

Report

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Test Method for Recyclable Electronic Substrates Utilising Additive Technology

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Test method for recyclable electronic substrates utilising additive technology

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ABSTRACT

Now that WEEE legislation has been implemented across Europe, there is significant interest in adopting more sustainable electronics manufacturing processes and materials. The changes may lead to alternative failure modes, and hence maintaining performance is key issue for the introduction of new materials. This work studies the performance of specific favoured materials to qualify the failure mechanisms and the effective stress screening regimes.

Flexible thermoplastic printed circuit assemblies based on printed polymer thick film inks and direct write copper on PET, were assembled using electrically conductive adhesives and tested using damp heat, thermal cycling, and combinations of these. Three generic interconnect styles were investigated.

For the majority of conductive adhesive/component combinations, damp heat conditioning was found to develop the most damage, and is typical of industrial environments. Where degradation was observed, conductive adhesive joints developed high resistance failures. Separation occurred along the component/adhesive interface. It is speculated that this is a combination of a cohesive failure of the epoxy binder in the conductive adhesive, plus an adhesive failure in the vicinity of the oxide film formed on the surface of the component, which could be adhesive to oxide or oxide to metal failures.

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1 INTRODUCTION

Fabrication of recyclable electronics will present major new opportunities over the coming decade. Current European legislation requires up to 75% of equipment in a range of applications to be recovered and recycled, with this percentage is expected to increase in the future. Existing assembly techniques, largely based on thermoset epoxy substrates, do not have viable recycling strategies, the only possible recovery mechanism is by hazardous incineration, as opposed to land-fill. With the introduction of the European WEEE (Waste in Electrical and Electronic Equipment) Directive in 2006 (reference 1), which aims to raise the level of recycling of electrical and electronic equipment (EEE) and encourages designers to create products with recycling in mind. There is therefore great interest in any potential low temperature manufacturing route for electronics that would enable the use of materials that are easy to disassemble/separate and recycle. Such routes could increase the potential recyclable content of electronics assemblies enabling a significant reduction in amount of electronics waste entering landfills. It was recently estimated in a DIUS-funded report (reference 2), that around 85% of all PCB scrap board waste goes to landfill, with around 70% of this being of non-metallic content (primarily reinforced epoxy substrate material) with little opportunity for recycling. Based on 1998 estimates, non-recyclable substrate materials contribute around 3.5 million tonnes or over 2% of the municipal waste stream annually and the growth in this waste stream is currently three times higher than the average municipal waste.

A potential route to enable higher levels of recycling in electronics assemblies is to form surface tracking using low temperature curing electrically conductive polymer inks in conjunction with low cost recyclable flexible substrates. These inks can be printed using a screen printer, similar to solder paste application. Such additive substrates (no material is removed during their manufacture) can then be assembled using electrically conductive adhesives.

The adhesives used are generally silver filled epoxy systems, with isotropic electrical properties, which can be applied and cured using the same equipment required for solder paste printing and reflow. There is no current test method for assessing the reliability of such systems, which differ in fundamental construction from the traditional solder/epoxy/glass constructions typical of electronics today. The failure modes for these novel 'solder and glass free' systems can be expected to be very different from those experienced with conventional solder joints.

Previous work at NPL (References 3 to 6) has indicated that thermal cycling, the conventional method of reliability assessment for soldered assemblies, is not the best method for stressing ICA joints. This is because these materials are compliant and thus deform to take up the thermal coefficient of expansion (TCE) mismatches between components and PCBs. Prolonged exposure to damp heat causes a more significant degradation in conductive performance of ICA joints. This damp heat environment is useful in driving this degradation process. This and similar regimes have also been used successfully by a number of other workers to age electrically conductive adhesives (References 7 to 14). Whilst the conductivity of the bulk material is generally unaffected by the damp heat conditioning because any silver oxide formed is still electrically conductive, the conditioning affects the conductivity of the surface finishes of the component terminations and PCB pads, due to the formation of oxides which are

non-conducting. The damp heat may also have the effect of reducing the adhesive bond between the epoxy based adhesive and the component and PCB terminations. The most recent work conducted on rigid thermoplastic substrate based assemblies (reference 3), the combination of thermal cycling followed by damp heat proved to be more deleterious than either thermal cycling or damp heat alone. It is speculated that the thermal cycling weakened the structure, which when exposed to damp heat enhances moisture ingress. The adhesive itself is relatively resilient to moisture effects, but the metallisation at the substrate and component suffer oxidation that leads to resistance increases.

The work described here covers the applicability of damp heat, thermal cycling and the new combinational test methods for the measurement of relative reliability of isotropic conductive adhesive (ICA) assemblies on flexible thermoplastic substrates.

2 METHODOLOGY

2.1 VEHICLE DESIGN

A single sided test vehicle was designed, incorporating Sn finished R1206, R0603 and SOIC gull-wing lead formats, NPL test board design TB75, shown in Figure 1. The assembly utilised daisy-chained components and zero ohm jumpers to enable electrical continuity to be measured through assembled components using the edge connectors. These components were chosen as the chip resistors have a large TCE and are normally terminated with a tin plated finish, which oxidises to increase joint resistance. The SOIC represent a different joint configuration which can prove problematic with conductive adhesives and is also representative of a typical solder terminated component. For ease of measurement all the individual circuits were led out to test points at the left hand end of the assembly.

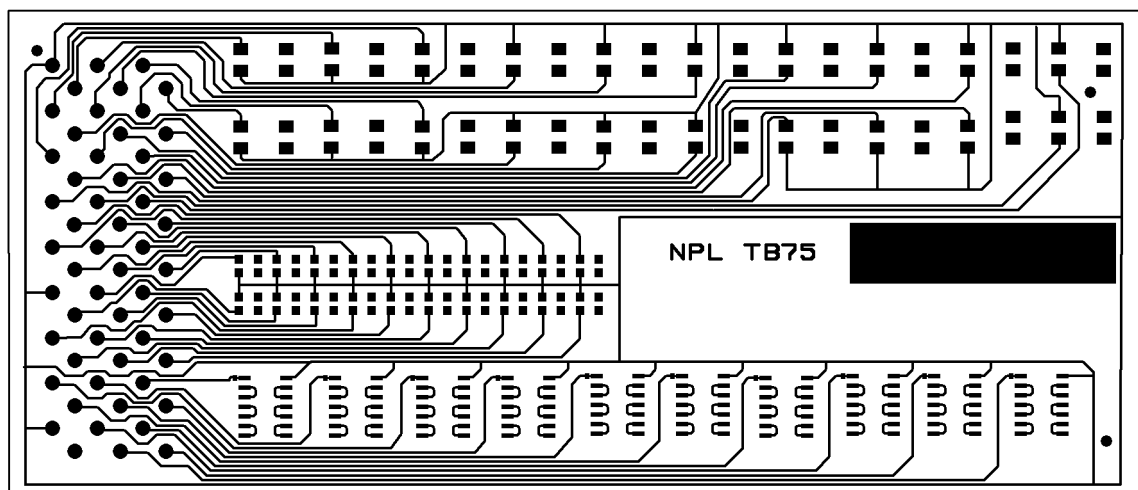


Figure 1: TB75 Test circuit design

2.2 TEST SUBSTRATE MANUFACTURE

2.2.1 PTF Substrates

The PTF test substrates were manufactured by stencil printing silver loaded ink using a stencil printer onto 100 μ m PET (Polyethylene terephthalate) substrates. The flexible substrate was held in position using a moving vacuum bed. Alignment to the stencil was achieved using fiducials on the vacuum bed, imaged through the transparent substrate. After printing, the ink was cured using an air circulation oven at 150 °C for 15 minutes. The resulting substrate is shown in Figure 2.

2.2.2 Direct-write Substrates

The direct-write test substrates were manufactured using a commercial ink-jet process. A UV curable catalyst was ink jetted onto PET substrates. After curing, the substrates are passed through an electroless copper plating solution to produce copper interconnect on the substrate surface. To improve oxidation resistance of the copper during stress screening, an additional coating of electroless Ag was then added onto the surface of the copper. The resulting substrate is shown in Figure 3.

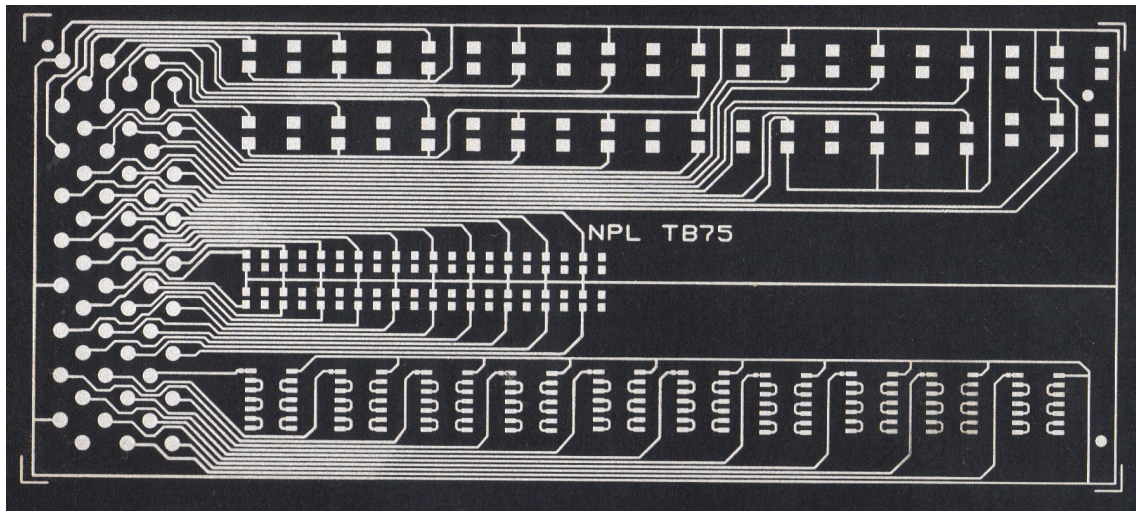


Figure 2: Completed transparent PTF substrate on black background

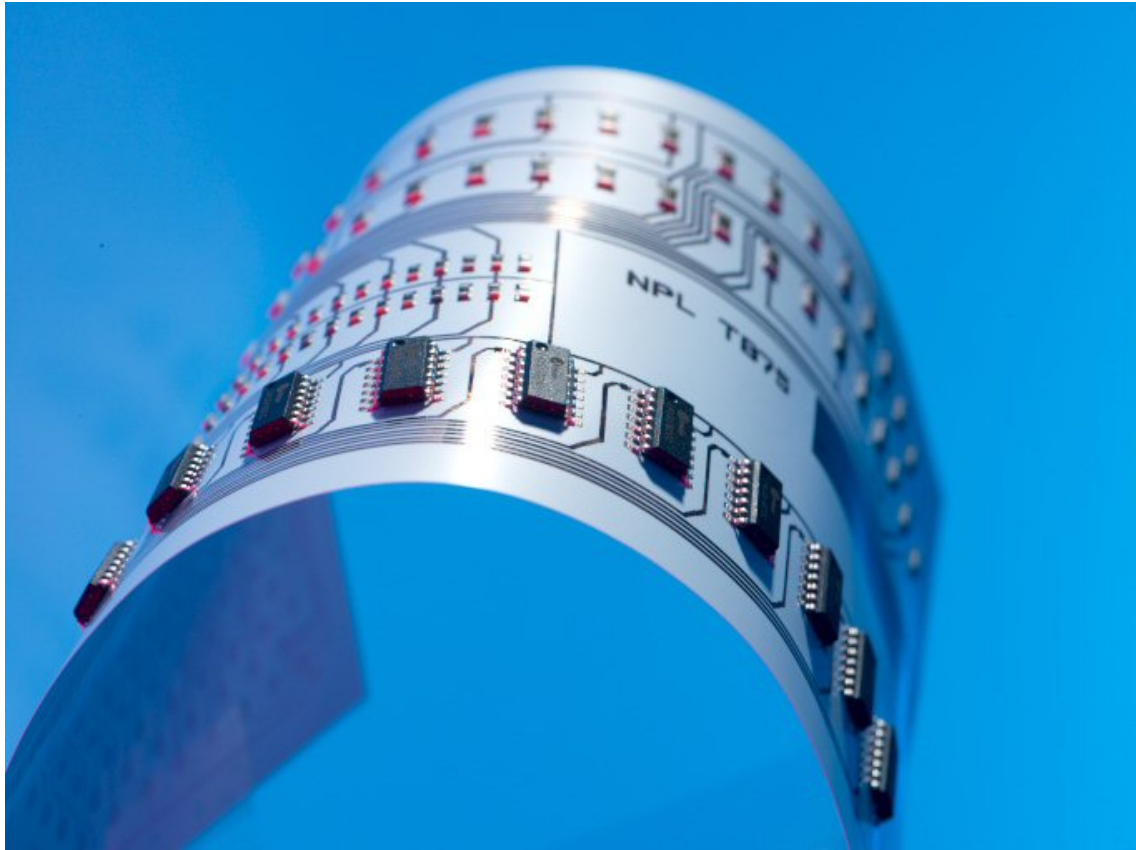


Figure 3: Assembled direct write substrate

2.3 TEST SAMPLE MANUFACTURE

Two different silver-filled epoxy electrically conductive adhesives were printed onto both PTF and direct-write substrates using a DEK 265 stencil printer, with a 75 μm laser cut stainless steel stencil. For chip resistor components, adhesive was printed on the inner half of the component lands only. For the gull-wing components, a full land print was utilised to overcome any variations in component lead bend configuration. Normal 60° metal squeegees were utilised.

After stencil printing, the components were placed using an automatic placement system. Cure of material P was undertaken in an air-circulation oven for 30 minutes at 150°C. Material X was cured in a 5-zone reflow oven for 5 minutes at 150°C. The assembly route followed standard SM assembly practices.

2.4 STRESS SCREENING REGIMES

After manufacture, groups of conductive adhesive assemblies were separately subjected to damp heat ageing at 85°C/85%RH for up to 2000 hours and thermal cycling (-55°C to +125 °C, 10 minute dwells, 10 °C /minute ramps) for up to 2000 cycles. Additional samples were also subjected to combinational testing, 500 thermal cycles followed by damp heat testing and 500 hours damp heat testing followed by thermal cycling.

2.5 ELECTRICAL CONTINUITY MONITORING

Every 250 hours during stress screening, the samples were tested at room temperature and the resistance of each circuit on the assembly logged via a PC, DVM and programmable switching system. A failure level of >100 ohms was set for inter-comparison purposes.

3 PTF STRESS SCREENING RESULTS

3.1 R1206 DAMP HEAT, THERMAL CYCLING AND COMBINATIONAL STRESS SCREENING RESULTS

A comparison of the electrical failures for damp heat, thermal cycle and combinational testing for R1206 is given in Figure 4. For single mode stress screening of PFT flexible assemblies, damp heat proved more detrimental than thermal cycling. For combinational testing, damp heat followed by thermal cycling did produce more failures after 1000 hours/cycles for ICA material X, but failure levels were low (<12%). For ICA material P, only thermal cycling followed by damp heat produced failures, which were less than 4%.

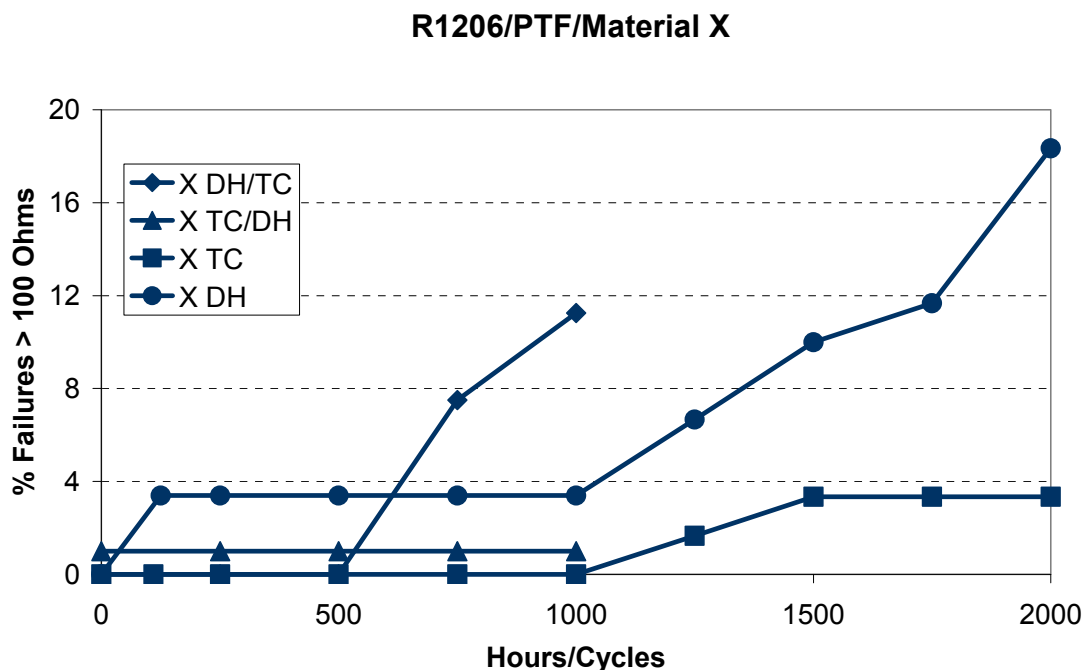


Figure 4: Comparison of electrical failures of R1206 for damp heat, thermal cycle and combinational testing for PTF assemblies

3.2 R0603 DAMP HEAT, THERMAL CYCLING AND COMBINATIONAL STRESS SCREENING RESULTS

A comparison of the electrical failures for damp heat, thermal cycle and combinational testing for R0603 is given in Figure 5. Again, for all stress screening regimes, failure levels were very low, (<7%).

For ICA material X, damp heat followed by thermal cycling did produce more failures after 1000 hours/cycles.

For ICA material P, both DH/TC and TC/DH produced less than 2% failures after 1000 hours testing and were indistinguishable.

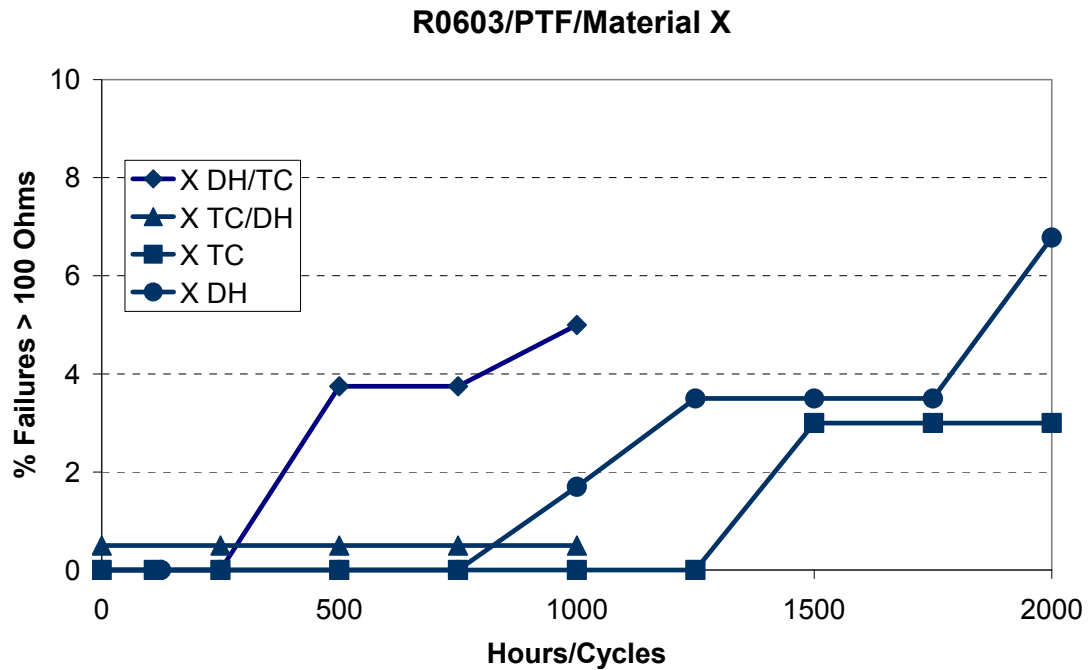


Figure 5: Comparison of electrical failures of R0603 for damp heat, thermal cycle and combinational testing for PTF assemblies with ICA material X

3.3 SOIC DAMP HEAT, THERMAL CYCLING AND COMBINATIONAL STRESS SCREENING RESULTS

A comparison of the electrical failures for damp heat, dry heat and thermal cycle testing of SOIC components, is given in Figure 6 and Figure 7. The failure levels for SOIC components were higher than for the other component types. The greatest failure levels were generated using damp heat testing. Thermal cycling alone had the lowest failure levels. For both ICA materials there were few differences between the different combinational testing.

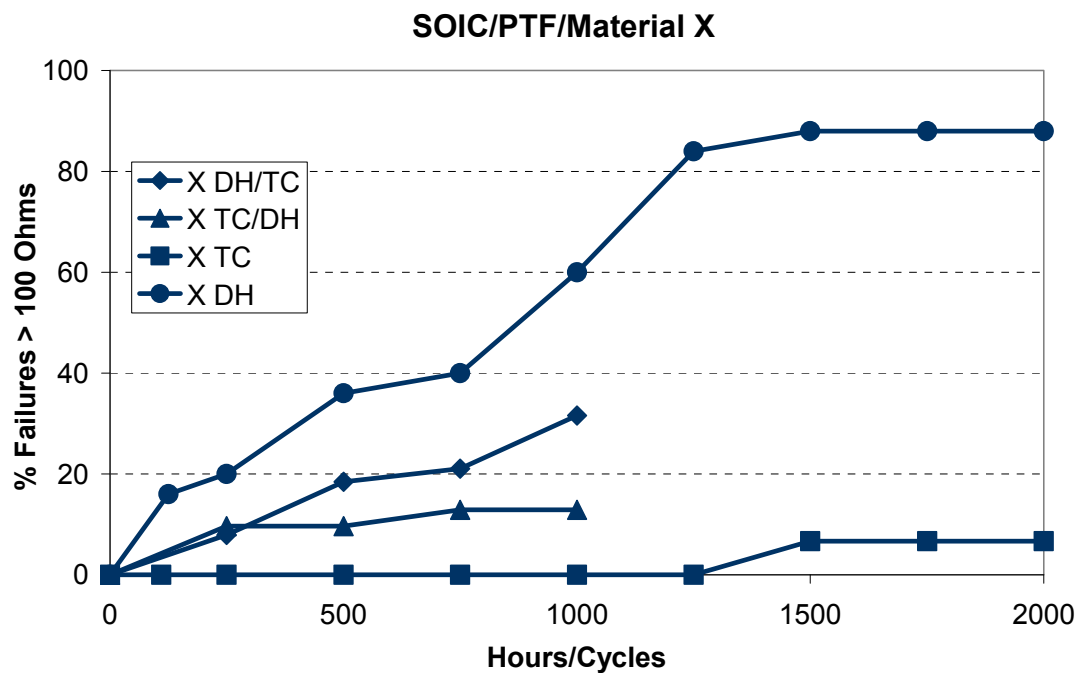


Figure 6: Comparison of electrical failures of SOIC for damp heat, thermal cycle and combinational testing for PTF assemblies for ICA material X

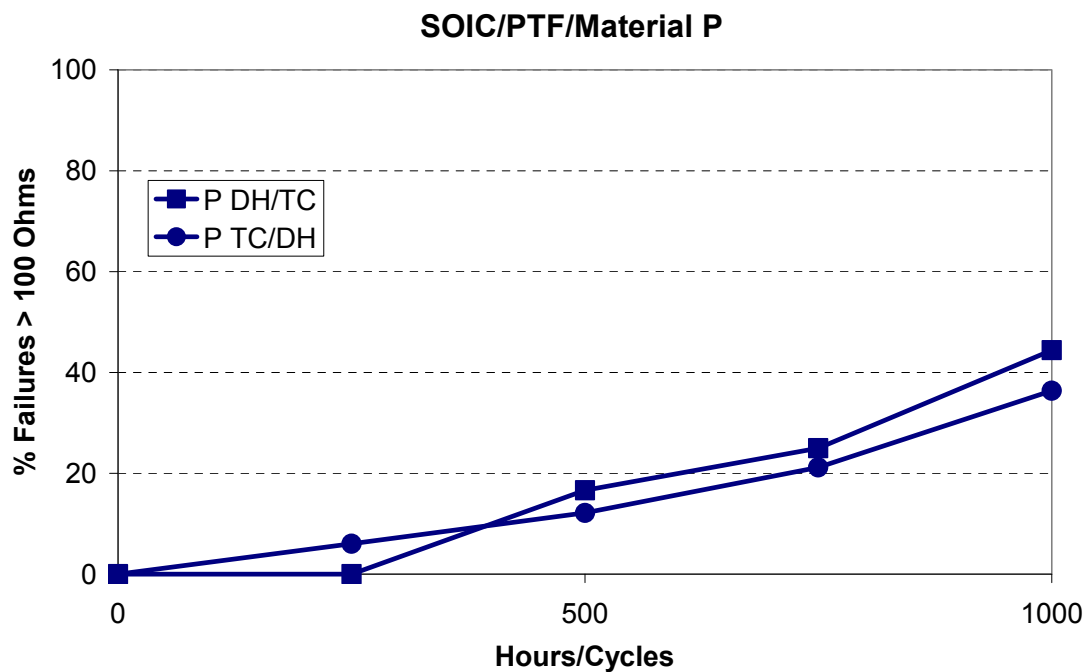


Figure 7: Comparison of electrical failures of SOIC for damp heat, thermal cycle and combinational testing for PTF assemblies for ICA material P

4 DIRECT WRITE RESULTS

4.1 R1206 DAMP HEAT AND THERMAL CYCLING STRESS SCREENING RESULTS

A comparison of the electrical failures for damp heat and thermal cycle testing of direct write assemblies for R1206, is given in Figure 8. For single mode stress screening of direct write flexible assemblies, it was not possible to differentiate between damp heat and thermal cycling. For samples just finished in copper, failures were significantly higher than for those with the additional silver finish. Silver finished samples, after 1000 hours/cycles of testing, exhibited insufficient failures (<3%) for conclusions to be made.

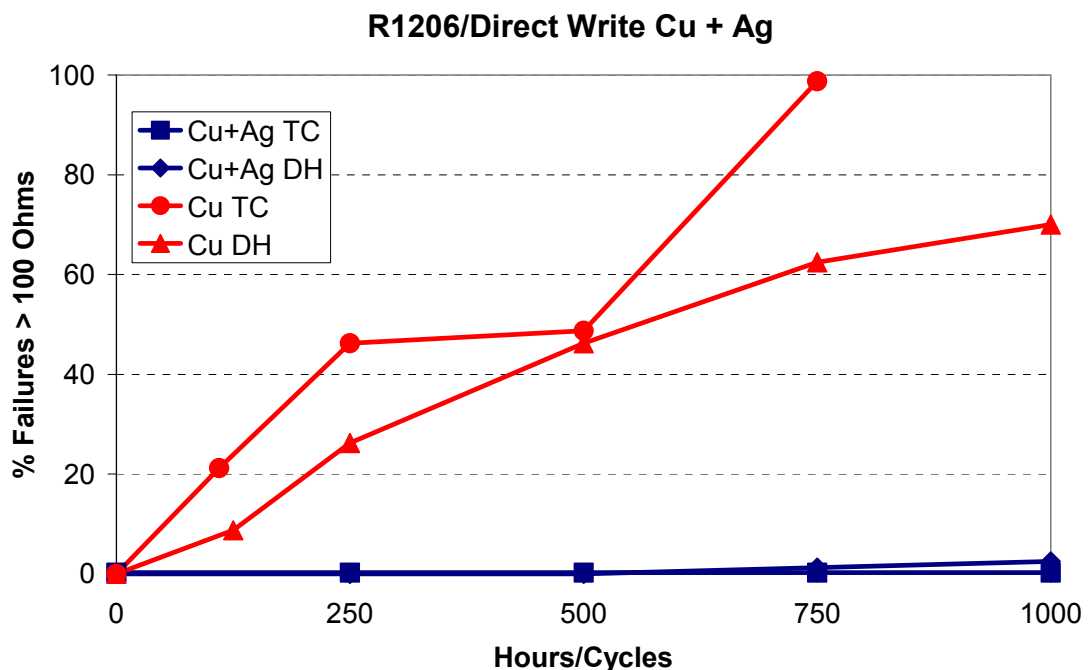


Figure 8: Comparison of electrical failures of R1206 for damp heat and thermal cycle testing for direct write assemblies

4.2 R0603 DAMP HEAT AND THERMAL CYCLING STRESS SCREENING RESULTS

A comparison of the electrical failures for damp heat and thermal cycle testing of direct write assemblies for R0603 components assembled with ICA material X, is given in Figure 9. For samples just finished in copper, failures were significantly higher than for those with the additional silver finish, with thermal cycling showing a higher level of failures. Failure levels for silver finished samples are shown in Figure 10. For the X ICA material, results were inseparable, but for ICA material P, thermal cycle stress screening produced a greater failure rate although this was still less than 10%.

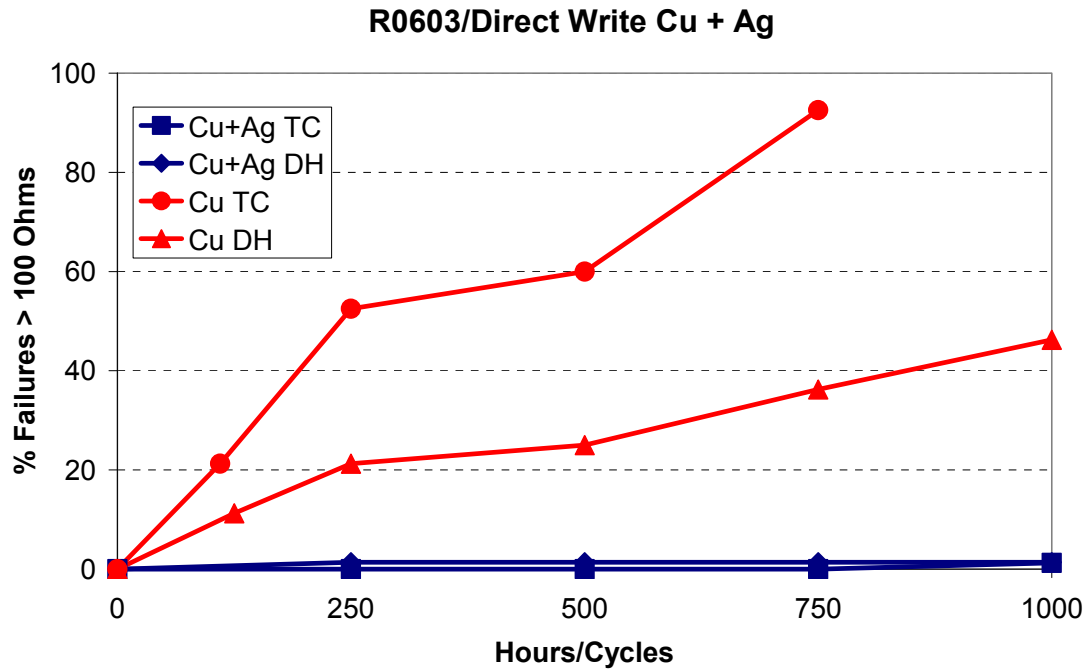


Figure 9: Comparison of electrical failures of R0603 for damp heat and thermal cycle testing for direct write assemblies with ICA material X.

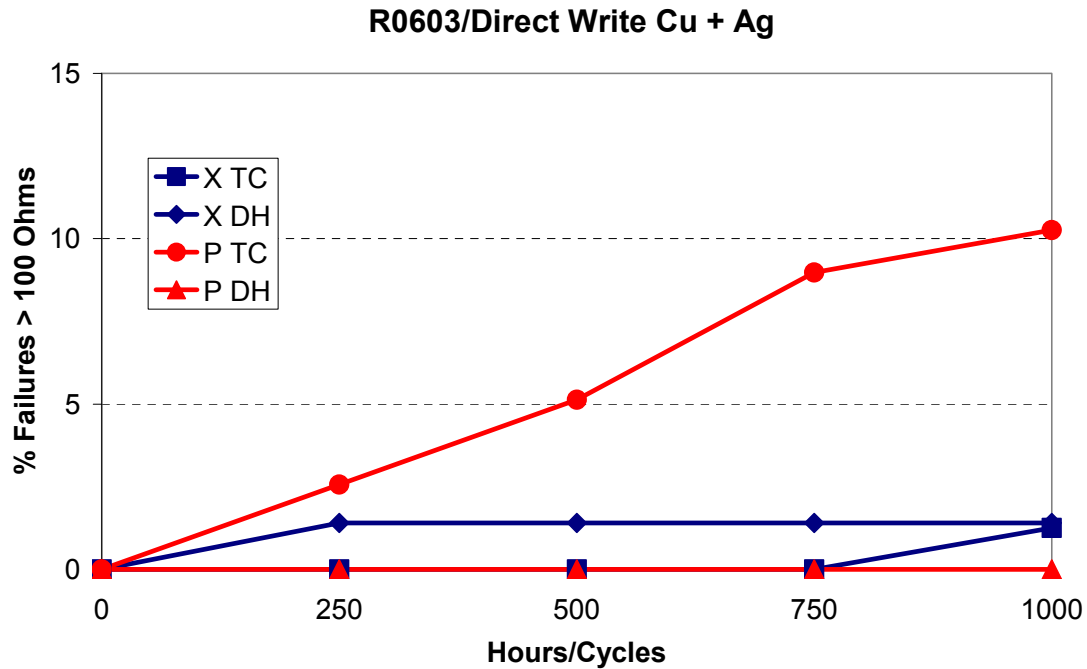


Figure 10: Comparison of electrical failures of R0603 for damp heat and thermal cycle testing for silver finished direct write assemblies

4.3 SOIC DAMP HEAT AND THERMAL CYCLING STRESS SCREENING RESULTS

A comparison of the electrical failures for damp heat and thermal cycle testing of direct write assemblies for SOIC components assembled with ICA material X, is given in Figure 11. For samples just finished in copper, failures were significantly higher than for those with the additional silver finish, with again thermal cycling showing a higher level of failures. Failure levels for silver finished samples are shown in Figure 12. For both X and P ICA materials, results were inseparable.

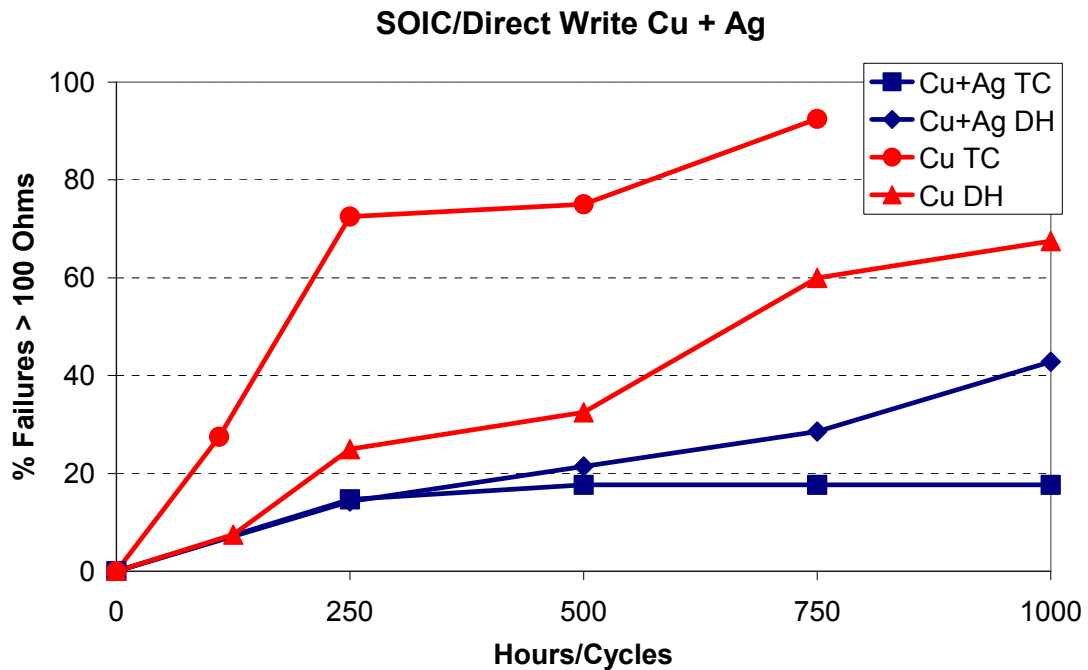


Figure 11: Comparison of electrical failures of SOIC for damp heat and thermal cycle testing for direct write assemblies with ICA material X.

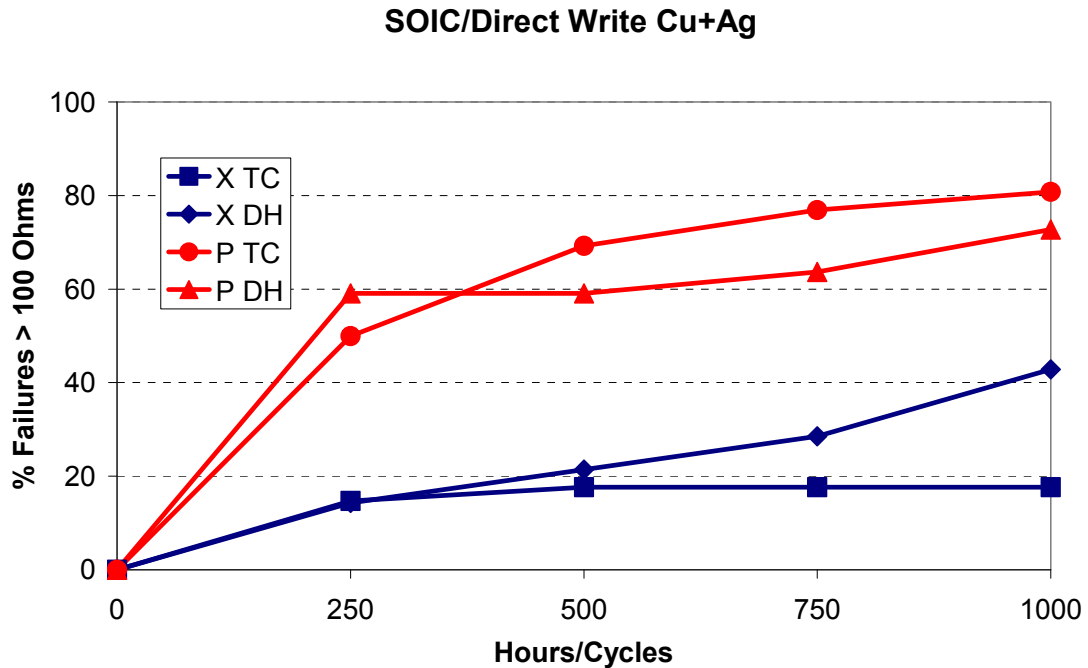


Figure 12: Comparison of electrical failures of SOIC for damp heat and thermal cycle testing for direct write assemblies with ICA material X.

5 DISCUSSION

Previous work at the National Physical Laboratory using isotropic conductive adhesives with conventional glass re-enforced thermoset (FR4) substrates (references 4, 5 and 6), has shown that the bulk properties of the ICAs changed little during damp heat, dry heat or thermal cycling. Isotropic conductive adhesive joints were also largely unaffected by dry heat ageing or thermal cycling. These joints have inherently flexible characteristics, which enabled them to overcome the coefficient of thermal expansion (CTE) mismatches between the substrate and chip resistors. For the adhesive types used, damp heat stressing proved more effective at inducing electrical failures due to oxidation of the tin plated component terminations and de-adhesion of the component to conductive adhesive interface. Recent work (reference 3) with un-reinforced rigid thermoplastic laminates with a high CTE mismatch between substrate and component, has shown that earlier failures can be generated by the combination of thermal cycling followed by damp heat testing. This combination produced failures of the same type but significantly earlier during testing than for thermal cycling or damp heat alone, or for the combination of damp heat followed by thermal cycling. It was speculated that the thermal cycling weakened the structure, which when exposed to damp heat enhances moisture ingress. The adhesive itself is relatively resilient to moisture effects, but the adhesive bond at the metallisation, of the substrate and component, deteriorates due to oxidation, and leads to resistance increases.

In this work deterioration in the joint due to combinational testing was not noted with the PTF flexible substrates. Whilst a combination of damp heat followed by thermal cycling did produce higher failures for the X ICA material for chip resistor components (Figure 4 and Figure 5), the technique only produced up to 10% failures in 1000 hours of testing, compared to 30 to 50% failures for rigid thermoplastic substrates

(reference 1). The same trend was not seen for the other adhesive used, or for the SOIC components. This is likely to be because thermal cycling induced ageing utilises the mismatch in CTE, which results in strain on a rigid substrate, but for these flexible substrates that strain is dissipated by the relaxation in the substrate. For all three component types, thermal cycling produced the lowest level of failures. Although the substrate has a high CTE (25 to 92 ppm/°C, reference 15), compared to the alumina base of the chip components (around 6 ppm/°C, reference 16), the substrates are only 100 microns thick. Therefore any stress placed on the structure due to CTE mismatch, is likely to deform the substrate rather than stress the adhesive interconnect. Indeed the general trend in the data suggests that damp heat testing would be the best stress regime to determine relative reliability between flexible samples. The conductive adhesive joint resistance across the substrate and component interface increased significantly with time. Typical failures are indicated in Figure 13 and Figure 14. Separation occurs along the component/adhesive interface, and will be associated with oxide growth. Failure occurs at either of three places, the adhesive oxide joint, the oxide itself, or the oxide metal joint. Electrical continuity failure will occur since the oxide is an insulator. Mechanical failure may also occur at one of the interfaces discussed above, which will accelerate the oxidation process and the overall failure of the joint. Similar failures were noted in the other component types.

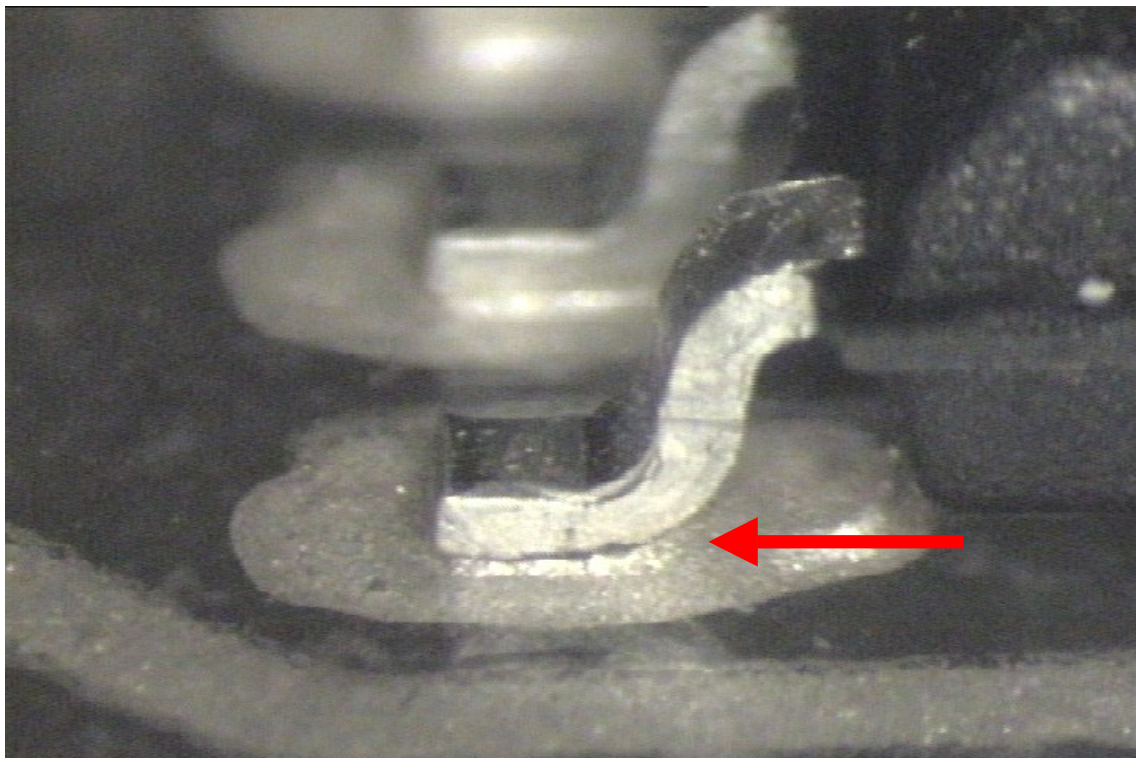


Figure 13: Typical failure in ICA/PTF joint after 2000 thermal cycles with separation along the component/adhesive interface

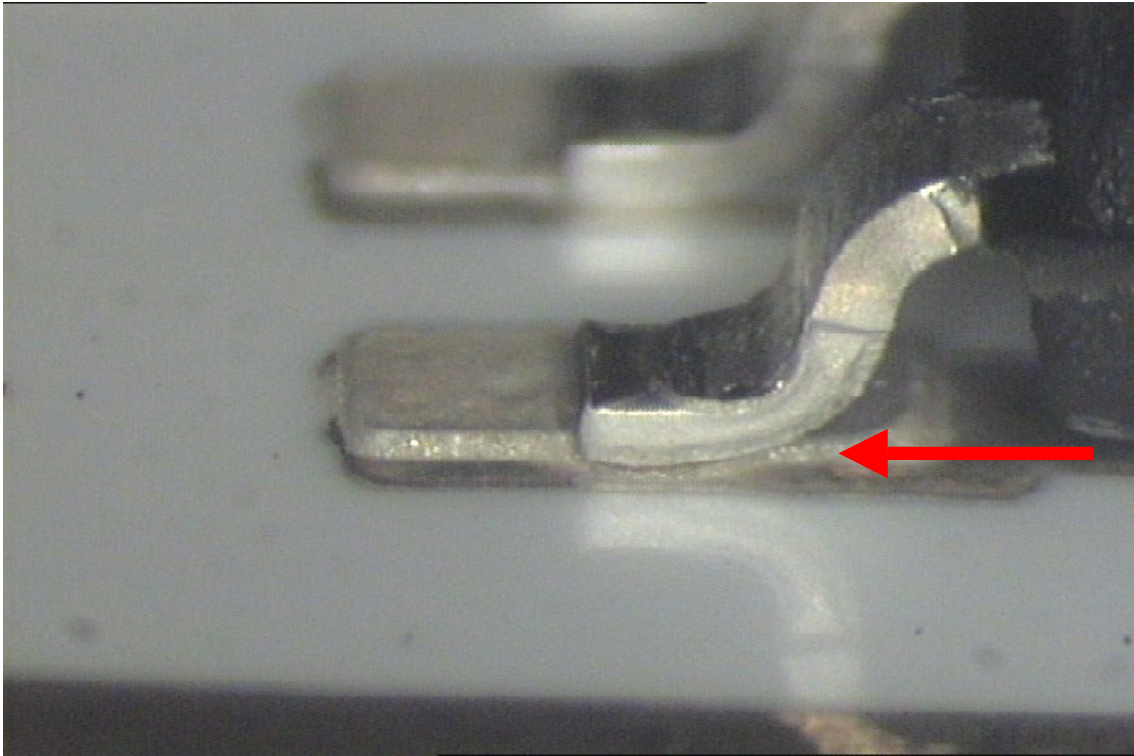


Figure 14: Typical failure in ICA/PTF joint after 2000 hours damp heat with separation along the component/adhesive interface

For the direct-write substrates without the immersion Ag coating, a different failure mechanism is present. Here, thermal cycling could be seen to produce greater failure rates (Figure 8 and Figure 9). Closer examination of these failures showed that the failures were occurring in the copper tracks not in the conductive adhesive joints. The very thin Cu here ($\sim 2\mu\text{m}$) is prone to oxidation over a 1000 hour/cycle test period, resulting in high track interconnect resistance and thus electrical failures. Although the thermal cycled samples are only at their higher temperature for approximately half their test period, the higher temperature (125°C compared to 85°C for damp heat testing) produces a faster oxidation rate (reference 17).

The addition of the immersion Ag coating on the copper significantly improves the performance of these substrates. For both chip resistor components, there were less than 3% failures for 1000 hours/cycles of damp heat or thermal cycling, compared to ~ 50 to 100% failures for the copper alone. For the SOIC components, the silver finish reduced failures for thermal cycling by 80%. For damp heat testing, failures were reduced by 40%. For these failures, the mode was the same as for the PTF substrates. Typical examples can be seen in Figure 15 and Figure 16. Separation again occurs along the component/adhesive interface.

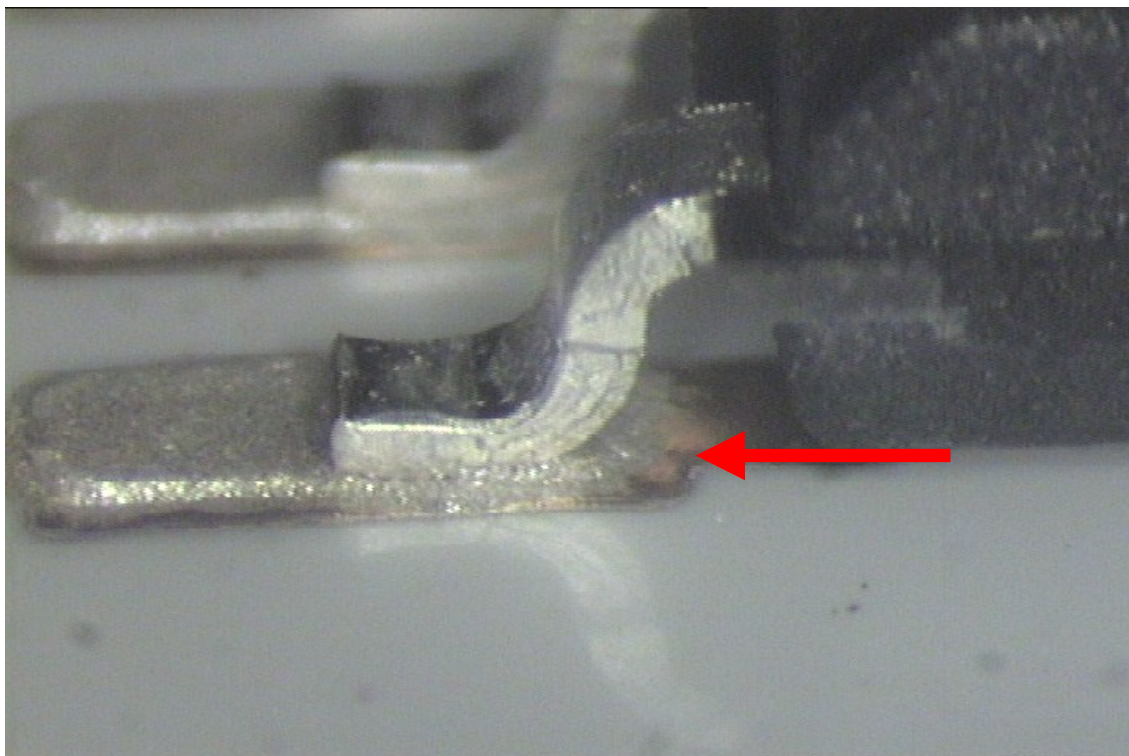


Figure 15: Typical failure in ICA/direct write joint after 1000 cycles thermal cycling with separation along the component/adhesive interface

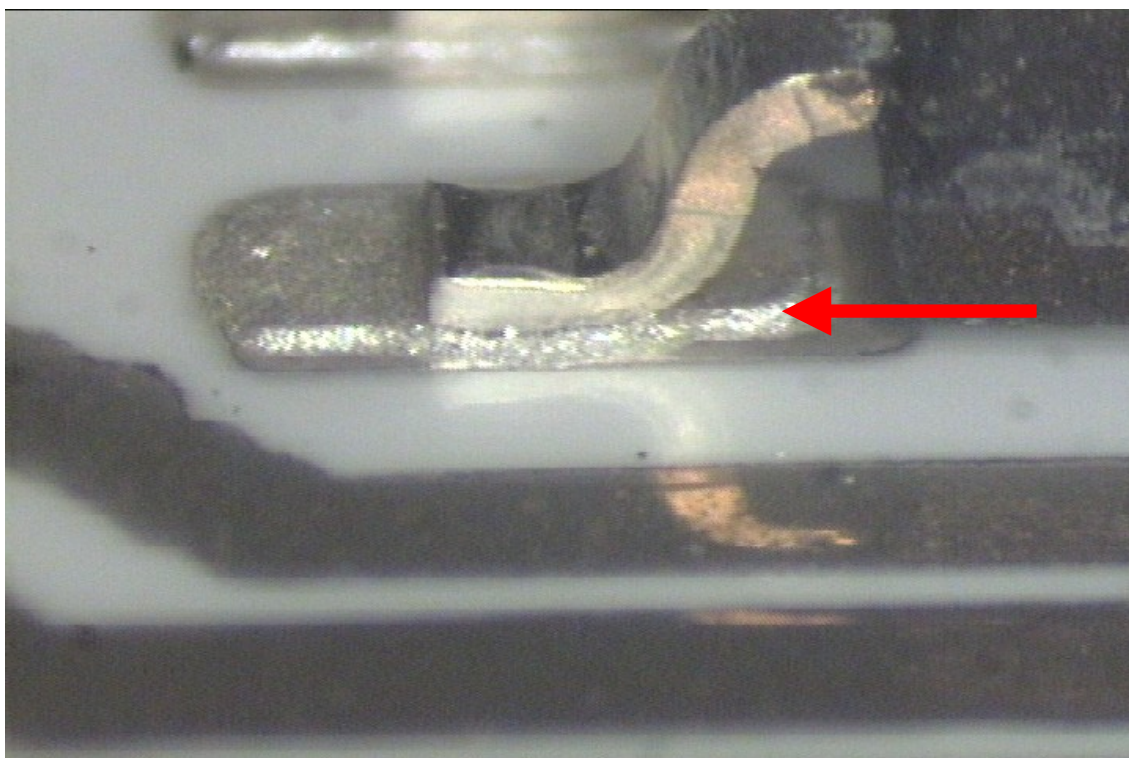


Figure 16: Typical failure in ICA/direct write joint after 1000 hours damp heat with separation along the component/adhesive interface

6 CONCLUSIONS

This underpinning work to develop a test method for characterising the reliability of flexible thermoplastic substrates and conductive adhesive interconnects has been advanced. This work has shown that these structures have intrinsically good reliability performance, with chip resistor joints surviving 1000 hours/cycles damp heat and thermal cycle testing with less than 3% failures for polymer thick film substrates and less than 10% failures for direct write copper with immersion Ag. These structures are susceptible to increasing resistance failures due to interfacial changes. The conductive adhesive joint resistance across the substrate and component interface increased significantly with time. The failure rate is product dependent, reflecting the complexities of a successful adhesive/component/substrate package.

Susceptibility to failure was found to be dependent on the stress regime. Damp heat was determined to be most deleterious. Previous work had shown that the combination of thermal cycling followed by damp heat proved to be more efficient at generating failures in similar assemblies based on rigid thermoplastic substrates. However, for the flexible assemblies investigated here, no such acceleration in interconnection failure rate was detected. The adhesive itself is relatively resilient to moisture effects, but the metallisation at the substrate and component suffer oxidation that leads to resistance increases. In terms of electrical failures, the order of robustness for the components tested was (most robust first): R0603>R1206>SOIC. For the direct write copper + immersion silver, there were insufficient failures after 1000 hours/cycles testing to distinguish between the two types of chip resistor. The use of unprotected thin interconnection tracks of direct write copper was found to be unpractical due to oxidation of the copper at the elevated test temperatures. Covering the copper with an immersion Ag finish significantly improved the longevity of the direct write option.

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