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Conductive Adhesives Versus Lead Based Solders: A Comparison of Performance

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SUMMARY

Fully functional electronic devices for managing office lighting systems have been manufactured using both conventional tin/lead solder and an isotropically conducting adhesive. The performance of the two joining media has been assessed through measurements of impact resistance and shear strength determined before and after exposure to an extended programme of thermal cycling (from -20°C to 100°C). Monitoring of the functionality of the device during the period of thermal cycling provides an additional performance indicator.

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1. INTRODUCTION

Increasing environmental awareness coupled with the threat of legislation concerning the use of lead in solders has lead to a proliferation of recipes for substitute lead free solder alloys. Unfortunately these substitute materials have to be used at significantly higher temperatures ($\sim 220^{\circ}\text{C}$) than conventional tin/lead solder (183°C) with the exception of tin/bismuth/copper. This increase in soldering temperature could have an adverse effect on the performance of thermally sensitive components such as multi-layer ceramic capacitors or analogue semiconductors.

An alternative class of electrically conducting materials that have almost been ignored in the race to develop lead free metallic alloys are the isotropically conducting adhesives¹⁻⁴. These materials are typically epoxy based matrices that contain relatively high levels of noble metal fillers that act as the conducting elements. The processing of an isotropic conducting adhesive (ICA) is very similar to that used for conventional solders except that the temperatures required to cure the adhesives are much lower at approximately 150°C . Besides being environmentally friendly materials that do not require fluxes, ICAs can be used to bond components to low cost substrates such as polyester or glass where conventional metallic alloys cannot be used.

The purpose of this study is to explore some of the issues associated with substituting a isotropic conducting adhesive for a traditional tin/lead based solder to manufacture a functional product in terms of production and performance.

2. THE DEMONSTRATION PRODUCT

The product used for this exploratory study is a management system for controlling lighting levels, typically within an office environment. The unit shown in Figure 1 contains three sensors i.e.

- a passive infra-red device for detecting movement
- an infra-red device for registering a remote control
- a photodiode for monitoring the ambient light level

and is mounted on to a ceiling either in a work or domestic setting. Management of the sensors and the lighting power supply is carried out by two circuit boards (Figure 2) that are located within the plastic housing of the unit. These boards are coupled using connecting blocks as indicated in Figure 2. The circuits contain a range of differently sized surface mount components e.g. chip resistors and SOICs as well as through hole components that are typical of those found in electronic devices that have pin-hole connections. The components have a variety of different IOs including gull wing leads and leadless chip terminations.

The Helvar Merca Group kindly provided a number of fully functional devices that had been factory assembled using tin/lead (Sn/Pb) solder together with unassembled components and PCBs. The unassembled components were identical to those used to assemble units using traditional solder manufacturing methods.

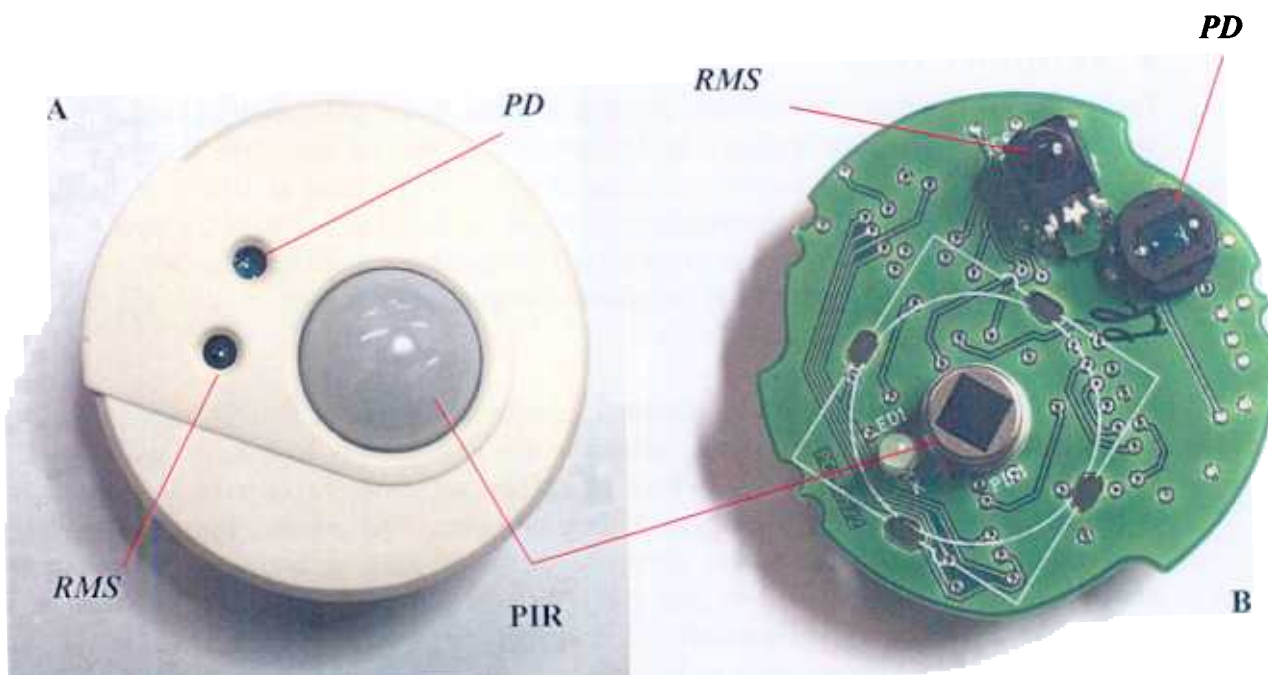


Figure 1: A) An overview of the light management unit showing the PIR, remote control sensor (RM) and light level monitor (PD). B) As A but with the outer casing removed.

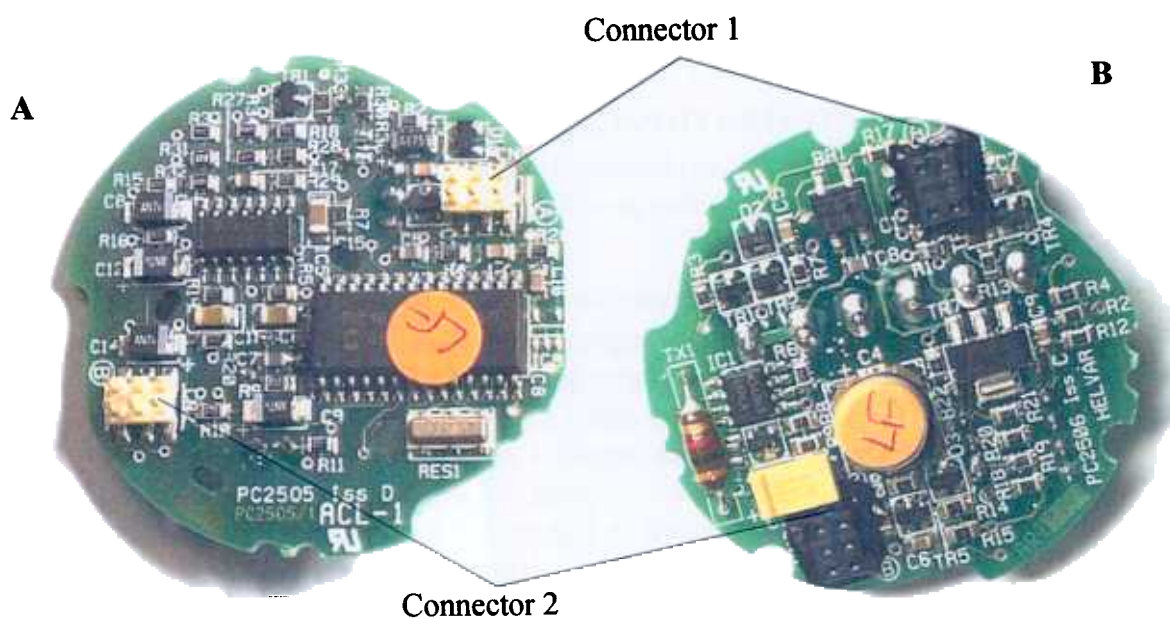


Figure 2: A) The underside of board 1B showing the range of components present and the connection pins that couple with the blocks shown in board B. The underside of board B contains a connection point for the power supply.

These 'kits' were assembled by:

- Stencil printing an ICA on to the PCB's
- Positioning the surface mount components on to the pad connections (by a hand pick and place machine)
- Curing the adhesive
- Assembling through hole components
- Dispensing ICA around pin-hole joints
- Curing the pin-in-hole joints (and second exposure of surface mount joints to the cure temperature).

The assembly process is described in detail in subsequent sections. The performance of these units were compared with those manufactured using Sn/Pb solder.

2.1 STENCIL PRINTING

The ICA was supplied as a two-part epoxy system that can be stored at room temperature in its un-mixed state. After mixing the adhesive has a pot life of 16 hours but this can be extended by storing it at -40°C . The paste was stencil printed on to solder resist coated FR-4 using a DEK 265 GSx printing machine. The printed adhesive showed no signs of slumping although the finest pitch on the board was only 1.27mm. Through hole components were attached by dispensing ICA around each pin, however the resultant bonds were found to be unsatisfactory, i.e. weak. This problem was overcome by removing the through hole components that were then soldered to the PCB using Sn/Pb solder. Cleaning the un-cured ICA from the stencil proved to be more difficult than a conventional solder paste requiring the use of a solvent (IPA) in addition to extensive wiping. A metal squeegee angled at 60° produced better prints than a flexible polyurethane blade, again this difference in performance of the two materials could be a reflection of the relatively high cohesive strength of the ICA.

2.2 COMPONENT PLACEMENT

All the components were placed using a hand pick and place machine. This device although enabling the operator to accurately position components does not allow components to be repeatedly placed in the same position with the same force on different boards. This limitation is important when using ICAs for some lead termination geometries (section 2.6). Accurate positioning of components on to ICA covered pads is particularly important as ICAs unlike metallic solders do not induce any self alignment of the components during the curing cycle. Some component terminations are prone to lack of wetting, particularly gull wing IOs as indicated by the absence of fillets and the presence of cusps around the lead termination. This may be due to the high cohesive strength of the ICA or due to a mismatch in surface tension between the adhesive and the component finish. Examples of different types of joints are shown in Figures 3 and 4. There is evidence to suggest that the finish on the component terminations does affect the quality of the joint formed using ICAs. In this exploratory work the component finishes have not been identified.

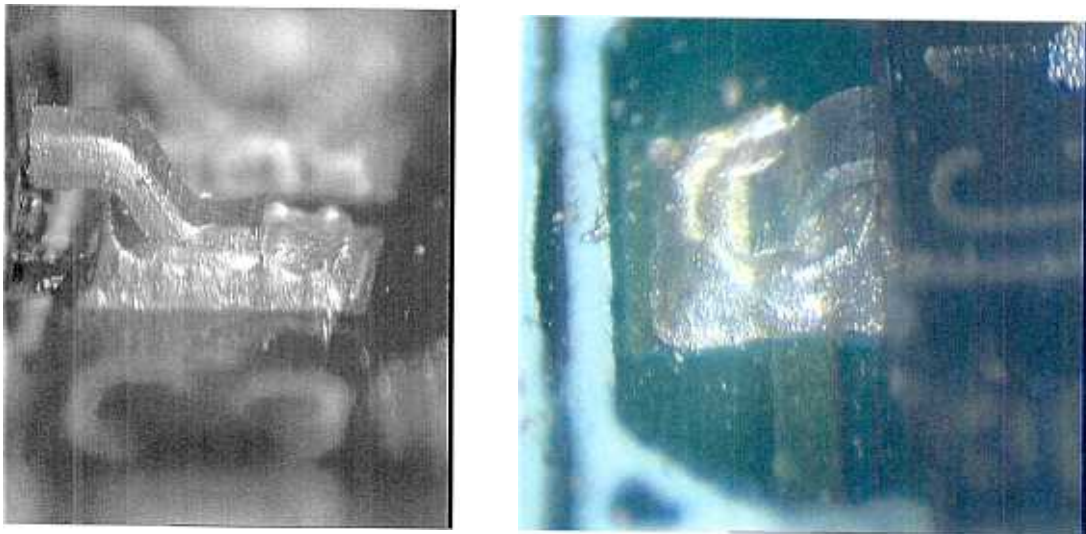


Figure 3 : Lack of wetting of gull wing lead joints results in a relatively weak bond between the component and the substrate. The cusps that form around the periphery of the joint are particularly evident behind the heel of the lead. Note that filleting does not occur.

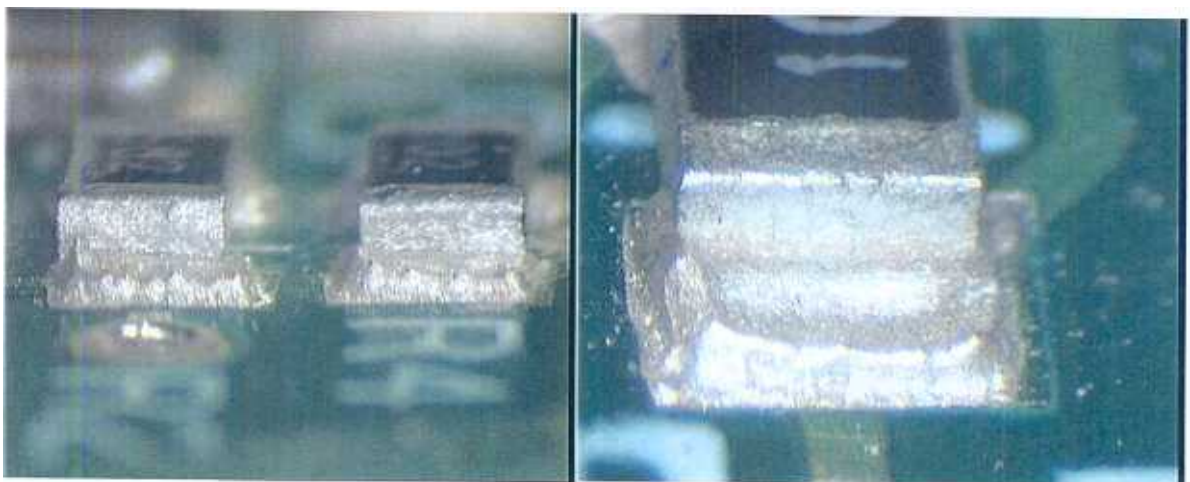


Figure 4 : Chip resistors or capacitors because of their brick-like shape form excellent joints even in the absence of fillets.

2.3 CURE OF THE ADHESIVE

The ICA was cured at 130°C for 20 minutes following the manufacturers recommendations. In practice the surface mount components on the PCB's were subjected to two 'cure' cycles. During the first cure cycle the surface mount component joints were cured. The boards were then cooled to room temperature and the through hole components were added to the board, these pin-hole joints were cured during the second cure cycle.

2.4 MEASUREMENT OF FUNCTIONALITY

The tests shown in Table 1 are designed to assess the functionality of each control unit. These were sequentially carried out by a specifically designed test rig.

Test Number	Test Description
1	Power the unit, EEPROM reset, LED
2	Check the communications link between the unit and the testing device
3	Assess the functionality of the hard wired touch switch
4	Checks the IR remote control
5, 6, 7	Logs the response of the photodiode to three levels of light intensity
8	Checks EEPROM r/w operations
9	Checks the performance of the PIR sensor
10	Switch off

Table 1: Tests of unit functionality

2.5 THERMAL CYCLING

Three ICA assembled units and 10 Sn/Pb soldered control units were subjected to 620 cycles over the temperature range -20°C to 100°C . A ramp rate of $10^{\circ}\text{C min}^{-1}$ was used and the samples were held at constant temperature for a period of 5 minutes at the dwells of each thermal cycle. The performance of the boards was assessed after 20, 70, 200 and 620 cycles by testing for functionality following Table 1.

Table 2 shows the results of the functionality tests. From Table 2 it is apparent that all the Sn/Pb soldered devices passed the functionality tests with the exception of 1 unit. Units containing conducting adhesive were less successful with some units failing after only 20 cycles. To what extent these failures are caused by the difficulty mounting the through hole components and the surface mounted connection blocks is a matter for conjecture. There is also some degree of uncertainty in the performance of the conducting adhesive that is associated with using component finishes designed for Sn/Pb solders.

Material used for joints	Board ID	Number of thermal cycles				
		0	20	70	200	620
Sn/Pb	7470	Pass	Pass	Pass	Pass	Pass
Sn/Pb	7134	Pass	Pass	Pass	Pass	Pass
Sn/Pb	7463	Pass	Pass	Pass	Pass	Pass
Sn/Pb	7476	Pass	Pass	Pass	Pass	Pass
Sn/Pb	7465	Pass	FAIL (1)	Pass	Pass	FAIL (5,6,7)
Sn/Pb	7238	Pass	Pass	Pass	Pass	Pass
Sn/Pb	7234	Pass	Pass	Pass	Pass	Pass
Sn/Pb	7464	Pass	Pass	Pass	Pass	Pass
Sn/Pb	7475	Pass	Pass	Pass	Pass	Pass
Sn/Pb	7143	Pass	Pass	Pass	Pass	Pass
ICA	26/3	Pass	Pass	Pass	FAIL (9)	FAIL (9)
ICA	17/17	Pass	FAIL (3)	FAIL (3)	Pass	FAIL (3)
ICA	6/27	Pass	FAIL (9)	Pass	FAIL (9)	FAIL (9)

Table 2: The test for functionality described in Table 1 were used to assess the performance of the light control units as a function of time during exposure to repeated thermal cycling. The number that appears in brackets after FAIL marking corresponds to the test number in the test series, Table 1, that the unit failed at.

2.6 MEASUREMENT OF THE SHEAR 'STRENGTH' OF COMPONENTS

The shear 'strength' of components shown in Figure 5 on both traditionally soldered boards and those manufactured using the ICA was determined using a Dage series 4000 tester. This equipment applies an increasing lateral force to a selected component until it becomes detached from the board. It is important to ensure that the force is applied over as much of the edge of a component as possible i.e. the sledge is positioned as close to the board as is practical as shown in Figure 6. The device then measures the force required to detach a component from the board. These values provide a qualitative ranking of the performance of different components on the board. The results are qualitative because the measurement method does not take into account the area of the I/Os in contact with the substrate or any absorption of load by the IOs. This latter issue is particularly important in

comparing the force required to detach a gull wing I/O component with that required to uncouple a chip resistor where significant deformation of the lead in the former will occur prior to failure.

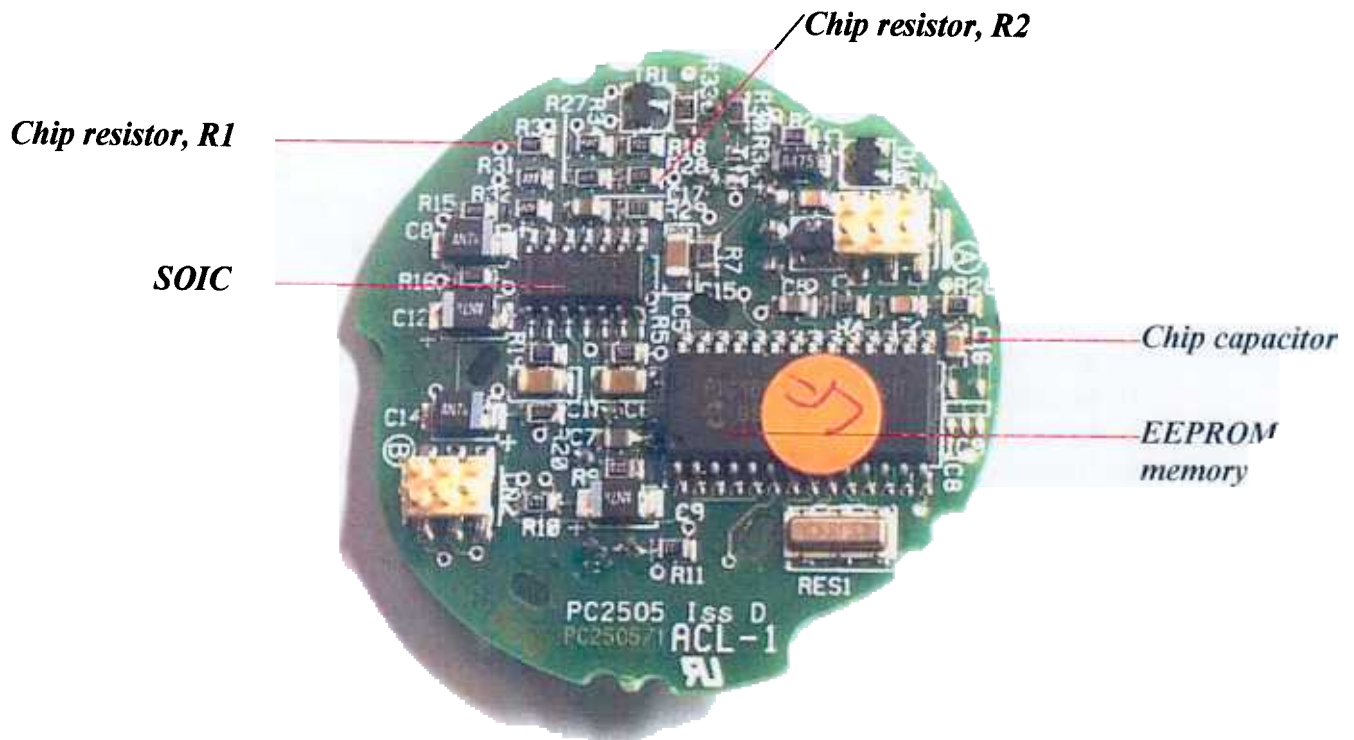


Figure 5 : The location of the components used in the shear test.

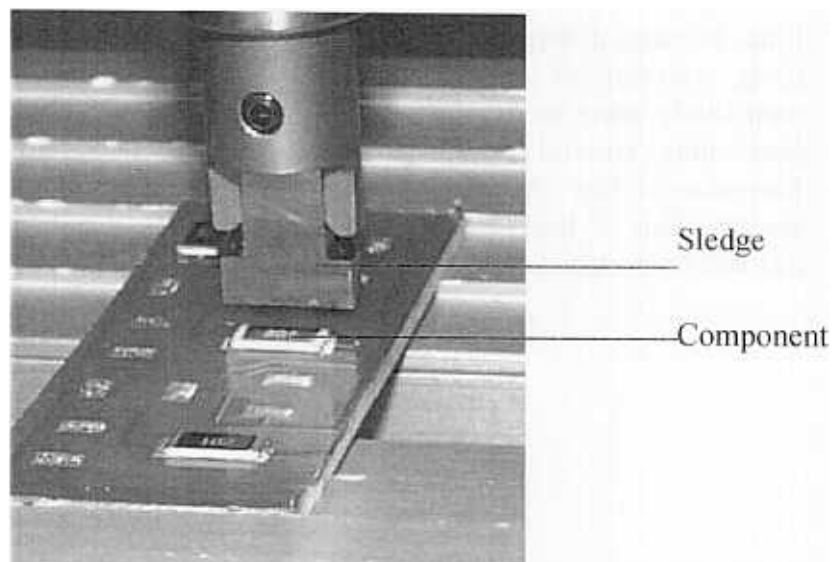


Figure 6 : The force required to shear a component away from the board is measured by a load cell located in the shaft of the sledge.

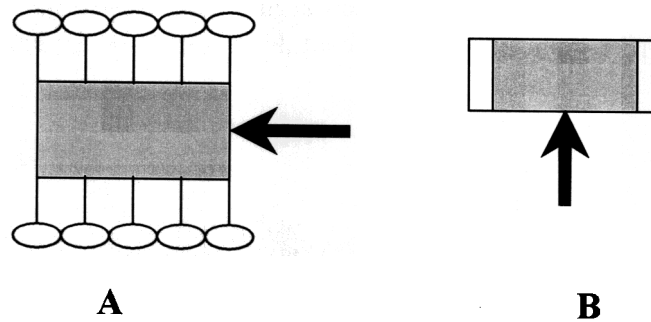


Figure 7: Lateral force was applied to different components as indicated by the arrows: A = SOIC and EEPROM, B = Chip resistors and capacitors

Figure 7 shows the direction in which the lateral force of the sledge was applied to each of the components under test. A plot of the force required to detach components attached to the substrate either by Sn/Pb solder or the ICA is shown in Figure 8. The data show that there is a significant difference between the strength of the conventionally soldered gull wing I/O components of the EEPROM and SOIC and those attached with the ICA. A similar mismatch in bond strength can also be seen in the data obtained for the inwardly formed L-shaped ribbon terminations of the tantalum capacitor C12. These differences in the bond strengths of Sn/Pb and ICA joints disappear for the leadless chip resistors and capacitors, R1, R2, R3 and C5. These results suggest that the strength of leadless chip resistors is independent of the medium used to attach them to the PCB. The disparity in the strength of joints formed between gull wing terminations and the PCB using Sn/Pb and the ICA could be attributed either to: poor wettability of the lead by the ICA or poor assembly technique.

Links between different component I/O geometries and the strength of the resultant joints using conventional solder and ICAs has been described elsewhere⁶. 'J' leads are particularly sensitive to the amount of ICA deposited on the underlying pad and in their positioning. Too little adhesive or direct contact of the 'J' lead with the pad results in the formation of low strength bonds. The planar region of gull wing IOs although less sensitive than 'J' lead terminations to position and the amount of ICA deposited on to the pad will be more sensitive than I/O with chip terminations.

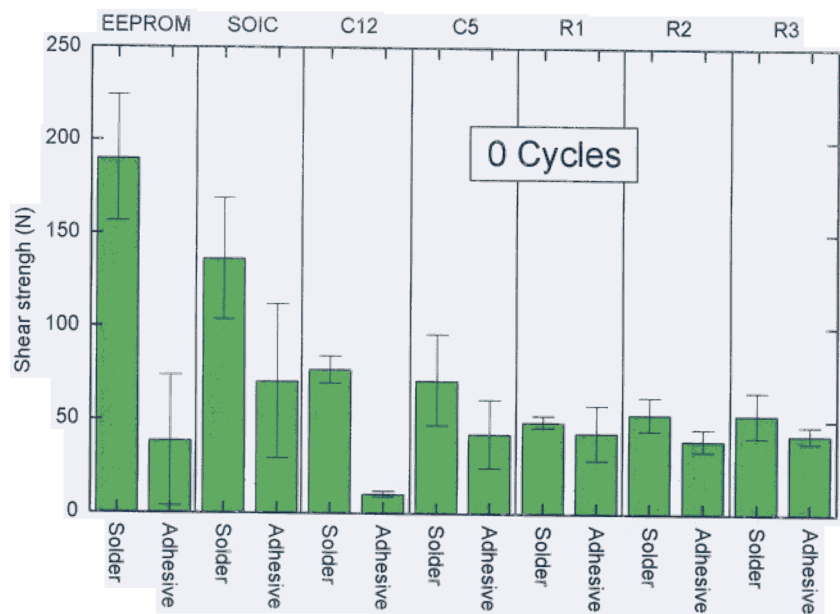


Figure 8: A comparison of the shear strength of different components attached either by ICA or Sn/Pb solder. The error bars represent the standard deviation within data obtained from three replicate tests.

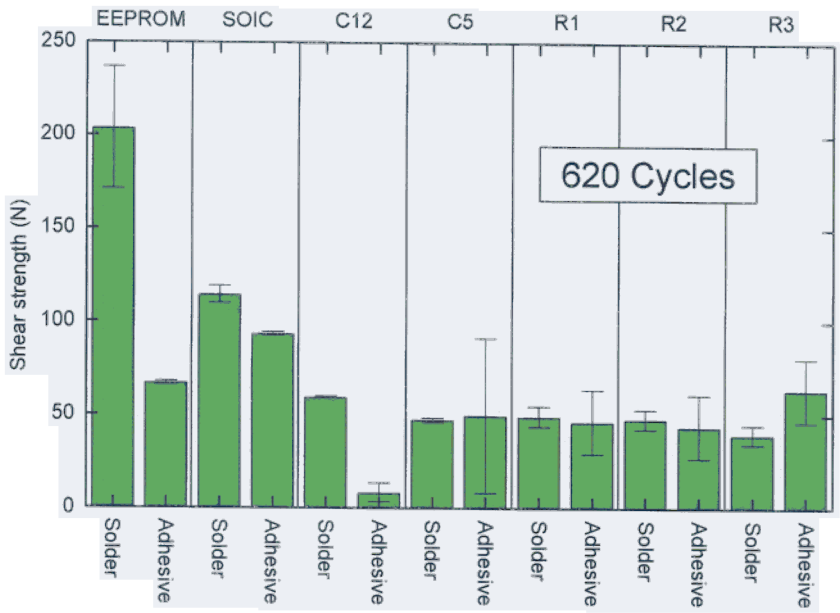


Figure 9: A comparison of the shear strength of different components attached either by ICA or Sn/Pb solder in lighting control units that have been subjected to 620 thermal cycles of -20°C to 100°C . The error bars represent the standard deviation of data obtained from three replicates.

The effects of thermal cycling on the 'shear' strength of same components is shown in Figure 9. Comparing these data with that shown in Figure 8 suggest that thermal cycling within experimental error has a negligible effect on the strength of joints formed using conventional solders or ICA.

2.7 IMPACT PERFORMANCE

The 'poor' impact performance of joints formed using ICAs has often been cited as a reason for not using these materials as metallic alloy solder substitutes¹. Often such claims are made on the basis of tests conducted using a single component^{1,5}. Such an approach ignores the influence of joint geometry, the contact area/component volume ratio and the component mass and therefore has its limitations.

In this study the impact performance of the board shown in Figure 2B has been assessed by dropping it edge on from a height of 1.5 m on to a solid metal surface. This test is based on one contained in references (1) and (5) that tests the adhesion of a PLCC44 attached to a board during repeated drops. Figure 10 shows the location of the some of the larger components on the board that became detached from the PCB during the impact test. None of the tin/lead soldered components became detached during the test unlike some of the larger components attached via the ICA. The order in which these components fell off from the board is shown in Figure 11.

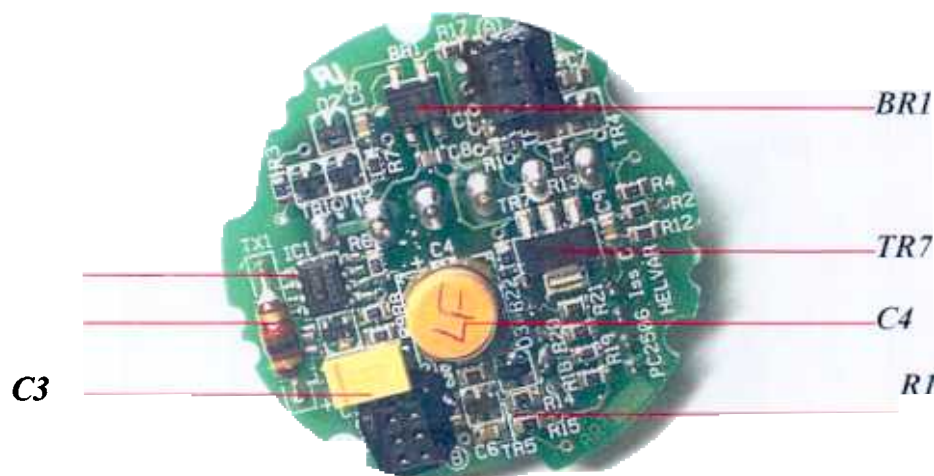


Figure 10: The location of the components that became detached during repeated impact test.

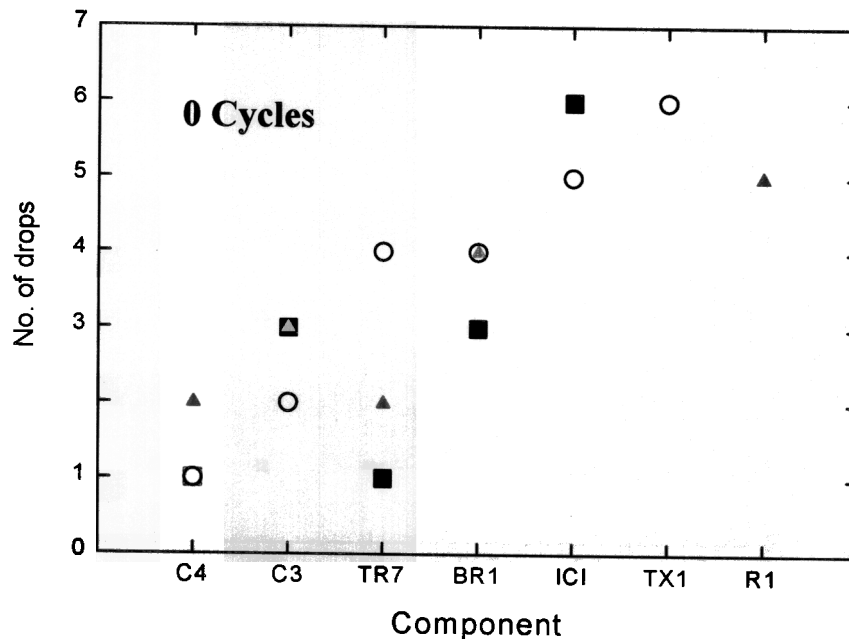


Figure 1. The number of repeat drops required to detach components from test board 2 (Figure 10) that were attached to the substrate using the ICA prior to thermal cycling. Different symbols are used for each of the three boards used in the test.

From figure 11 it is apparent that the weakest joints are formed by components that have inwardly formed L shaped ribbon terminations i.e. C4 and C3 followed by gull wings, TR7, BR1, ICI. Only one of the chip termination resistors (R1) failed after 5 successive drops. Note also that the order in which the components became detached from the board reflects their size and mass. It is therefore not surprising that capacitor C4 became detached after only one or two repeat drops since it is the largest and heaviest component on the board and it is attached via inwardly formed L shaped ribbon terminations.

Impact data obtained after the boards had been exposed to 620 thermal cycles of -20°C to 100°C are shown in Figure 12. Correlations between impact performance and component size, mass and termination are less evident for boards that have been thermally cycled compared with those that were not. There is no obvious explanation for this behavior further curing of the joints during thermal cycling is unlikely given that the maximum temperature is 30°C lower than that used for curing. In addition the surface mount components were exposed twice to the cure temperature during manufacture. It should also be noted that fewer components fail after thermal cycling, but thermally cycled components are falling off after fewer drops.

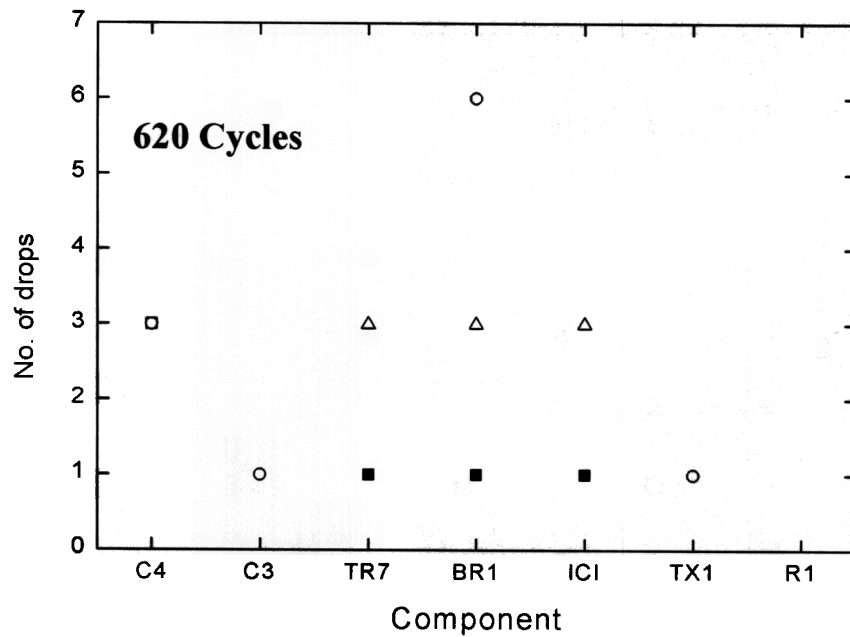


Figure 12: The number of repeat drops required to detach components from test board 2 (Figure 10) that were attached to the substrate using the ICA after thermal cycling. A different symbol has been used for each of the three boards tested.

3. MICROSECTIONING

In Figure 13 there is a microsection of CA joint after 620 temperature cycles. There are no fatigue cracks in the joint, the marked locations of the joint are conducting points joining resistor termination with matrix of Ag flakes and providing sufficient path for conduction of electrical current.

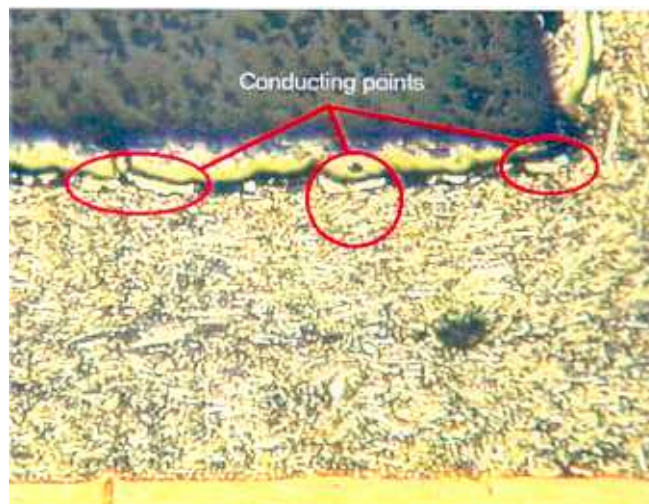


Figure 13: Conductive adhesive joint with marked jointing points

4. CONCLUSIONS

In this investigation specific problems occurred when manufacturing functional lighting control units with currently commercially available isotropic conductive adhesive. These have been assembled by hand from components intended for traditional tin/lead solder assembly. Measurements of the 'shear' strength of a range of different components have shown that those with gull wing or inwardly formed L shaped ribbon terminations are weaker than those with chip terminations. This weakness is also apparent in impact tests. No differences in the impact or 'shear' strength performance between ICA and tin/lead soldered chip terminated components such as resistors or capacitors were detected.

Extensive thermal cycling of both tin/lead and ICA assembled boards over the temperature range -20°C to 100°C has an adverse effect on the functionality of units assembled using ICA. The functionality of the tin/lead soldered boards remained unaffected. However measurements of the 'shear' strength of both ICA and tin/lead soldered components showed that thermal cycling had no effect on performance. 620 thermal cycles of tin/lead soldered components also had no effect on impact performance however fewer failures occurred in the ICA assembled boards.

5. ACKNOWLEDGEMENTS

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