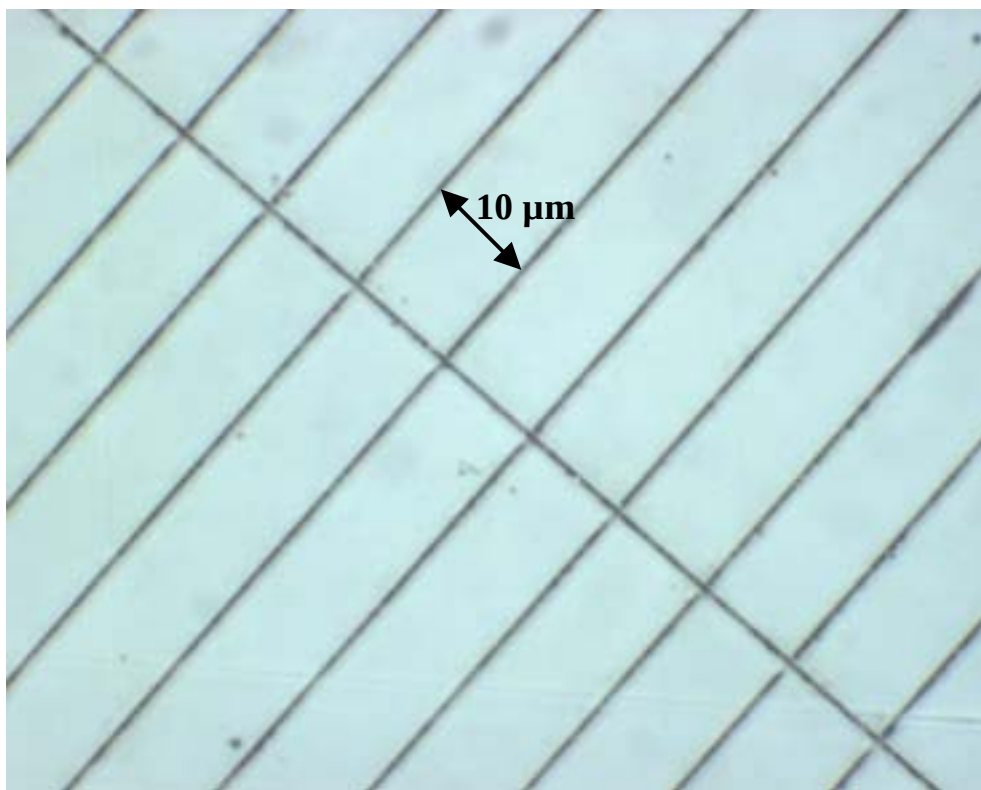
Table of apertures for intrusive reflowed 32x3 connector
(stencil thickness 200μm)

Label	Pad size [mm]	Aperture size [mm]	Aperture shape	Drill [mm]
A	1.47	Ø 1.524	Round	0.9
B	1.47	□ 1.524	Square	0.9
C	1.47	Ø 1.778	Round	0.9
D	1.47	□ 1.778	Square	0.9
E	1.47	Ø 2.032	Round	0.9
F	1.47	□ 2.032	Square	0.9
G	1.47	Ø 2.286	Round	0.9
H	1.47	□ 2.286	Square	0.9
I	1.47	⬡ 2.286	Octagon	0.9
J	1.47	2.667 x 2.159	Diamond	0.9
K	5.1	□ 6.858	Square	2.54
L	5.1	Ø 7.722	Round	2.54

10 APPENDIX D. Microsections of Solder Joint Fillets and Intermetallic layers Formed Using Different Combinations of Solder, Board Finish and Cycling Regime



20 x zoom scale (used for fillet microsections)



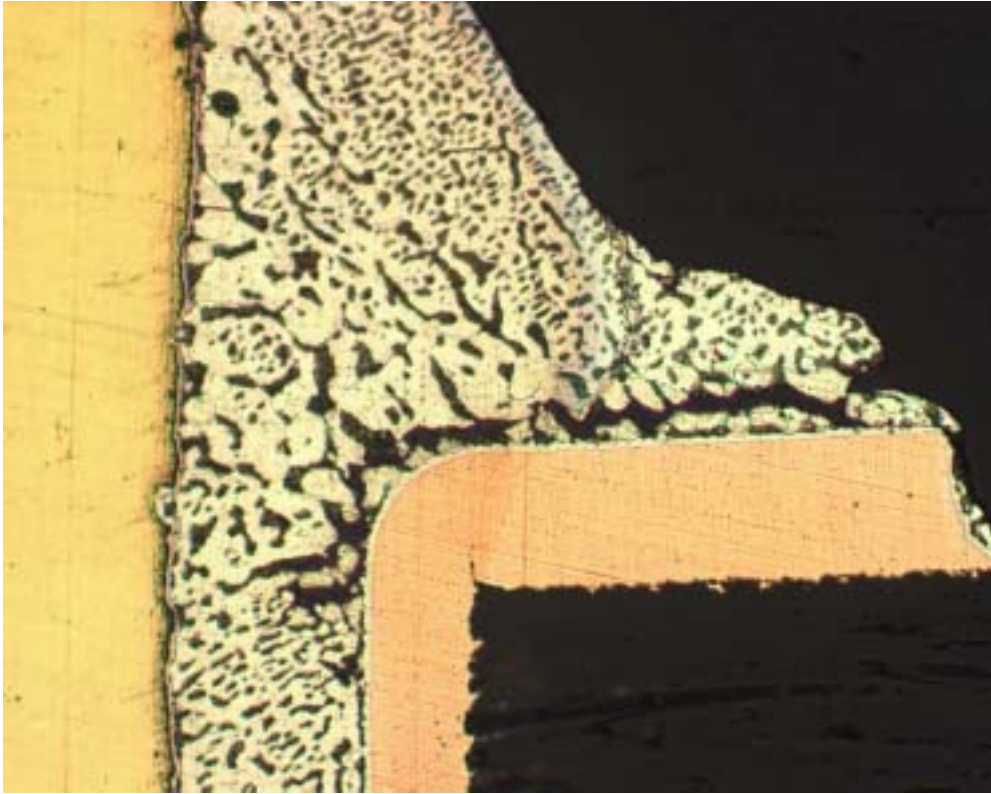
100 x zoom scale (used for intermetallic microsections)



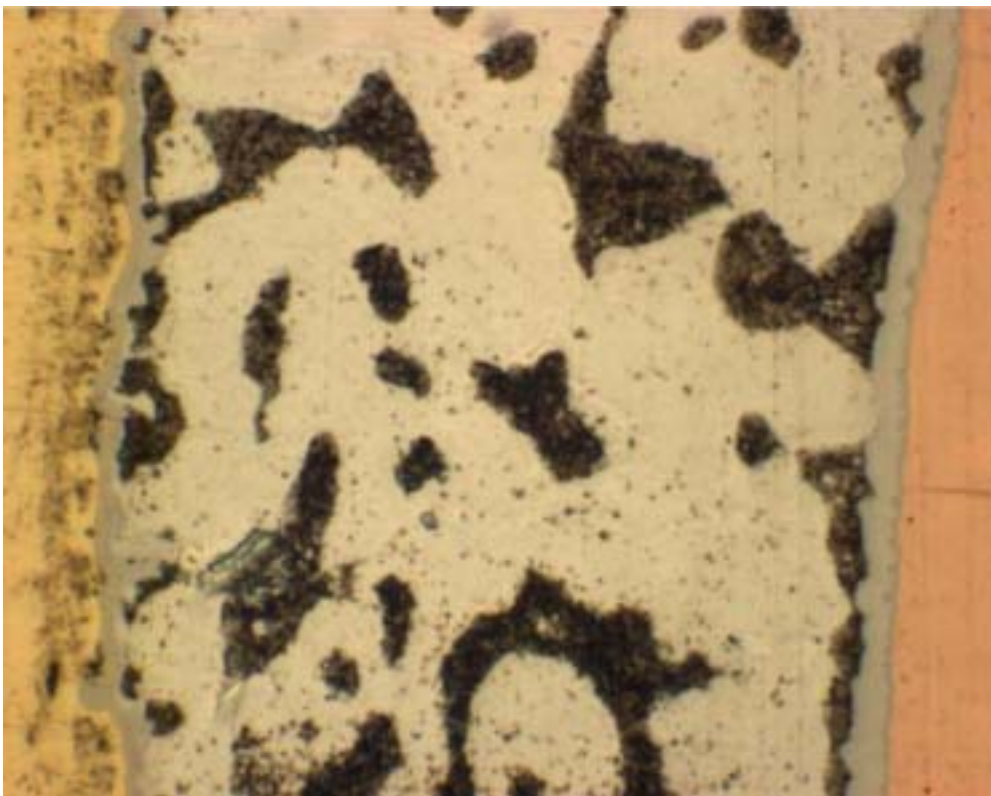
Fillet of SnPb / Cu after 2200 cycles



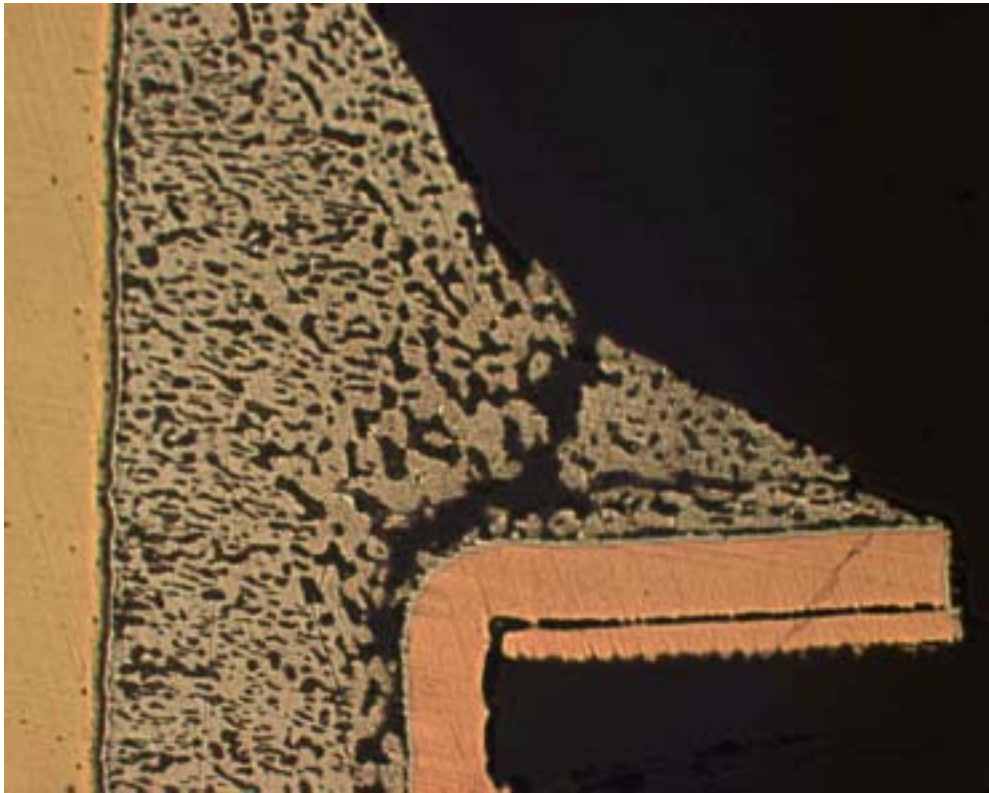
Intermetallic layer of SnPb / Cu after 2200 cycles



Fillet of SnPb / HASL 2200 after cycles



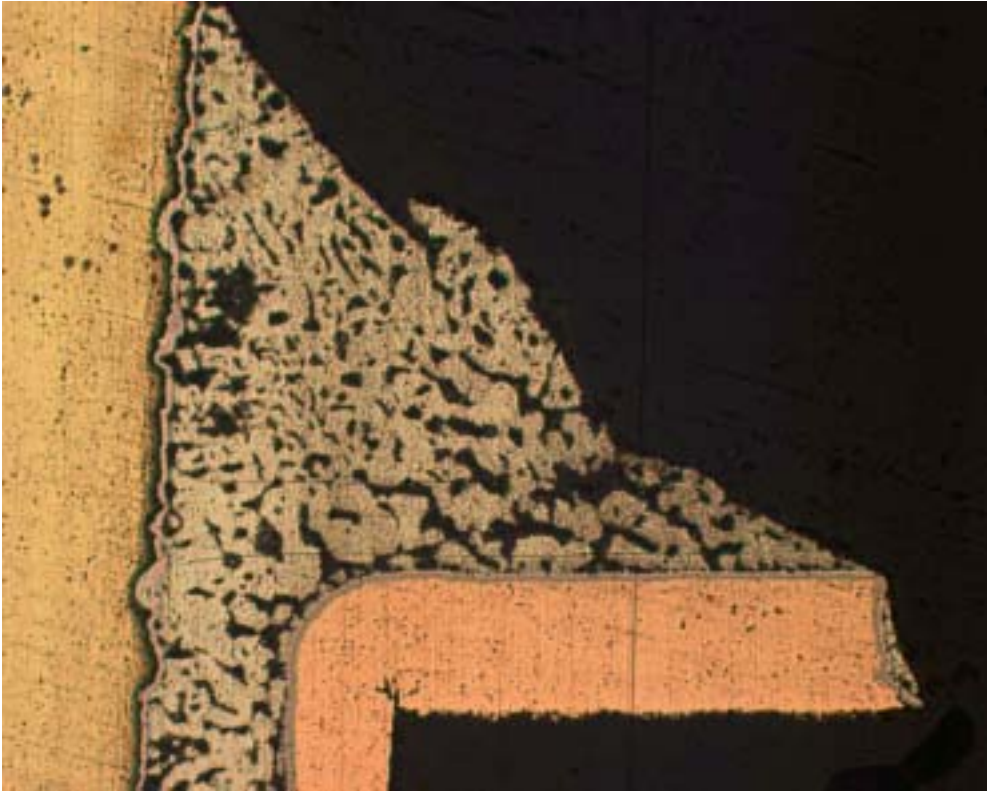
Intermetallic layer of SnPb / HASL after 2200 cycles



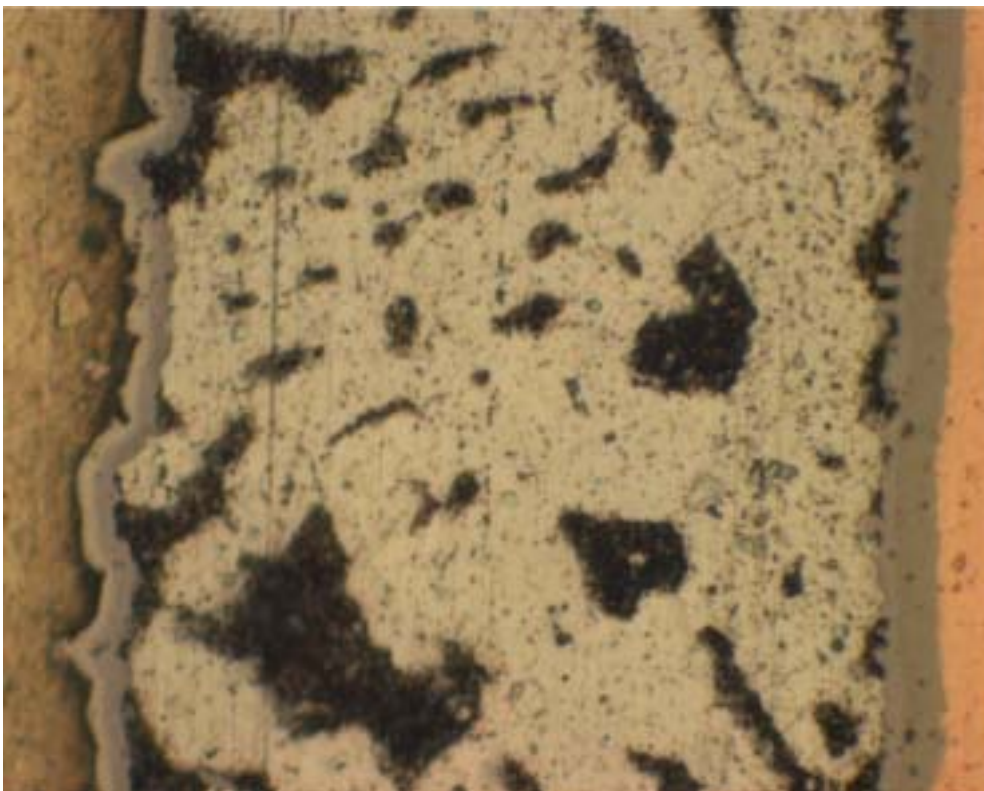
Fillet of SnPb / Sn after 2200 cycles



Intermetallic layer of SnPb / Sn after 2200 cycles



Fillet of SnPb / AuNi after 2200 cycles



Intermetallic layer of SnPb / AuNi after 2200 cycles



Fillet of SnAgCu / Cu after 1000 cycles



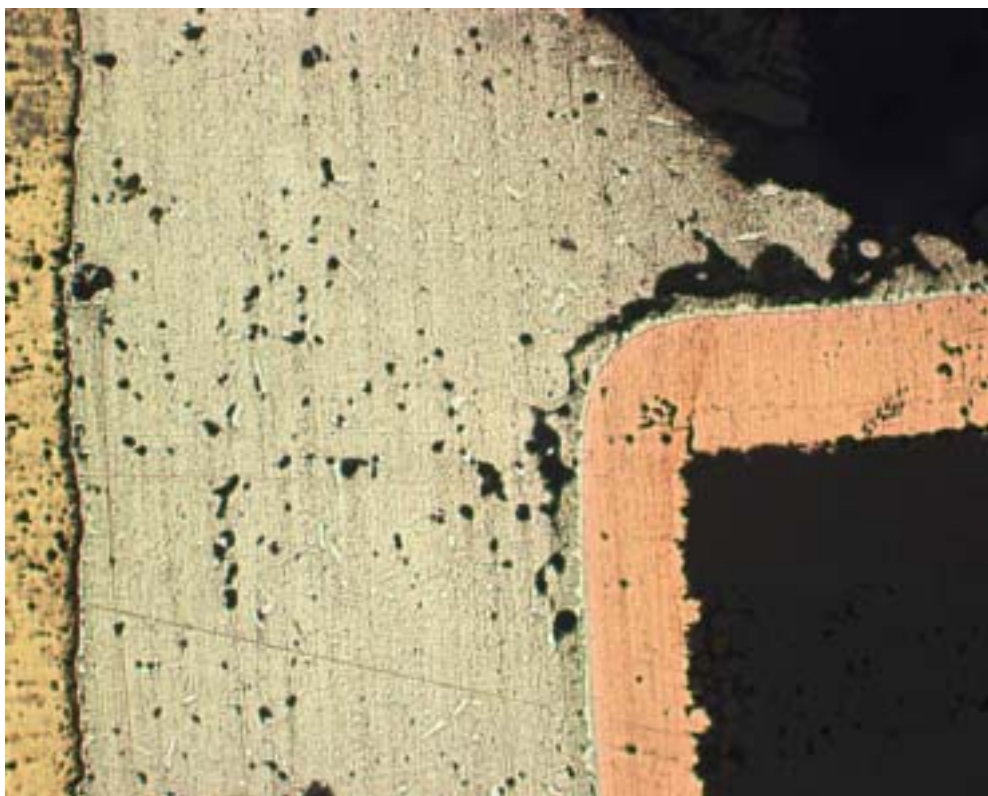
Intermetallic layer of SnAgCu / Cu after 1000 cycles



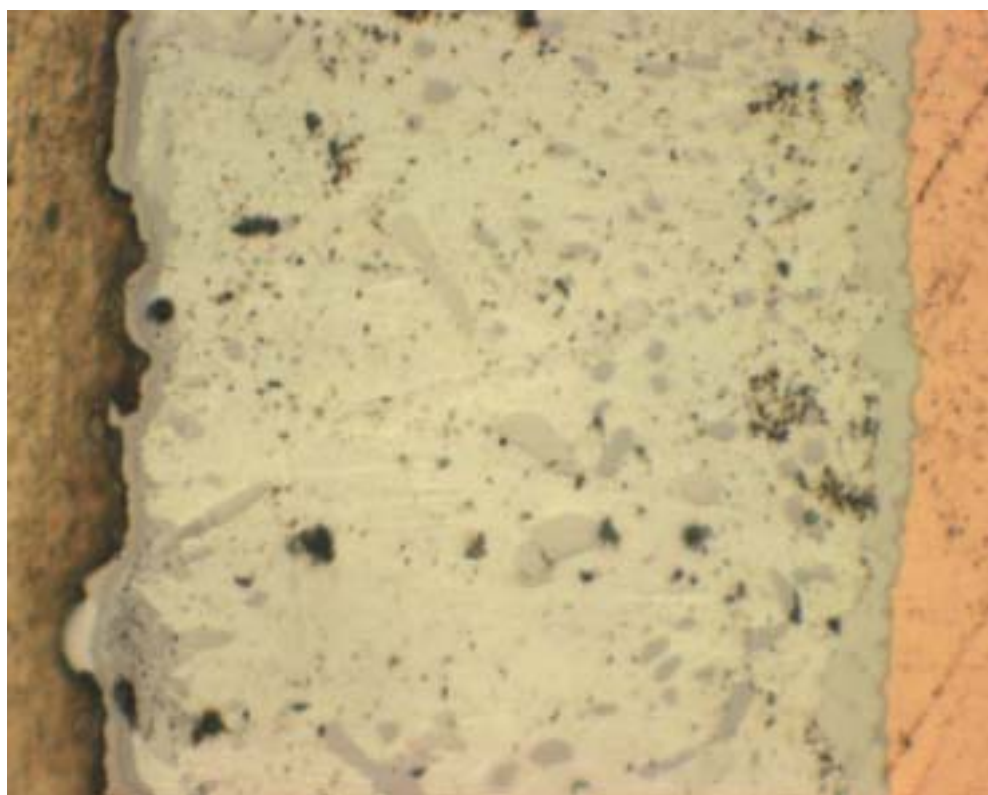
Fillet of SnAgCu / HASL after 2200 cycles



Intermetallic layer of SnAgCu / HASL after 2200 cycles



Fillet of SnAgCu / Sn after 2200 cycles



Intermetallic layer of SnAgCu / Sn after 2200 cycles



Fillet of SnAgBiCu / Cu after 400 cycles



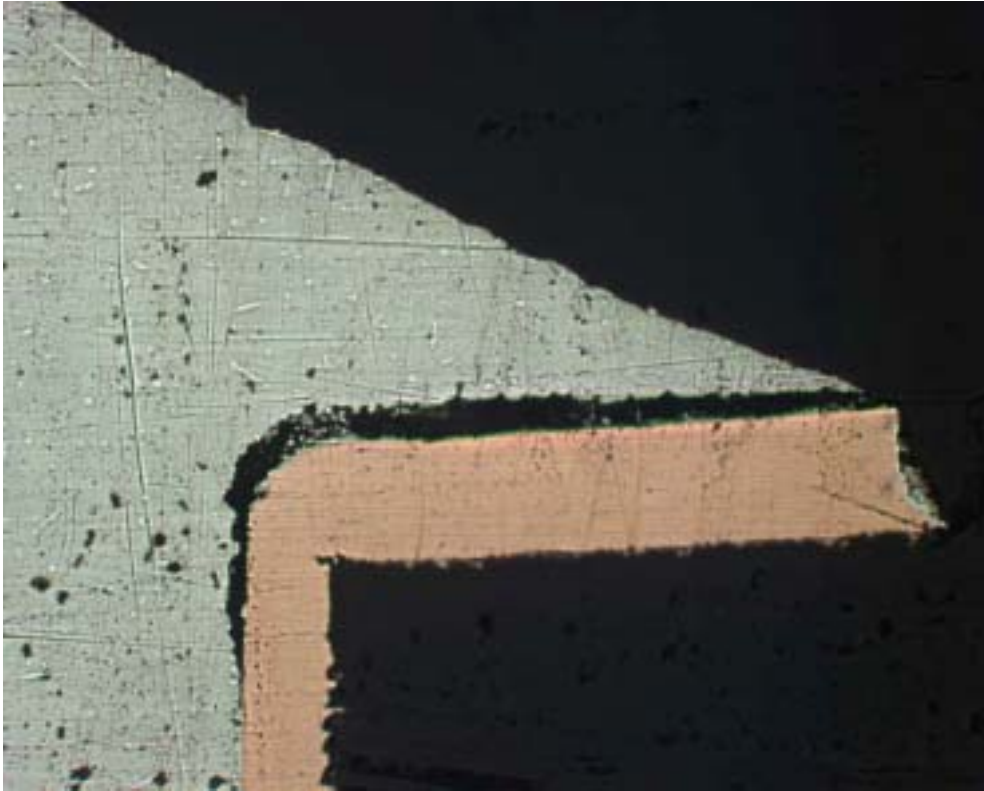
Intermetallic layer of SnAgBiCu / Cu after 400 cycles



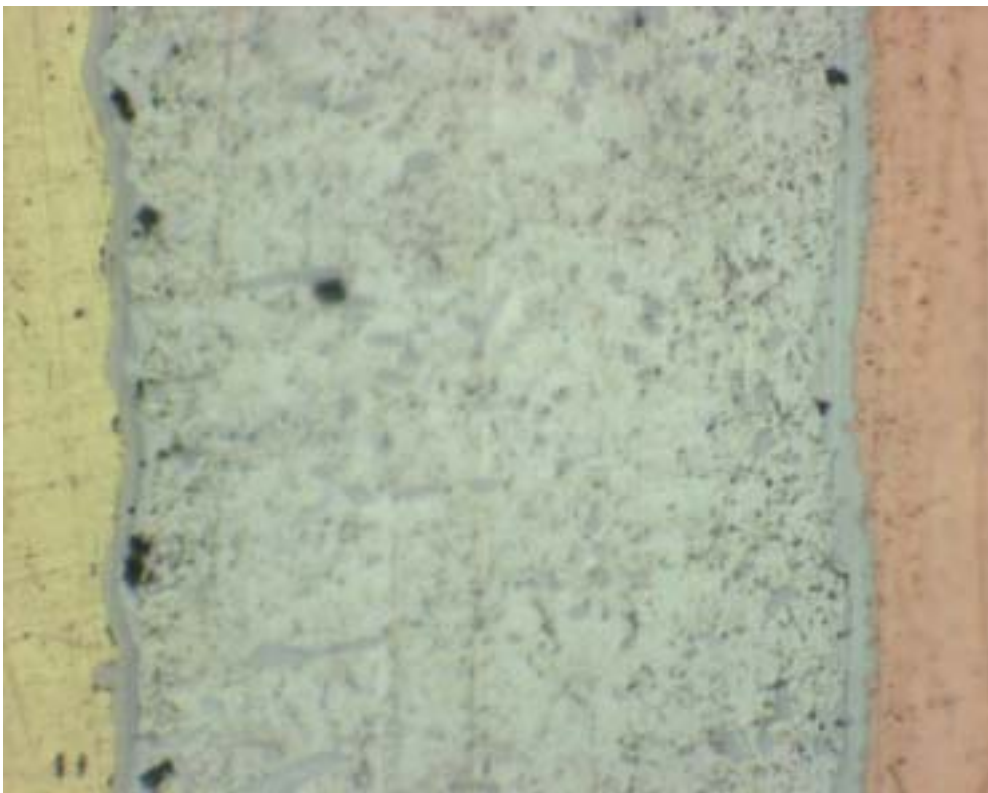
Fillet of SnAgBiCu / HASL after 1000 cycles



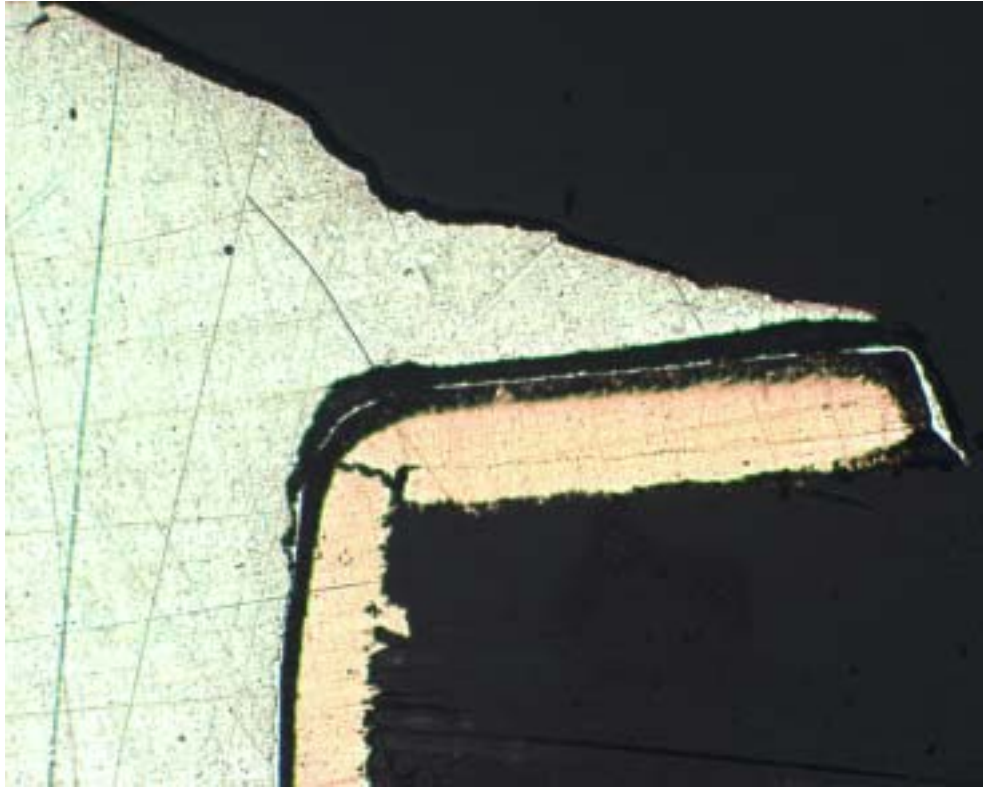
Intermetallic layer of SnAgBiCu / HASL after 1000 cycles



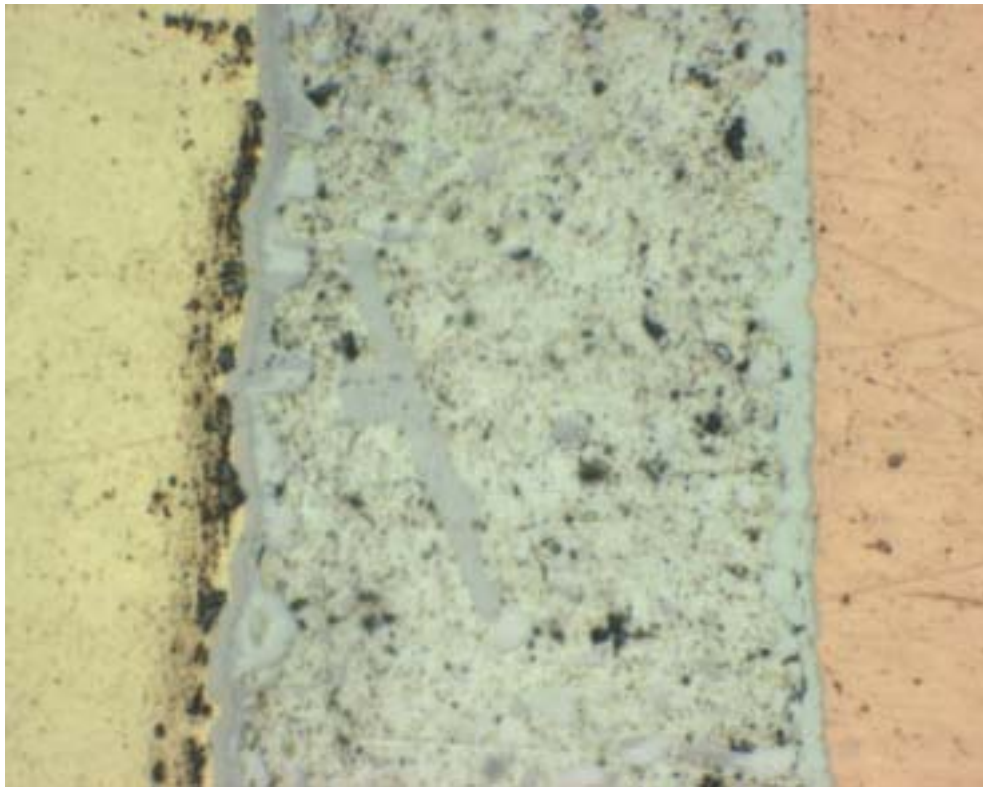
Fillet of SnAgBiCu / Sn after 1500 cycles



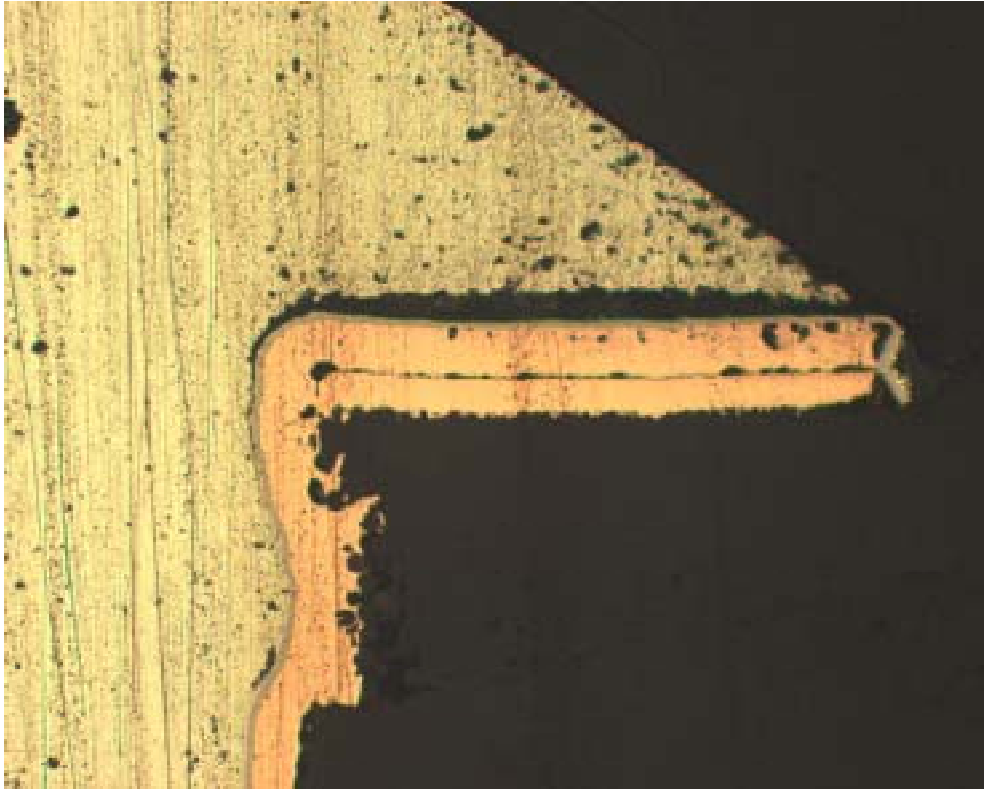
Intermetallic layer of SnAgBiCu / Sn after 1500 cycles



Fillet of SnAgBiCu / Ag after 2200 cycles



Intermetallic layer of SnAgBiCu / Ag after 2200 cycles



Fillet of SnAgBiCu / AuNi after 2200 cycles



Intermetallic layer of SnAgBiCu / AuNi after 2200 cycles