

Report

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Preliminary Measurements for Thermoplastic Electronics: Developing a Stress Screening Test

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ABSTRACT

Following the implementation of WEEE legislation, there is an increasing interest in adopting more sustainable manufacturing processes and materials, while maintaining performance. These material and structural changes to the assemblies can lead to alternative failure modes. This work studies the performance of specific favoured materials to qualify the failure mechanisms and the effective stress screening regimes, and hence put in place the underpinning work for developing a test method for characterising these materials.

Thermoplastic printed circuit assemblies based on polyetherimide, were assembled using electrically conductive adhesives and tested using damp heat, dry heat and thermal cycling, and combinations of these. Three generic interconnect styles were investigated.

For the majority of conductive adhesive/component combinations, the combination of thermal cycling followed by 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 earlier than either with damp heat testing or thermal cycling alone, and there was a drop in the shear strength of the joint. Further work will look at developing the detection of failing electrical resistance.

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1 INTRODUCTION

With the introduction of the European WEEE (Waste in Electrical and Electronic Equipment) Directive in 2006, 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 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 DTI-funded report, 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 use low temperature curing electrically conductive polymer adhesives (CAs) in conjunction with low cost recyclable substrates. Thermoplastic substrates can be fabricated by electroless plating of the plastic, followed by imaging, electroplating and etching. Conventional electroless surface finishes such as ENIG (electroless nickel/immersion gold) and immersion Ag can be applied. Such subtractive substrates (additional material is added and then removed during their manufacture) have the advantage of being able to be fabricated using the existing PCB fabrication industry infrastructure.

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 are very different from those experienced with conventional solder joints.

Previous work at NPL (References 1 to 3) has indicated that thermal cycling, the conventional methods 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. 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 not 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. It should be noted that thermoplastic substrates generally have a higher TCE than their conventional glass fibre reinforced equivalents.

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

2 METHODOLOGY

2.1 VEHICLE DESIGN

A test vehicle was designed, incorporating Sn finished R1206, R0603 and SOIC gull-wing lead formats, NPL test board design TB71. The component side of a double-sided circuit is 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 mismatch with the substrate 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. The test circuit also included two sets of daisy-chained vias (0.7mm drilled diameter, 3:1 aspect ratio and 0.5mm drilled diameter, 4:1 aspect ratio) to evaluate z-axis expansion effects on via reliability.

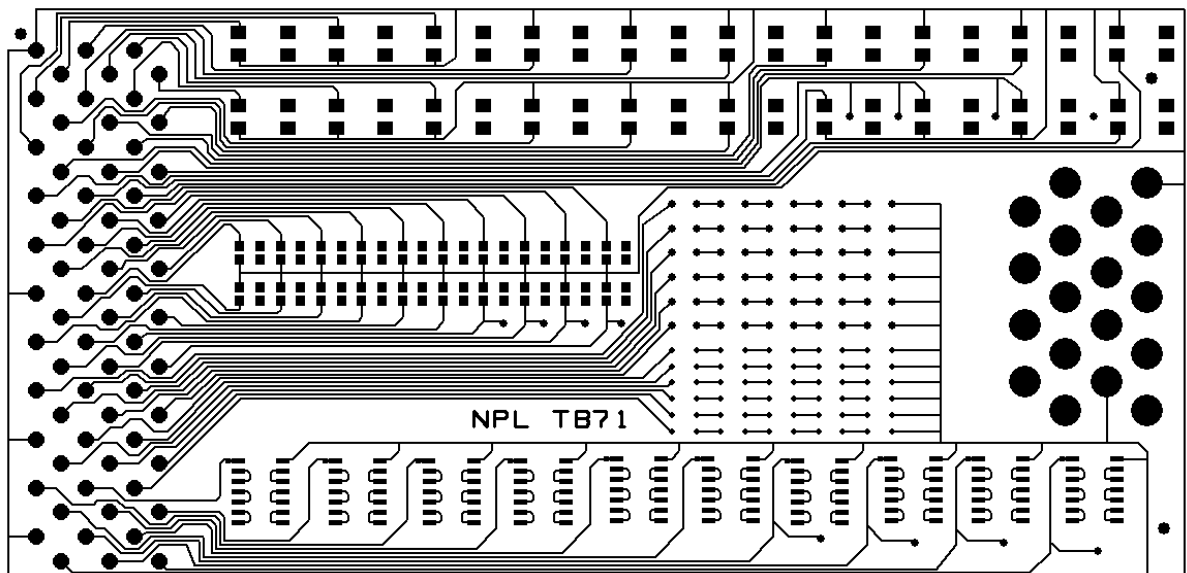


Figure 1: TB71 Test circuit design

2.2 TEST SUBSTRATE MANUFACTURE

The test substrates were manufactured using conventional PCB fabrication methods from $150 \times 150 \text{ mm} \times 2 \text{ mm}$ thick moulded plates of 30% glass-filled polyetherimide (as shown in Figure 2). Scrap from moulding process is recycled into more substrates. After drilling, the plates are electroless plated with copper and then electroplated with copper to produce a 1oz/sq. foot copper thickness. After imaging, Sn plating, etching, and stripping, a surface finish of immersion gold on electroless nickel (ENIG) was added. A solder mask was incorporated onto the board. Whilst not required for restricted solder spread, the mask does provide surface insulation between tracks and pads. Two test circuits were included on each plate.

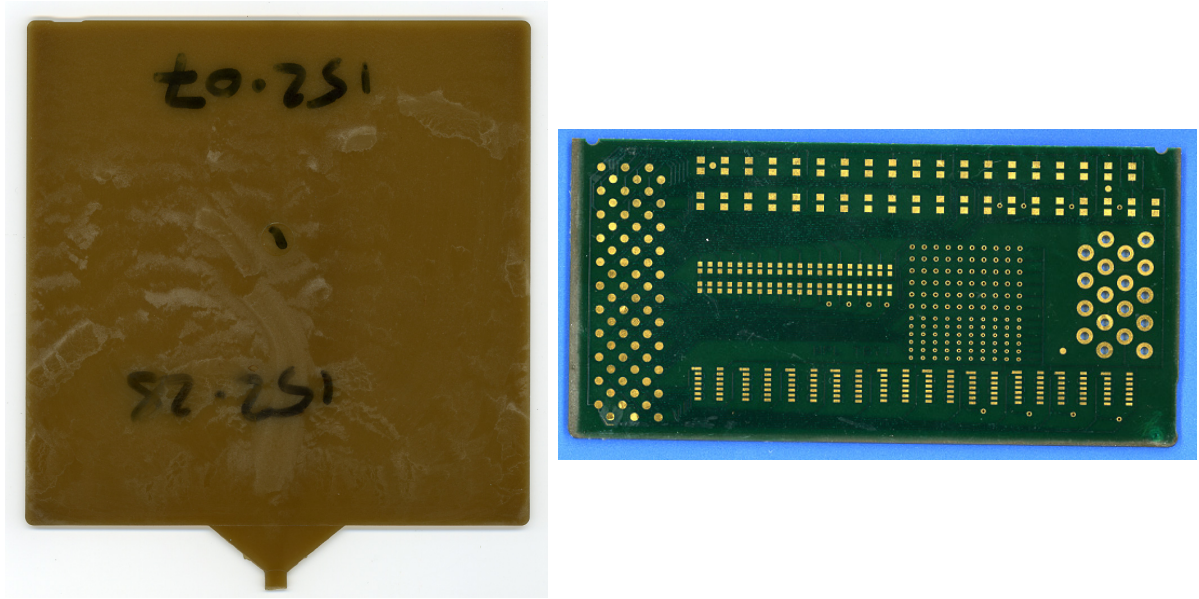


Figure 2: Polyetherimide plate prior to PCB fabrication (left) and completed PCB (right)

Table 1: Comparison of FR4 and polyetherimide properties

Properties	FR4 (Typical 150°C T _g)	Polyetherimide (Typical 30% filled)
CTE z axis (ppm/degC)	60	20-60
CTE x/y axis (ppm/degC)	13-16	20-60
Thermal Conductivity (W/mdegC)	0.4-0.5	0.3
Glass Transition Temperature (deg C)	150	217

2.3 TEST SAMPLE MANUFACTURE

Two different silver-filled epoxy electrically conductive adhesives were printed using a DEK 265 stencil printer, with a laser cut stainless steel stencil. The stencil thickness used was 75 μm . 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.

Substrates were also assembled using a SnBi solder paste (Bi57Sn43 eutectic with a melting point of 137 °C). Conventional SM assembly practices were employed with a peak reflow temperature of 150 °C).

2.4 SHEAR TESTING

Some R1206 resistor components were subjected to shear testing, before and after stress screening. Figure 3 illustrates a typical shear test. These tests were undertaken on a Dage Series-4000 modular multi-function bond-tester. The stand-off height of the tool was set equal to $h/2$ (typically 80 μm), between the bottom of the shear tool and board surface (h is the stand-off height between the component and the board surface). During each test, the shear tool was moved forward at a defined speed (200 $\mu\text{m/s}$) against the test component, and the applied force increased until the attachment was broken.

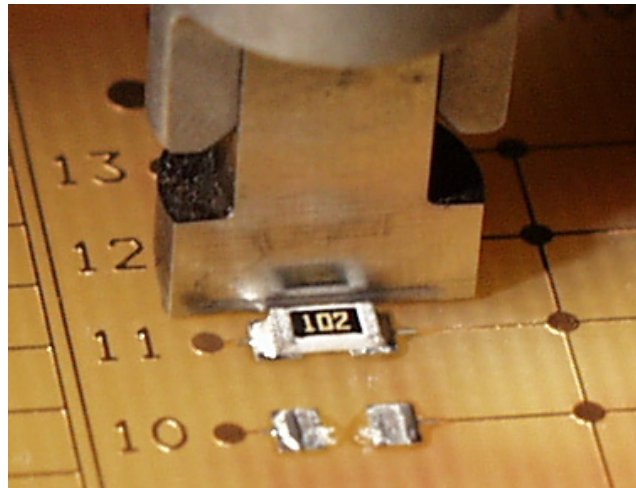


Figure 3: Shear Test Jig and Push-off Tool Before a Shear Test

2.5 STRESS SCREENING REGIMES

After manufacture, groups of conductive adhesive assemblies were separately subjected to damp heat ageing at 85°C/85%RH for 2000 hours, dry heat ageing at 125 °C for 2000 hours and thermal cycling (-55°C to +125 °C, 10 minute dwells, 10 °C /minute ramps). 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.

SnBi soldered samples were subjected to two different thermal cycling regimes of -55 °C to +125 °C, 10 minute dwells, 10 °C /minute ramps and -20 °C to +80 °C, 10 minute dwells, 10 °C /minute ramps.

2.6 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.

3 ISOTROPIC CONDUCTIVE ADHESIVES RESULTS

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

A comparison of the electrical failures for damp heat, dry heat and thermal cycle testing is given in

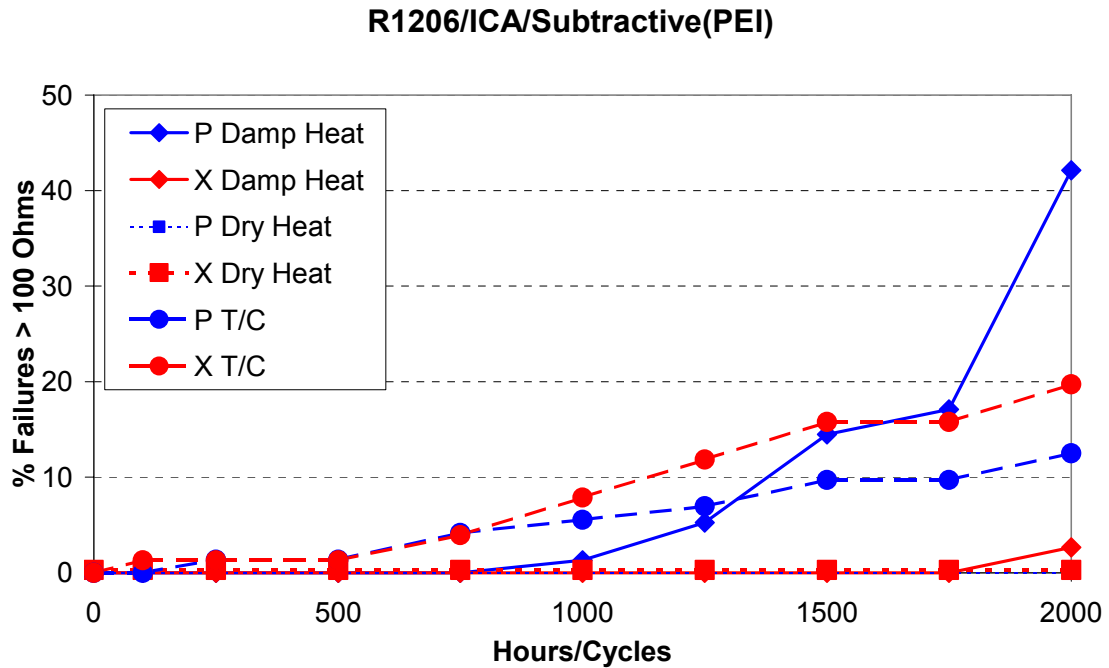


Figure 4. For damp heat testing, conductive adhesive material X performed better than material P. For thermal cycling, the materials offered similar performance. ICA material X showed more failures for thermal cycling than for damp heat testing. The opposite was true for material P, which exhibited more failures for damp heat testing than for thermal cycling. Dry heat testing produced few failures.

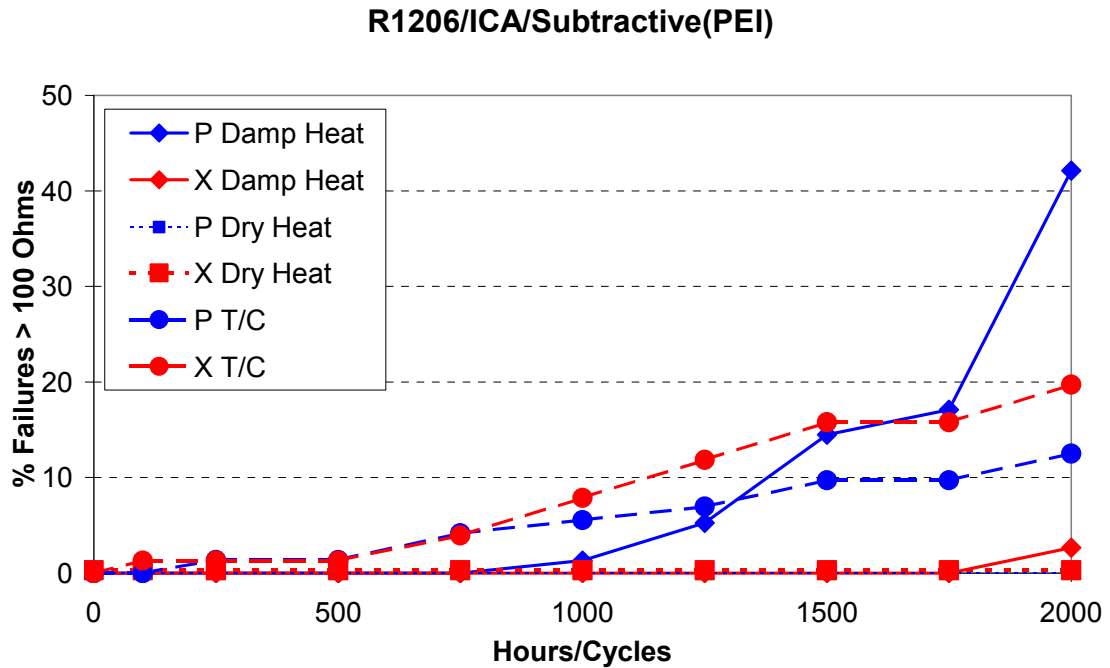


Figure 4: Comparison of electrical failures of R1206 for damp heat, dry heat and thermal cycle testing

3.2 R1206 COMBINATIONAL STRESS SCREENING RESULTS

A comparison of the electrical failures for combinational testing is given in Figure 5. For both materials (P and X) thermal cycling followed by damp heat testing (TC+DH) proved more severe than damp heat testing followed by thermal cycling (DH+TC). Failure levels for both materials were similar.

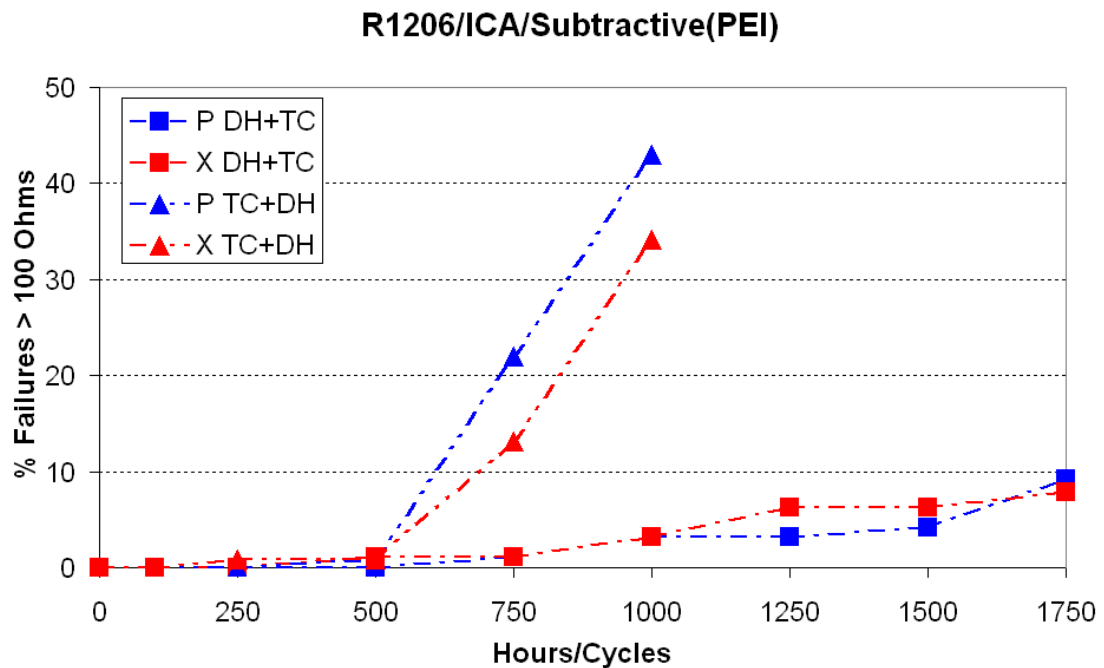


Figure 5: Comparison of electrical failures of R1206 for combinational testing

3.3 R0603 DAMP HEAT, DRY HEAT AND THERMAL CYCLING STRESS SCREENING RESULTS

A comparison of the electrical failures for damp heat, dry heat and thermal cycle testing is given in Figure 6. For damp heat and thermal cycle testing, conductive adhesive material X performed better than material P. With these smaller components, both ICA materials (X and P) showed more failures for damp heat testing than for thermal cycling. Dry heat testing produced few failures.

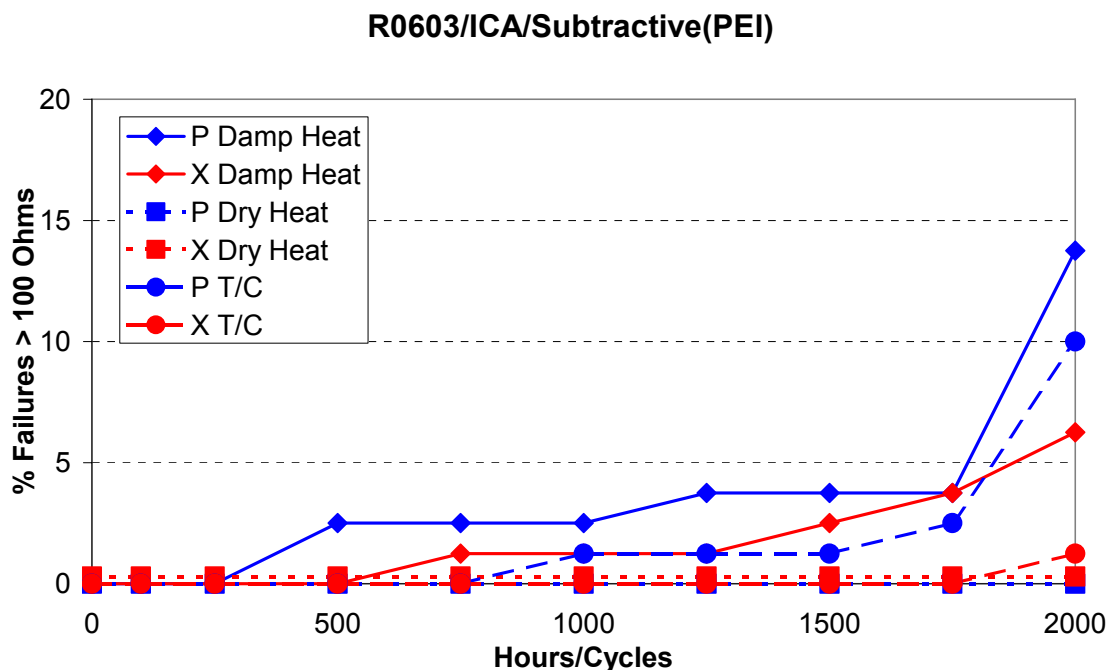


Figure 6: Comparison of electrical failures of R0603 for damp heat, dry heat and thermal cycle testing

3.4 R0603 COMBINATIONAL STRESS SCREENING RESULTS

A comparison of the electrical failures for combinational testing is given in Figure 7. For material P, thermal cycling followed by damp heat testing (TC+DH) proved more severe than damp heat testing followed by thermal cycling (DH+TC). Failure levels were similar for both regimes for material X. There were also similar failure levels for both materials for damp heat testing followed by thermal cycling (DH+TC).

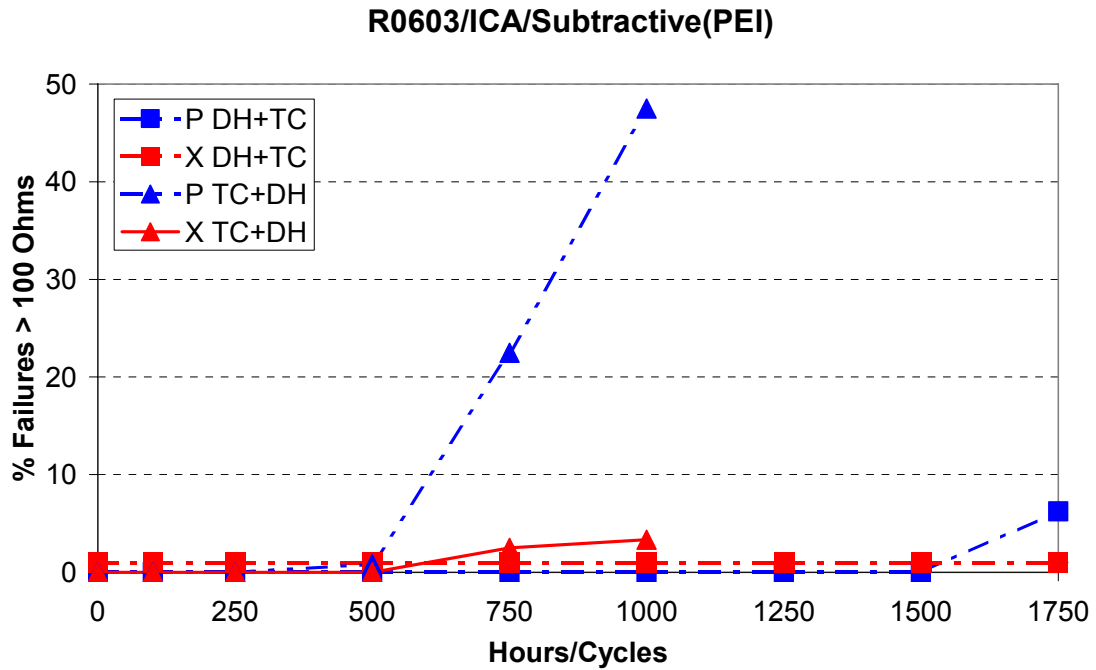


Figure 7: Comparison of electrical failures of R0603 for combinational testing

3.5 SOIC DAMP HEAT, DRY HEAT AND THERMAL CYCLING STRESS SCREENING RESULTS

A comparison of the electrical failures for damp heat, dry heat and thermal cycle testing is given in Figure 8. For damp heat and thermal cycle testing, conductive adhesive material X performed better than material P. ICA material P showed earlier failures for damp heat testing than for thermal cycling. For material X, both damp heat and thermal cycling exhibited similar failure levels. Dry heat testing produced few failures.

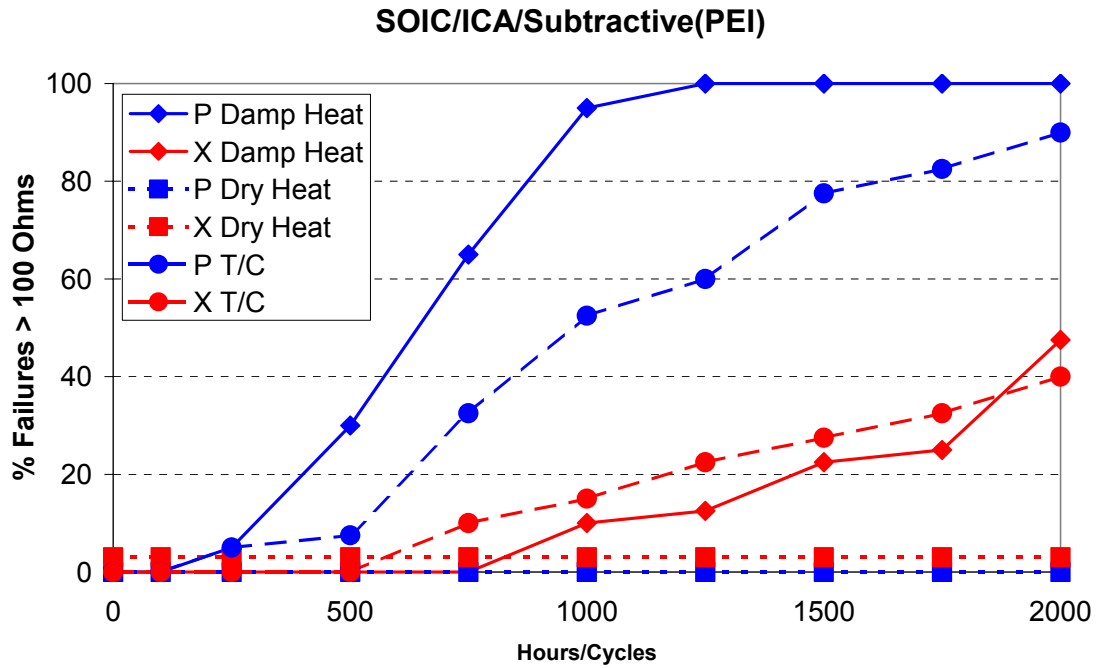


Figure 8: Comparison of electrical failures of SOICs for damp heat, dry heat and thermal cycle testing

3.6 SOIC COMBINATIONAL STRESS SCREENING RESULTS

A comparison of the electrical failures for combinational testing is given in Figure 9. For material P, thermal cycling followed by damp heat testing (TC+DH) proved more severe than damp heat testing followed by thermal cycling (DH+TC). Failure levels were similar for both regimes for material X. For both regimes, material X performed better than material P.

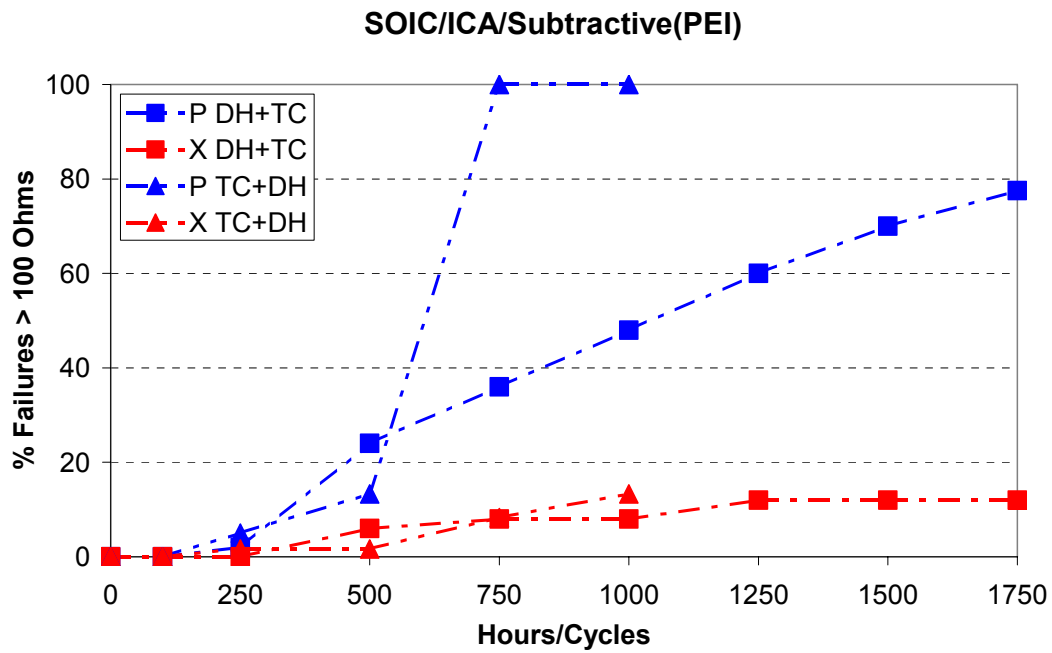


Figure 9: Comparison of electrical failures of SOIC components for combinational testing

3.7 VIA DAMP HEAT, DRY HEAT AND THERMAL CYCLING STRESS SCREENING RESULTS

A comparison of the electrical failures for vias, for damp heat, dry heat and thermal cycle testing is given in Figure 10. There were insufficient failures even after at 2000 cycles/hours to distinguish between conditions.

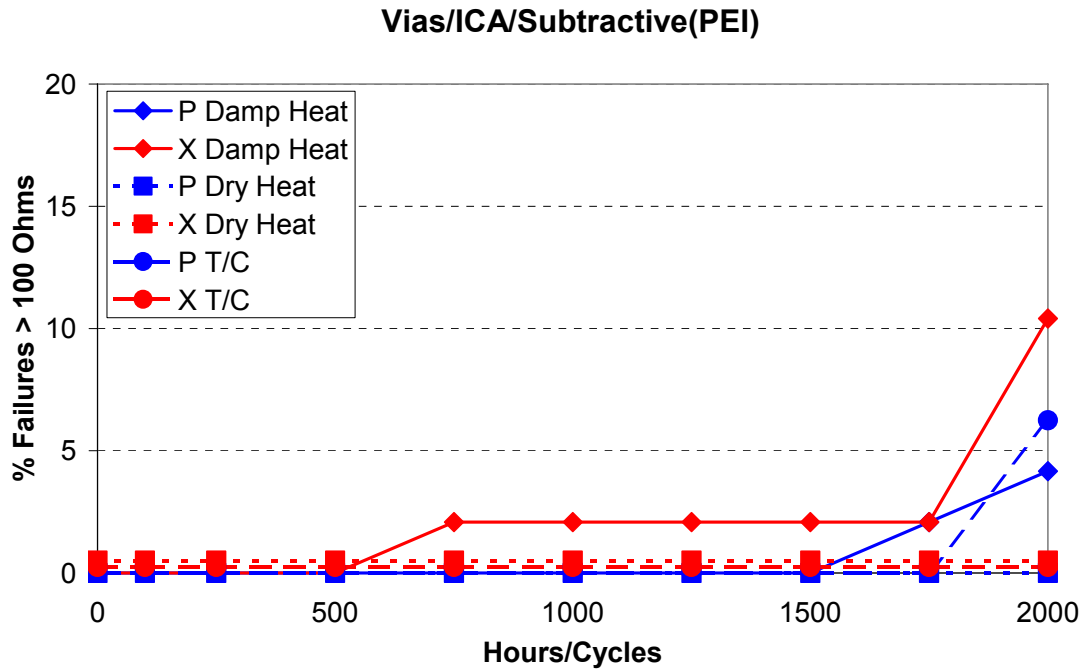


Figure 10: Comparison of electrical failures of Vias for damp heat, dry heat and thermal cycle testing

3.8 VIA COMBINATIONAL STRESS SCREENING RESULTS

Combinational stress screening did not produce significant failures in the vias.

3.9 DAMP HEAT AND THERMAL CYCLING SHEAR TESTING RESULTS

A comparison of shear strengths of R1206 components for damp heat and thermal cycle testing is given in Figure 11. Both materials (P and X) showed significant but similar reductions in shear strengths after 1000 thermal cycles and 1000 hours damp heat testing. In both cases, damp heat testing exhibited lesser reductions than thermal cycling.

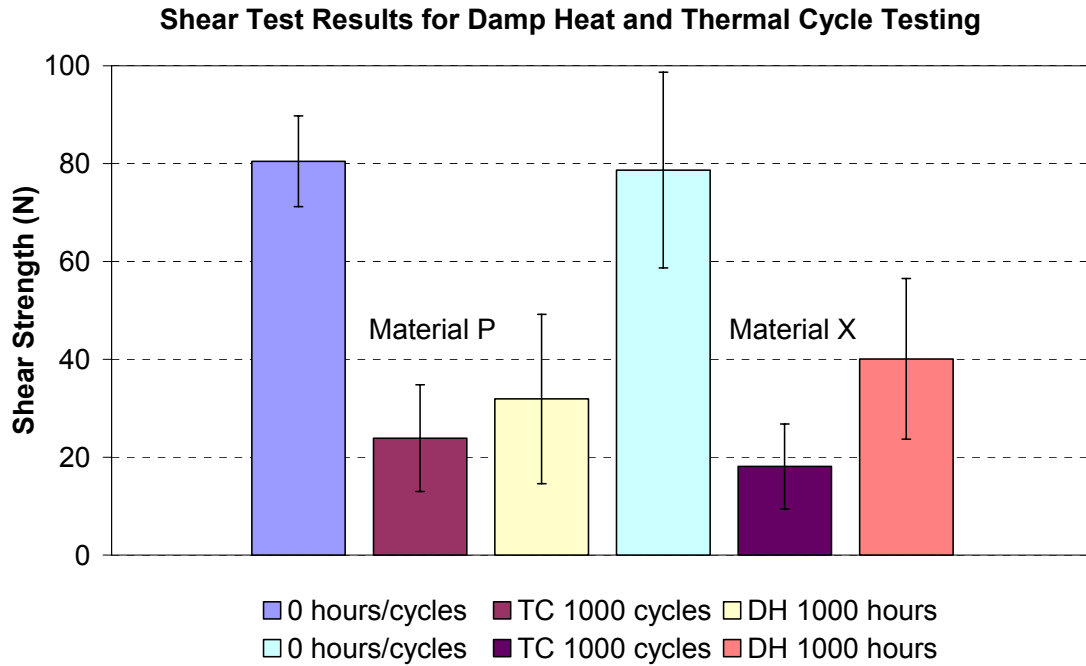


Figure 11: Comparison of shear strengths of R1206 components for damp heat and thermal cycle testing

3.10 COMBINATIONAL STRESS SCREENING SHEAR TEST RESULTS

A comparison of shear strengths of R1206 components for combinational testing is given in Figure 12. Both materials (P and X) showed significant but similar reductions in shear strengths after 1000 cycles + hours combinational testing (DH + TC and TC + DH). In both cases, thermal cycling followed by damp heat testing (TC + DH) exhibited greater reductions than damp heat followed by thermal cycling.

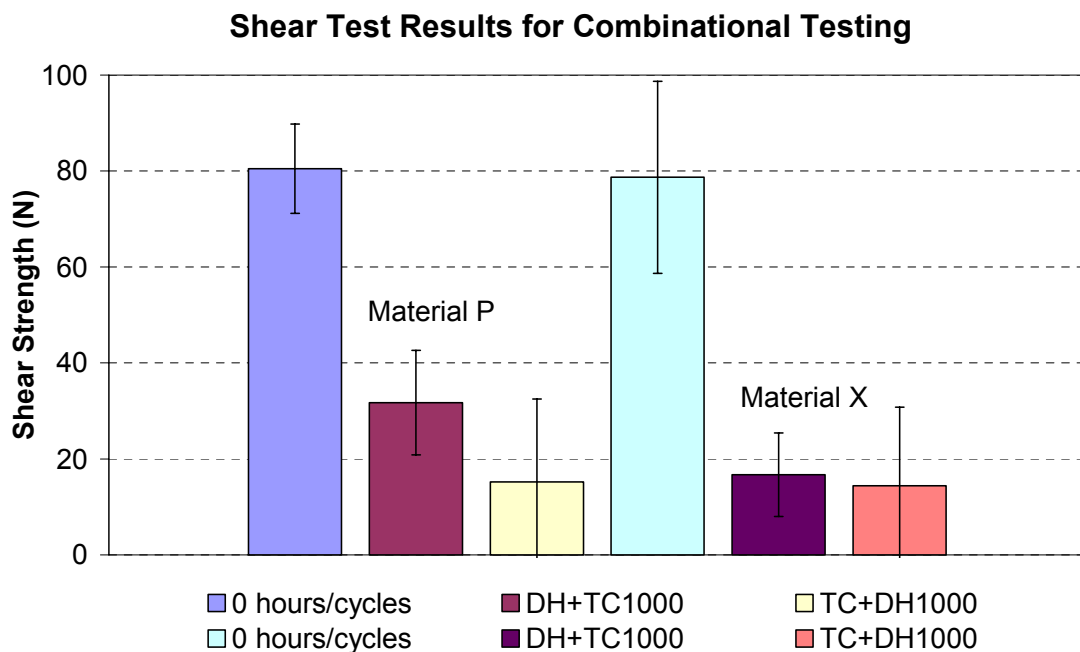


Figure 12: Comparison of shear strengths of R1206 components for combinational testing

4 TIN BISMUTH RESULTS

4.1 SNBI THERMAL CYCLING STRESS SCREENING RESULTS

No electrical test failures were generated in 1250 cycles, -20 to $+80$ °C or 1200 cycles, -55 to $+125$ °C.

4.2 SNBI SHEAR TEST RESULTS

A comparison of shear strengths of SnBi soldered joints before and after the two types of thermal cycling are given in Figure 13. As manufactured, the SnBi shear strengths are at a similar level to the conductive adhesives. Both thermal cycling regimes show a reduction of shear strengths after 1000 cycles, but the -55 to $+125$ °C samples showed a greater reduction.

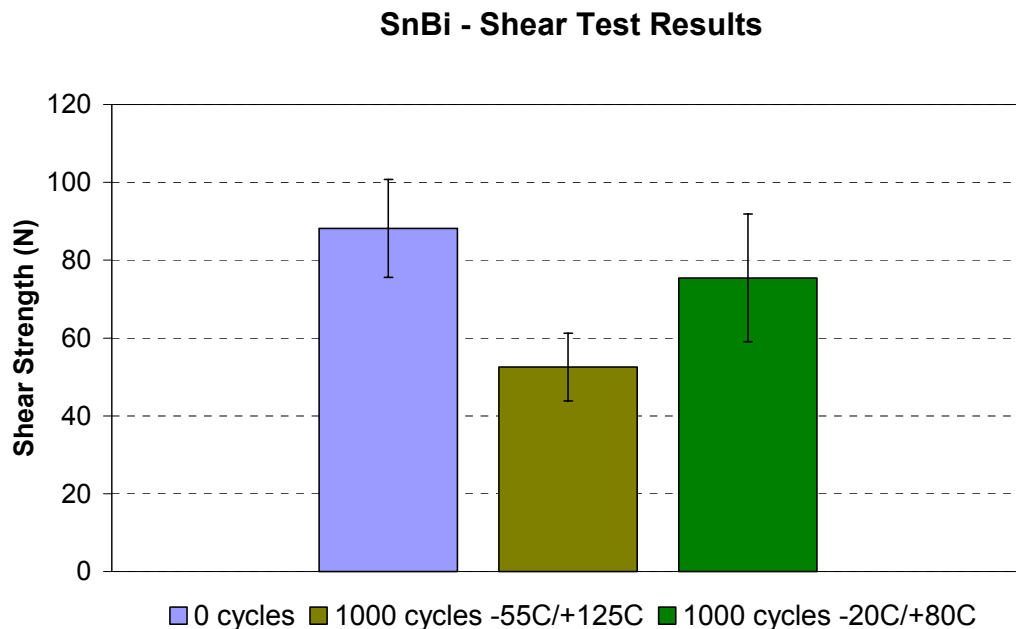


Figure 13: Comparison of SnBi shear test results

5 DISCUSSION

Previous work at the National Physical Laboratory using isotropic conductive adhesives with conventional glass re-enforced thermoset (FR4) substrates (references 1, 2 and 3), 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 had inherently flexible characteristics, which enabled them to overcome the coefficient of thermal expansion (CTE) mismatch between the substrate (16 to 20 ppm/°C) and chip resistors (6 to 8 ppm/°C). 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. However, in this work, the CTE of the

PEI substrate material is significantly higher at 50 ppm/°C (reference 4) as the material did not contain glass re-enforcement.

As with the FR4 substrates in the previous work, for the un-reinforced thermoplastic assemblies, significant failures were only generated after 1000 hours or cycles of damp heat, dry heat or thermal cycling. However, with reference to

R1206/ICA/Subtractive(PEI)

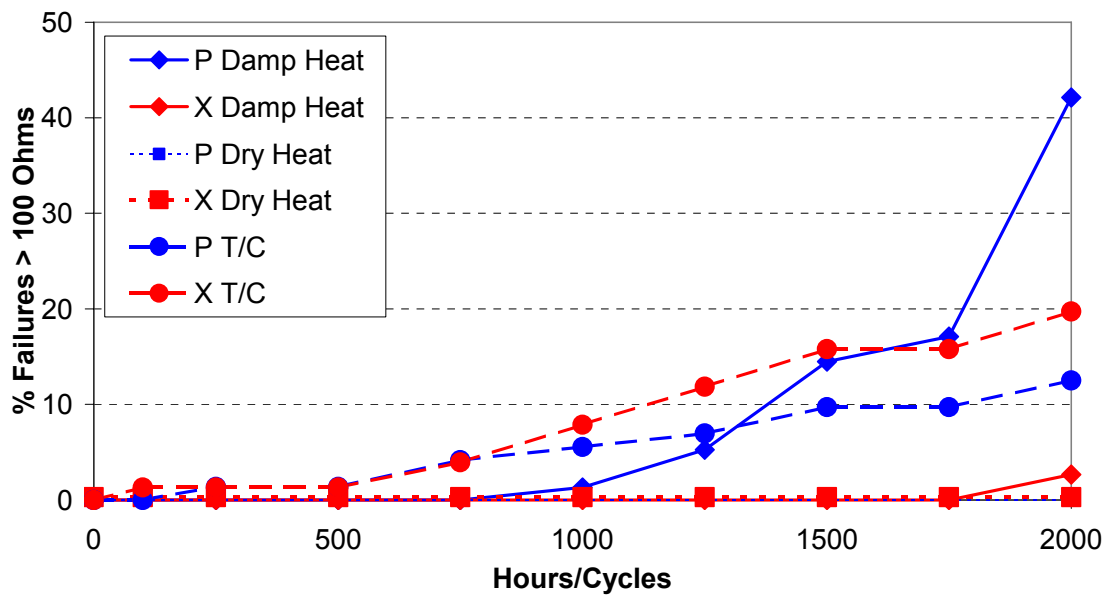


Figure 4, for R1206 components, material X showed more failures for thermal cycling than for damp heat testing, the opposite of material P, indicating improved damp heat resistance for this material compared to those used in earlier work. For the R0603 components, where the smaller component size results in smaller strains during thermal cycling, material X exhibited similar failure levels for both damp heat and thermal cycling. The same were true for the SOIC components which do not have a smaller CTE mismatch to the substrate.

A comparison of the level of failures generated for 1206 resistors across all testing regimes is shown in Figure 14. Here it can be seen that combinational testing of 500 thermal cycles followed by 500 hours damp heat stressing, had a significant effect on the level of failures generated, with failure levels approaching 50%. The opposite order for combinational testing did not produce failure levels significantly greater than damp heat or thermal cycling alone. Figure 15 and Figure 16 show micro-sections of joints after damp heat and combinational testing respectively. Both examples show similar failure modes, with the tin plated component to adhesive interface failing.

The efficacy of the combinational testing is further borne out by the shear testing results. A comparison of the data for material P is shown in Figure 17, where the reduction in shear strength is greatest for the thermal cycling followed by damp heat.

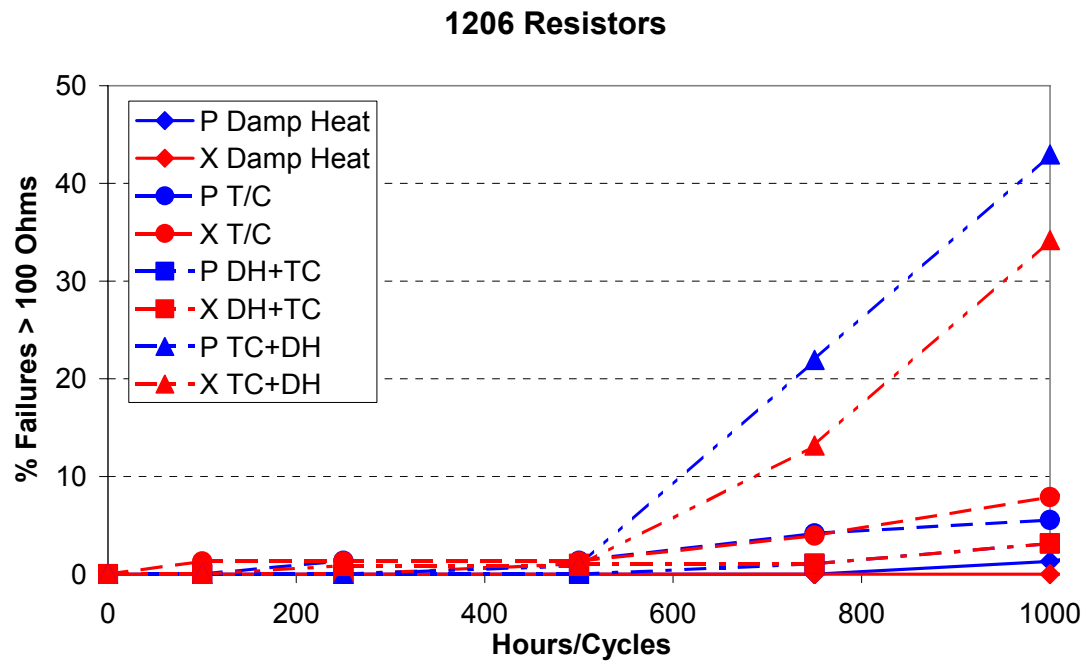


Figure 14: Comparison of R1206 failure levels for all testing regimes up to 1000 hours/cycles

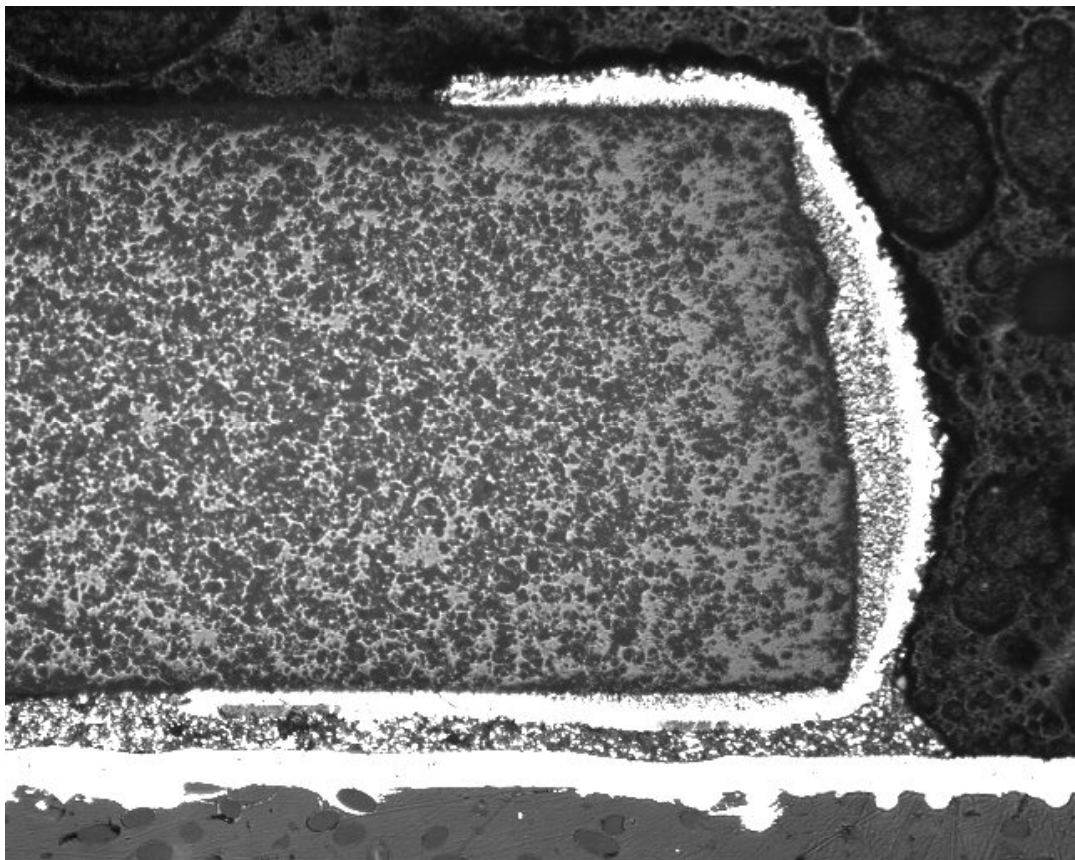


Figure 15: SEM micrograph of R1206 after 2000 hours damp heat stressing @ 85degC/85%RH

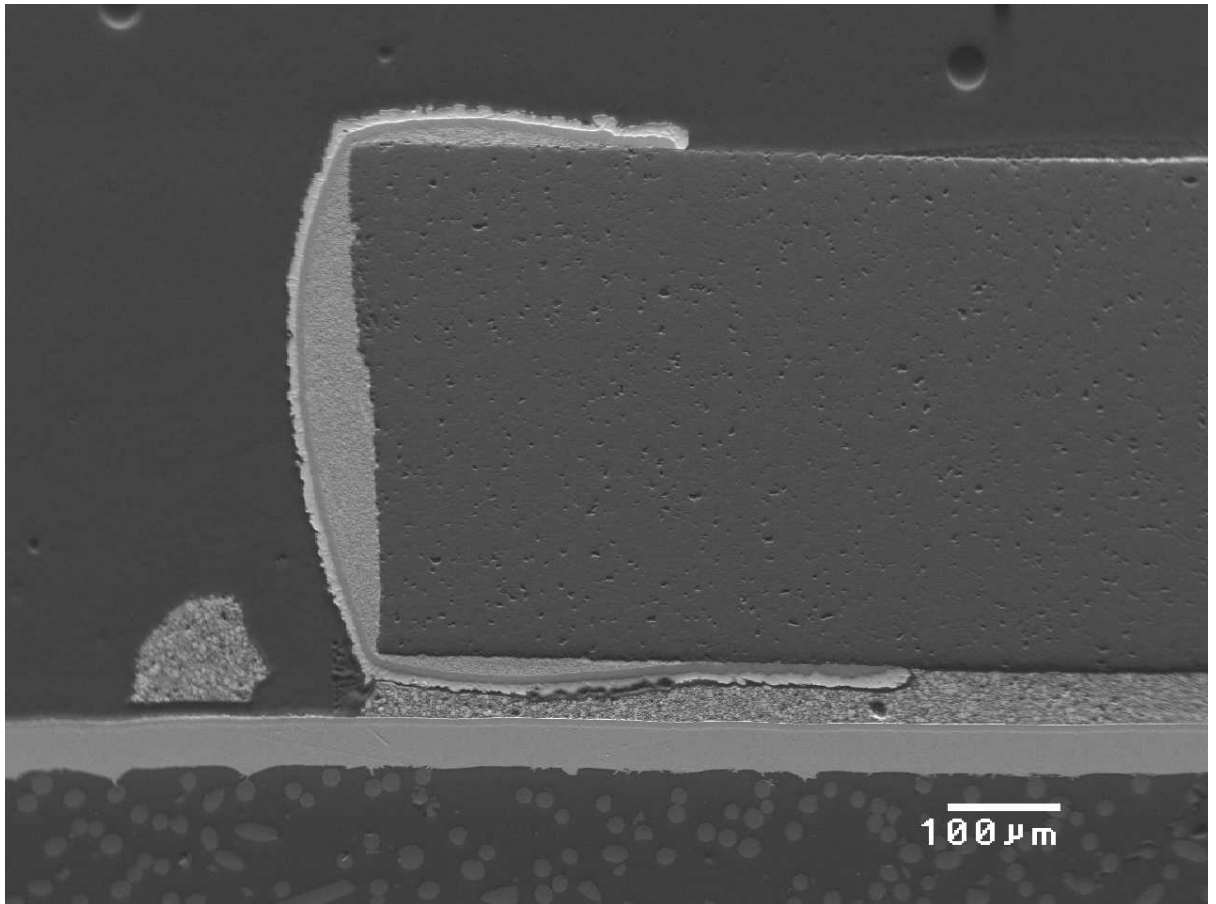


Figure 16: SEM micrograph of R1206 after 500 thermal cycles (-55 to 125°C) + 500 hours damp heat stressing @ 85°C /85%RH

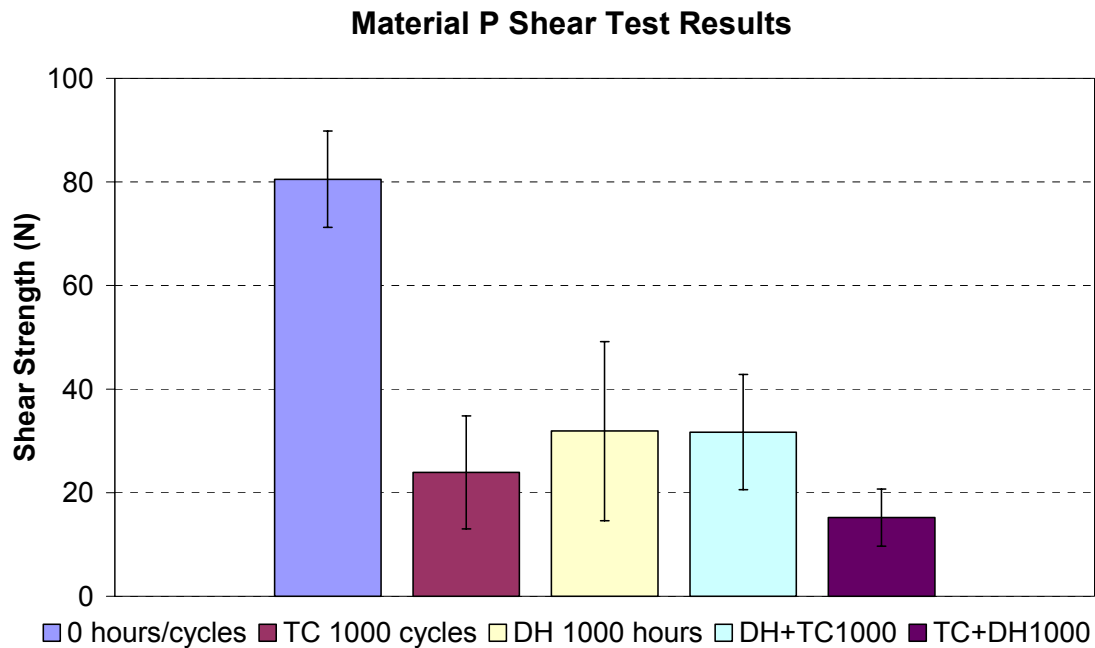


Figure 17: Comparison of material P, R1206 shear testing results for different 1000 hours/cycles stress screening regimes

A comparison of the percentage failures up to 1000 hours/cycles of testing are given in Figure 18 for the smaller R0603 components. The effect of combinational testing to less for these components but still significant for material P. Failure levels for material X are similar to other testing regimes.

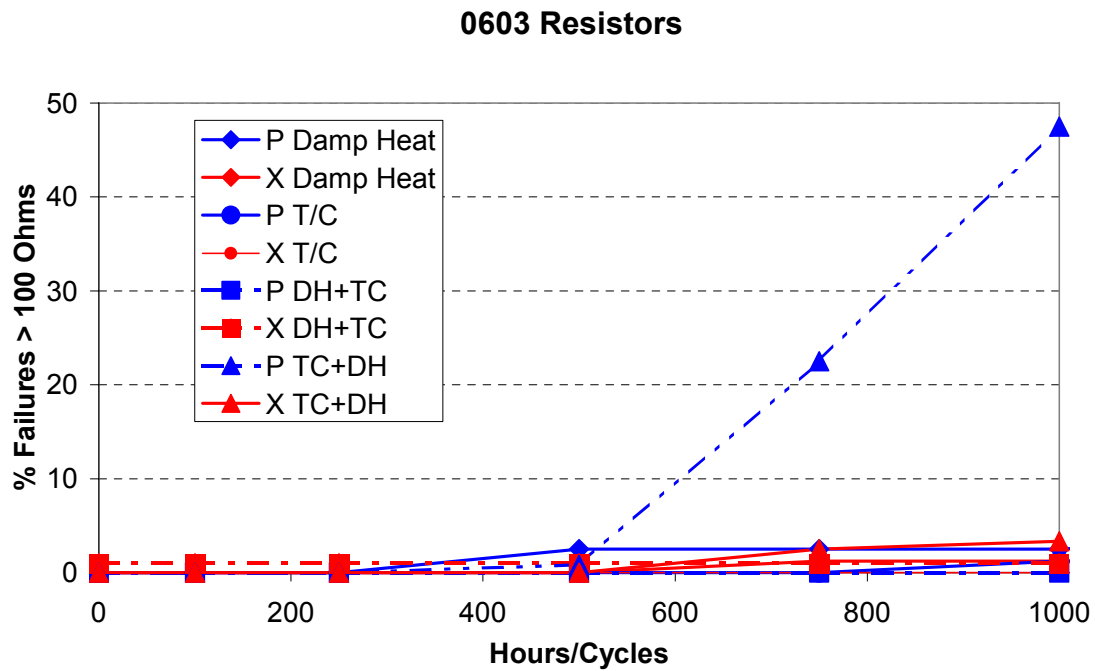


Figure 18: Comparison of R0603 failure levels for all testing regimes up to 1000 hours/cycles

For SOIC components, results are similar to the R0603 components. For material X, there were few differences between the failure levels for damp heat, thermal cycling and combinational testing. For material P, a comparison of the failure levels is shown in Figure 19. In this example, combinational testing of thermal cycling followed by damp heat generated earlier failures than thermal cycling alone and similar levels to damp heat. Failure modes are similar with SOIC components. A typical failure is shown in Figure 20, with the failure again at the interface between the adhesive and the tin plated lead.

There were no significant via failures during testing. The Z-axis expansion of PEI substrates (~ 50 ppm/ $^{\circ}\text{C}$ below T_g) is similar that of a typical FR4 materials (reference 5) and thus this is not unexpected.

Thus the combination of thermal cycling followed by damp heat conditioning was found to develop high resistance failures in conductive adhesive joints earlier than either damp heat testing or thermal cycling alone for R1206 components and for one of the two conductive adhesive materials for R0603 components. For SOIC components combinational testing gave similar performance to damp heat testing. The combination in this order also develops earlier failures than damp heat testing followed by thermal cycling.

Assemblies manufactured using SnBi solder paste did not show any failures during 1200 thermal cycles at -55°C to $+125^{\circ}\text{C}$ or 1250 thermal cycles at -20 to $+80^{\circ}\text{C}$. Shear testing of R1206 components indicated that the wider temperature excursions caused more damage to the SnBi solder joints.

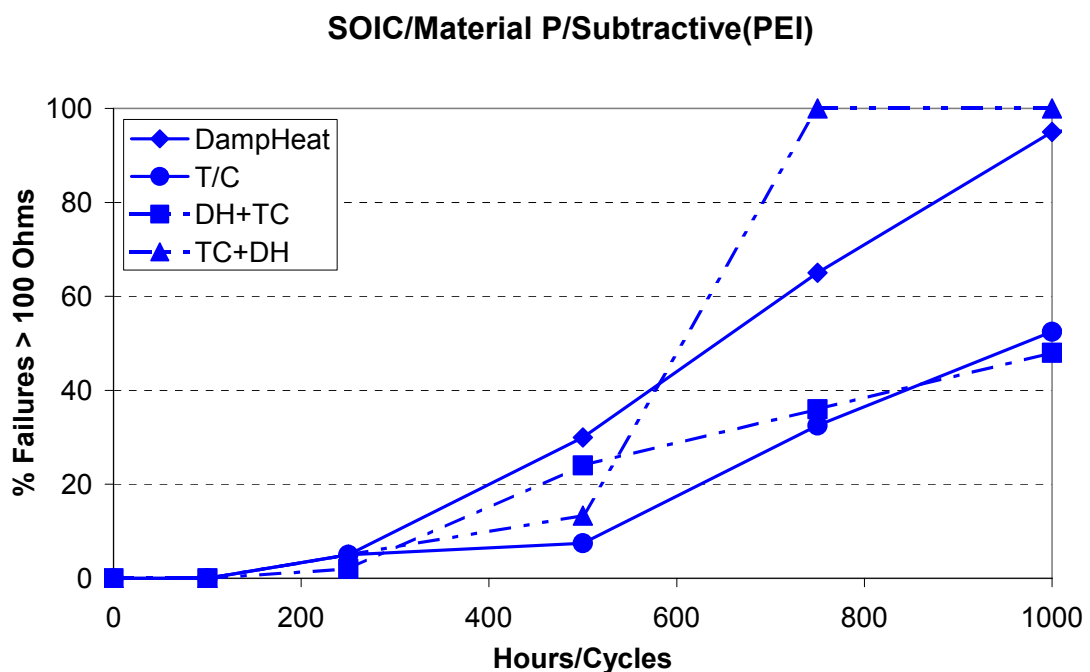


Figure 19: Comparison of material P SOIC failure levels for all testing regimes up to 1000 hours/cycles

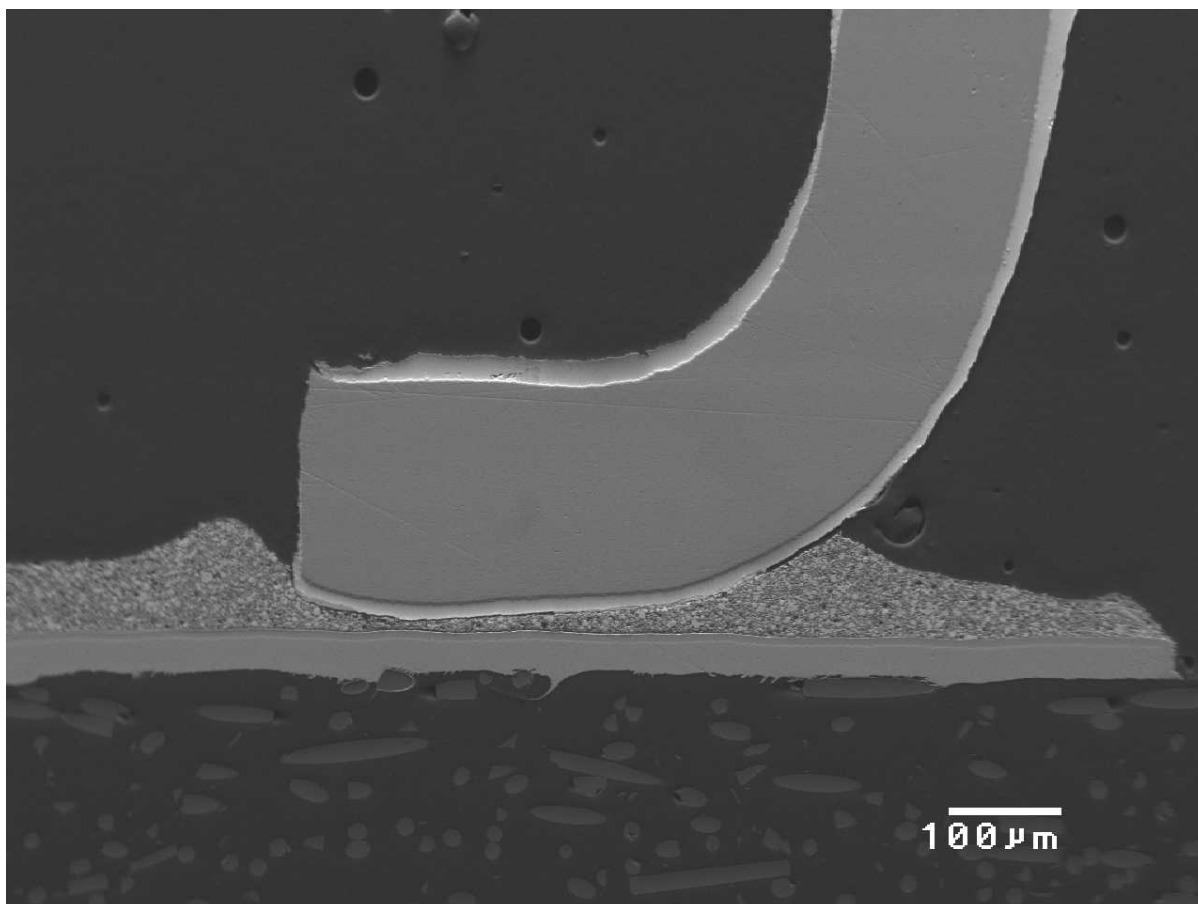


Figure 20: SEM micrograph of SOIC after 500 thermal cycles (-55 to 125°C) + 500 hours damp heat stressing @ 85°C /85%RH

6 CONCLUSIONS

This underpinning work to develop a test method for characterising the reliability of 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 10% failures. 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. Future studies will broaden the materials covered and look in more detail at the resistance failure mechanism.

Susceptibility to failure was found to be dependent on the stress regime. Simple dry heat exposure was the most innocuous, whereas the combination of thermal cycling followed by damp heat was most deleterious. 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. In terms of electrical failures, the order of robustness for the components tested was (most robust first): Vias>R0603>R1206>SOIC.

Assemblies manufactured using a similar process window but using a metal interconnect, SnBi solder paste, did not show any failures during 1200 thermal cycles at -55 to +125°C. Shear testing of this regime tended to cause more damage to the joints than the -20 to +80°C regime. The metallic interconnect was of course impervious to damp heat.

7 ACKNOWLEDGEMENTS

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Merlin Circuit Technology Ltd.

Emerson & Cuming

Heraeus Materials Ltd.

Multicore Solders

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