

**An Evaluation of Prototype Circuit Boards
Assembled with a Sn-Ag-Bi Solder¹**

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Abstract

An evaluation was performed which examined the aging of surface mount solder joints assembled with 91.84Sn-3.33Ag-4.83Bi solder. Defect analysis of the as-fabricated test vehicles revealed excellent solderability, good package alignment, and a minimum number of voids. Continuous DC electrical monitoring of the solder joints did not reveal opens during as many as 10,000 thermal cycles (0°C, 100°C). The solder joints exhibited no significant degradation through 2500 cycles, based upon an absence of microstructural damage and sustained shear and pull strengths of chip capacitors and J-leaded solder joints, respectively. Thermal cycles of 5000 and 10,000 resulted in some surface cracking of the solder fillets and coatings. In a few cases, deeper cracks were observed in the thinner reaches of several solder fillets. There was no deformation or cracking in the solder located in the gap between the package I/O and the circuit board pad nor in the interior of the fillets, both locations that would raise concerns of joint mechanical integrity. A drop in the chip capacitor shear strength was attributed to crack growth near the top of the fillet.

Introduction

¹ Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin Company, for the United State Dept. of Energy, under contract DE-AC04-94AL85000.

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An important objective in the design and manufacture of electronic products is to minimize the amount of hazardous materials being introduced into process waste streams or that may accumulate in landfill facilities when the product is discarded, particularly with regards to the Pb content of solders used to make interconnects. Therefore, efforts are underway to identify potential solders as replacements for the Pb-bearing alloys that are currently in use. This paper describes the results of an investigation into the suitability of a Sn-Ag-Bi solder for surface mount electronics on traditional FR-4 organic laminate. The discussion will concentrate on the reliability of Sn-Ag-Bi solder joints following extended thermal cycling exposure.

The Sn-Ag-Bi, Pb-free solder alloy had the composition 91.84Sn-3.33Ag-4.83Bi (wt.%). This alloy was developed at Sandia National Laboratories as a lower melting temperature alternative to the 96.5Sn-3.5Ag eutectic alloy[1]. Differential scanning calorimetry (DSC) determined the onset temperature of the alloy to be 212°C, compared with the eutectic temperature of 221°C for the 96.5Sn-3.5Ag solder. The Sn-Ag-Bi alloy microstructure (Fig. 1) is comprised of a Sn-rich matrix having approximately 4-5 wt.% Bi in solid solution; regions of precipitated elemental Bi particles, and Ag₃Sn particles. The alloy has shown satisfactory solderability on both laboratory test coupons as well as on prototype through-hole and surface mount circuit boards[2,3,4,5,6]. Tin-silver-bismuth solder joints made in the ring-and-plug configuration exhibit a shear strength value of 81 ± 12 MPa which is nearly twice the strength of 38 ± 2 MPa for similarly made, Sn-Pb solder joints. Transmission electron microscopy studies have confirmed that solid solution strengthening by Bi dissolved in the Sn-rich matrix and precipitation strengthening ("hardening") by the Bi particles as the mechanisms responsible for the high monotonic strength of the Sn-Ag-Bi alloy (Fig. 2)[7]. Data will be presented which describes the impact that the thermal cycling had on the integrity of solder interconnects made between common "50 mil" pitch, surface mount packages and FR-4 printed circuit board.

Experimental Procedures

Laminate prototype test vehicles assembled with Sn-Ag-Bi solder.

A photograph of the prototype circuit board is shown in Fig. 3. The layout of the board included the following components: (1) 50 mil pitch, 68 I/O plastic leaded chip carriers (PLCC) having J-leads, (2) 50 mil pitch, 20 I/O small outline integrated circuit (SOIC) devices having gull-wing leads, and (3) 1206 discrete chip capacitors. The PLCC and SOIC lead frames were constructed of 0.010 in. thick Cu. A Ni barrier layer was deposited on the lead frames; the final finish for both lead configurations was electroplated 100% Sn. The laminate was 1.59 mm thick FR-4 and covered with Probimer 52 solder mask. All conductive features were on a single side. A daisy chain pattern was available for monitoring the electrical continuity of the solder joints. (Only

the PLCC and SOIC solder joints were assessed; the chip capacitors were not shorted to permit signal conveyance.) The Cu features were coated with an immersion Sn layer to preserve solderability. The chip capacitors were received from the manufacturer with a 100% Sn finish.

The solder alloy used in this study had a composition of 91.84Sn-3.33Ag-4.83Bi (wt.%). The powder was produced by a commercial source and later mixed with a no-clean flux vehicle containing a rosin-based, mildly activated (RMA) flux formulation. The metal load in the paste was 90 wt.%. The paste was screen printed onto the circuit boards using a stainless steel stencil having 1:1 feature size correlation. After being populated in a pick-and-place machine, the circuit boards were passed through an infra red reflow furnace under a N₂ blanket (<20 ppm) and subsequently air-cooled. The surfaces of the circuit boards were not cleaned of flux residues. The solder joints were inspected for solderability, voids or “blow holes”, and package misalignment; no significant defects were observed in any of these categories.

The circuit boards were exposed to thermal cycling environments defined by the following parameters:

0°C, 100°C limits
10°C/min ramp rate between limits
5 min hold times at the limits
Cycles: 1000, 2500, 5000, and 10000

The electrical continuity of the SOIC and PLCC solder joints was monitored by means of the daisy chain connections that terminated at a DC continuity event detector.

Following thermal cycling (including the as-fabricated condition), the integrity of the solder joints was evaluated in the following manner. First, a surveillance was made of the solder joints using low-magnification, stereo microscopy, to detect large-scale damage to the interconnect. Several joints were also examined by scanning electron microscopy (SEM) in order to identify smaller scale defects. Then, several solder joints from amongst those on each of the PLCCs, SOICs, and chip capacitors, were selected for metallographic cross sectioning. The prepared sample mounts were examined by optical microscopy.

Solder joints from the remaining PLCC packages and chip capacitors were used for mechanical testing. The test geometries are shown in Fig. 4. These tests were performed in order to document the relative strengths of the solder joints. Sixteen solder joints on a PLCC unit, four from each of the four sides of the package, were separated from the molding compound and pull tested on a table-top load frame (Fig.4b). The displacement rate was 0.2 mm/min. The chip capacitor solder joints were tested in a shear mode (Fig. 4a) by applying force in a transverse direction at the side of the chip,

parallel to the circuit board surface. Sixteen capacitors were tested by this technique. In both the chip capacitor and J-lead (PLCC) cases, the strength data were compiled and expressed as a mean value and error term (\pm) represented by one standard deviation.

Results and Discussion

Laminate test vehicles assembled with Sn-Ag-Bi solder.

The Sn-Ag-Bi solder exhibited excellent solderability on both the circuit board pads and package I/Os as is evident in the photographs in Fig. 5 showing each of the package types after assembly. Shown in Fig. 6 are SEM micrographs of the chip capacitor, SOIC, and PLCC solder joints along with optical micrographs of cross sections of the respective joints. In the SEM photographs, the black patches on the solder joints were flux residues; recall that a no-clean flux was used in the paste to assemble the test vehicles. There was no significant void ("blow hole") formation in the joint fillets. The absence of voids from the solder joints as well as excellent wettability of all substrate surfaces was confirmed by the cross sectional views. Also, microstructural features such as Ag_3Sn particle distribution within the solder were consistent amongst the three solder joint types. Finally, the alignment between the package I/O and the underlying circuit board pad was excellent. The absence of significant solderability defects, voids, or poor package alignment as well as a consistent microstructure confirm the uniformity of the solder joints between the packages. Such consistent, defect free solder joints are required in order to establish reliable trends of interconnect aging from the thermal cycling experiments.

1000 thermal cycles.

Exposure of the test vehicle to 1000 thermal cycles did not have a significant effect on the solder joints. Shown in Fig. 7 are low and high magnification optical micrographs of a J-lead solder joint from the PLCC package. It is also representative of the quality of the SOIC (gull wing) and chip capacitor solder joints, in that the latter showed no evidence of deformation within the solder. There was no loss of electrical continuity in any of the joints.

2500 thermal cycles.

Next, the integrity of the solder joints following 2500 thermal cycles are discussed. Shown in Figs. 8, 9, and 10 are optical micrographs of solder joint cross sections representing the chip capacitor, the SOIC package, and the PLCC package, respectively. The cross sectional view of the solder joint from the chip capacitor (Fig. 8a) shows excellent integrity. Two small voids were observed in the fillet and gap. The only deformation observed is that of a crack that has formed at the top of the termination fillet. This damage scenario is also observed with Sn-Pb solder joints following thermal

cycling and, therefore, was not unexpected. The extent of cracking did not jeopardize the electrical function of joint nor would significantly degrade its mechanical strength. The SOIC and PLCC solder joints shown in Figs. 9 and 10, respectively, exhibited no indication of damage within the solder microstructure. Of particular interest is the solder within the gap formed between the lead and the bonding pad. It is here that thermal expansion mismatch strains in the Sn-Ag-Bi solder (global and local) will be very high. Views of the gap regions in the gull wing solder joint (Fig. 9b) and J-lead solder joint (Fig. 10b) confirmed the absence of significant deformation there. There was no loss of electrical continuity recorded in any of the joints.

5000 thermal cycles.

The test vehicles exposed to 5000 thermal cycles were examined by both SEM and optical microscopic techniques. The chip capacitor solder joints are shown in Fig. 11. The SEM photograph in Fig. 11a shows the chip capacitor solder fillet. The dark area showing "mud cracks" at the base of the fillet is the flux residue that had hardened and then fractured under the variable temperature environment. Cracking is observed near the top of the fillet. This crack formation is observed in cross section by Fig. 11b. This cracking is similar to that referred by Fig. 8a for the fillet exposed to 2500 thermal cycles, except that it was more prevalent and extensive in travel after 5000 cycles. On the other hand, the micrograph in Fig. 11c of the gap region clearly shows that no deformation or damage had developed in the solder under the chip structure.

The appearance of the SOIC solder joints is documented in Fig. 12. Figure 12a is an SEM photograph of a gull-wing joint. A small degree of cracking was observed in the solder located on the surfaces of the lead as shown in Fig. 12b. In some instances, the cracks were discernable in cross sectional views. In those latter cases, the fractures did not appear to be associated with any particular phase or feature of the microstructure. Rather, the cracks may have been a result of localized thermal expansion mismatch between the lead material and the Sn-Ag-Bi. The high strength of the solder limited its ability to deform, resulting in the localized fracture. However, as is evidenced by the optical micrographs in Figs. 12c and 12d, cracks were not observed in the critical fillet or under-lead gap regions which provide a large extent of the mechanical attachment function. The micrographs also illustrate the important point that the presence of voids did not aggravate fatigue damage in the joints.

Shown in Fig. 13 is (a) an SEM image and (b, c, d) optical micrographs of a PLCC solder joint after 5000 cycles. The SEM photographs show that there was no large-scale deformation or cracking in the solder. However, viewing other joints did reveal some surface cracks similar to those observed with the SOIC solder joints. Those cracks are more clearly delineated in the optical micrographs of solder joint cross sections shown in Figs. 13b and 13c; a high magnification view of the cracks at the top of

the heel fillet are shown in Fig. 13c. There were no cracks apparent in the solder joint fillet nor in the gap region under the lead (Fig. 13d) that would jeopardize mechanical integrity or electrical continuity.

A comparison was made between the above observations and those developed from similar test vehicles that were assembled with 96.5Sn-3.5Ag or 58Bi-42Sn solders[8]. Those prototypes were subjected to the same thermal cycling environments. The Sn-Ag solder joints appeared very similar to those of the Sn-Ag-Bi interconnects after 5000 cycles. On the other hand, the Bi-Sn solder joints rapidly degraded with thermal cycling. This point is exemplified by the optical micrograph in Fig. 14 showing an SOIC solder joint after 5000 thermal cycles. The mechanism by which the Bi-Sn joint degraded is a result of the accelerated intermetallic compound layer growth at solder/Cu interfaces[9]. In this case, that interface is that between the SOIC gull wing lead and the Bi-Sn solder. Specifically, the Bi component of the solder does not participate in the layer development. As a result, it is rejected ahead of the growing intermetallic compound layer, forming a brittle, continuous layer ahead of the latter. Consequently, the Bi layer readily fractures, producing voids as a result of the sample fabrication process but more importantly, causing a significant drop in the strength of the interface.

Finally, there was no loss of electrical continuity in Sn-Ag-Bi solder joints after the 5000 cycle duration.

10,000 thermal cycles

The chip capacitor Sn-Ag-Bi solder joints retained excellent integrity after 10,000 thermal cycles (Figs. 15a, 15b). The most persistent failure mode was that of crack formation at the top of the solder fillet. The extent of the crack development was greater than that observed after 5000 thermal cycles; a worse case is shown in Figs. 15c and 15d. The surface profile of the fillets showed a slightly rougher appearance. In one case, a crack had initiated at the rough, fillet surface and propagated about 75% of the distance *towards* the termination. There was no appearance of deformation or cracking of the solder in the gap between the capacitor and the bond pad. Also, there was no discernable evolution by the microstructure when the images in Fig. 15 were compared with those of chip capacitor solder joints in the as-fabricated condition.

Damage to the SOIC solder joints was largely absent in the cases that were examined (Fig. 16a). Some roughening of the fillet surfaces was observed. In the joint shown in Fig. 16b, small cracks formed in the top surface solder film as well as on the lower reaches of the fillet surface. However, those cracks did not extend to a degree that would pose a significant threat to the functionality of the interconnect. There was no indication of damage to the solder in the gap found between the lead and the bonding pad. The general microstructure of the solder throughout the joint was not significantly changed by the thermal cycling environment.

The PLCC solder joints exhibited some damage. Shown in Figs. 17a and 17b are low magnification micrographs of the solder joint cross sections. The solder fillet surfaces have roughened with the cycling exposure. Cracks were observed on the thin solder film coating the top of the leads. A crack was also noted in the heel fillet of the joint shown in Fig. 17a. An improved view of the crack is shown in Fig. 17c which, along with Fig. 17d, provide high magnification images of the heel fillets. The crack does not appear to be associated with any microstructural inhomogeneity of the solder. The location of the crack suggests that its source was global thermal expansion mismatch between the package and laminate that resulted in bending (tensile) loads by the J-lead and subsequent cracking in the fillet. Shear fatigue loads caused by both global and local residual stresses had no observable effect on the Sn-Ag-Bi solder because in the gap region at which such stresses were of maximum magnitude, no damage was observed in the solder microstructure. Only isolated areas of grain boundary slip within the Sn-rich matrix were noted.

In summary, exposure of the chip capacitor solder joints, SOIC gull-wing lead solder joints, and the PLCC J-lead solder joints to 10,000 thermal cycles did not degrade the integrity of the solder joints to a degree that would jeopardize their functionality. Clearly, the solder fillets incurred some crack damage which, in all but a few instances, remained as largely near-surface defects. There was no evidence of interfacial failures between the solder and the lead or bonding pad surfaces. Also, the Sn-Ag-Bi solder microstructure appeared to be stable under the thermal cycling exposure by having shown no distinguishable changes when compared to similar, as-fabricated solder joints. There was no loss of electrical continuity in any of the joints.

Solder joint strength measurements

The shear strength values as a function of the number of thermal cycles for the chip capacitor solder joints, are shown in Fig. 18. It is observed that the very high, as-fabricated strength (0 cycles) of 135 N did not change significantly when the parts were subjected to 1000 and 2500 thermal cycles. The mean strength began to decrease with 5000 and 10,000 cycles. It should be noted that the strength level after 10,000 cycles, 92 N, is higher than that of similar Sn-Pb solder joints without thermal cycling (87 N). Therefore, the Sn-Ag-Bi chip capacitor solder joints retained adequate strength after 10,000 thermal cycles.

Although the mean strength values were affected by the thermal cycling conditions, the fracture morphology was not sensitive to the range of cycles. An SEM photograph of a failed solder joint from the test vehicle exposed to 5000 cycles is shown in Fig. 19; it is representative of all of the shear tested capacitors, from the as-fabricated condition to the 10,000 cycle condition. A low magnification view in Fig. 19a shows that the solder fillet remained intact with no apparent damage to it beyond the immediate

vicinity of the fracture. The high magnification image in Fig. 19b shows the differing morphologies between the vertical wall ("A") of the fillet and the "floor," the latter being the gap region between the chip and the bonding pad ("B"). Fracture along surface "A" had propagated in the solder, very close to its interface with the chip termination. The solder sheared in a relatively ductile manner as is evidenced by an absence of small cracks. The surface morphology representing the gap region ("B") was caused by fracture between the Ag-based, thick film metallization (or "frit") and the ceramic body of the chip capacitor. That is, the strength of the solder in joint's gap exceeded that of the capacitor structure. This trend was not unexpected. The gap geometry imposes a constraint on deformation from occurring in the solder. Therefore, the solder appears to be stronger in the gap than it is in regions of little or no constraint, such as the fillet. In the gap region, the strength of the Sn-Ag-Bi solder exceeded that of the capacitor structure, causing failure at the metallization/ceramic interface.

The shear strength (Fig. 18) and fracture morphology information (Fig. 19) can be correlated as follows. As noted above, the fracture path propagated in both the solder and the chip capacitor structure over the range of thermal cycle conditions. The shear strength exhibited a decline at 5000 and 10,000 cycles. Assuming that the adhesion strength between the metallization and the capacitor was not affected by the thermal cycling conditions, then the drop in strength was due to a decrease in load-bearing area at the solder/termination interface (top of region "A"). Further growth of the fillet tip cracks shown in Figs. 11 (5000 thermal cycles) and 15 (10,000 thermal cycles) was the likely cause for the drop in shear strength of the solder joints.

The pull strength of the J-leads on the 68 I/O PLCC packages was determined as a function of thermal cycling; those data appear in Fig. 20. No pull tests were performed on the J-leads of PLCC packages exposed to 10,000 thermal cycles. The data show that the cycling environment had no consistent effect on the solder joint strength. Therefore, the surface and fillet cracks observed in the metallographic cross sections appear to have been inconsequential to the overall mechanical integrity of the J-lead solder joints. The strength levels in Fig. 20 can be compared against that for similar solder joints made with the traditional Sn-Pb solder - 12 N (as-fabricated condition). Therefore, the Sn-Ag-Bi solder retained strength levels that are comparable with those of Sn-Pb solder, even after the former has been thermally cycled.

The reason that the J-lead pull strengths of solder joints made with inherently stronger Sn-Ag-Bi are comparable to, rather than higher than, the pull strengths of similar Sn-Pb solder joints is due to the test configuration. Pulling the lead from the substrate surface places the solder joint structure in primarily a tensile stress mode. The deformation/fracture process becomes more sensitive to interfaces that are perpendicular to the applied load than it would be if tested in shear. The interface structures of Sn-Ag-

Bi and Sn-Pb solder joints are nearly identical in composition (Cu_6Sn_5) and thickness. Therefore, the Sn-Ag-Bi and Sn-Pb soldered J-leads exhibited similar failure strengths.

Summary

1. An evaluation was performed which examined the aging of surface mount solder joints made with 91.84Sn-3.33Ag-4.83Bi bearing solder. Defect analysis of the as-fabricated test vehicles revealed excellent solderability, good package alignment, and a minimum of voids, all properties that allowed the prototypes to serve as suitable test vehicles for a thermal cycling ($0^\circ\text{C} - 100^\circ\text{C}$) reliability assessment.

2. Continuous DC electrical monitoring of the solder joints did not reveal any opens for any of the test conditions through 10,000 cycles.

3. The solder joints exhibited no significant degradation through 2500 cycles. This observation is based upon: (a) an absence of microstructural damage in the way of deformation or crack formation in the joint and (b) sustained shear and pull strengths of chip capacitors and J-leaded solder joints, respectively.

4. Thermal cycles of 5000 and 10,000 caused some surface cracking of the solder joints, and in a few cases, deeper cracks in thinner reaches of a few solder fillets. However, the crack morphologies did not have the same characteristics as do those which indicate substantial thermal mechanical fatigue damage in Sn-Pb solders. That is, there was no deformation or cracking in the solder located in the gap between the package I/O and the circuit board pad nor in the interior of the fillets, both locations that would raise concerns of joint mechanical integrity. A drop in the chip capacitor shear strength was attributed to further growth of a crack that traditionally develops at the top-most tip of the fillet.

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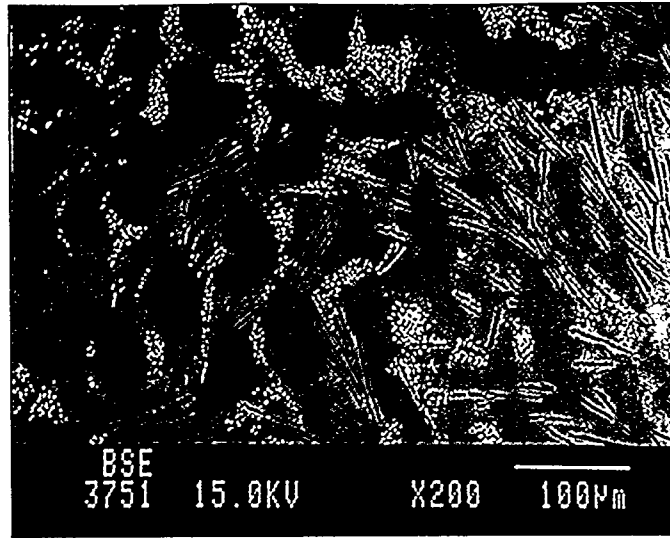


Fig. 1 SEM photograph of the microstructure of the Sn-Ag-Bi alloy.

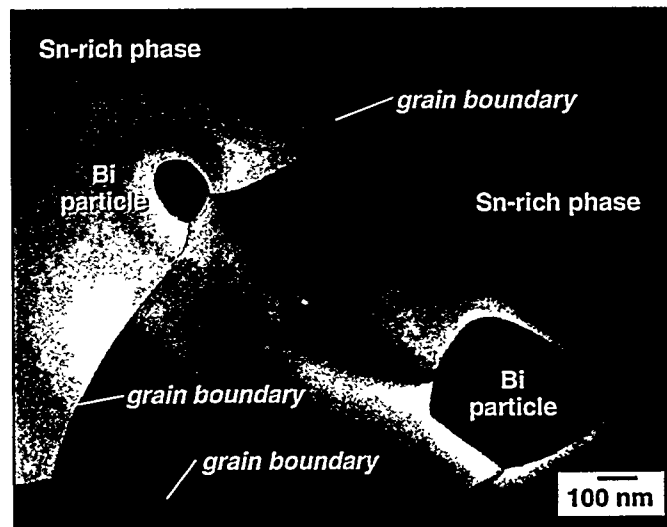


Fig. 2 TEM micrograph of the Sn-Ag-Bi solder microstructure showing boundary pinning by the Bi particles.

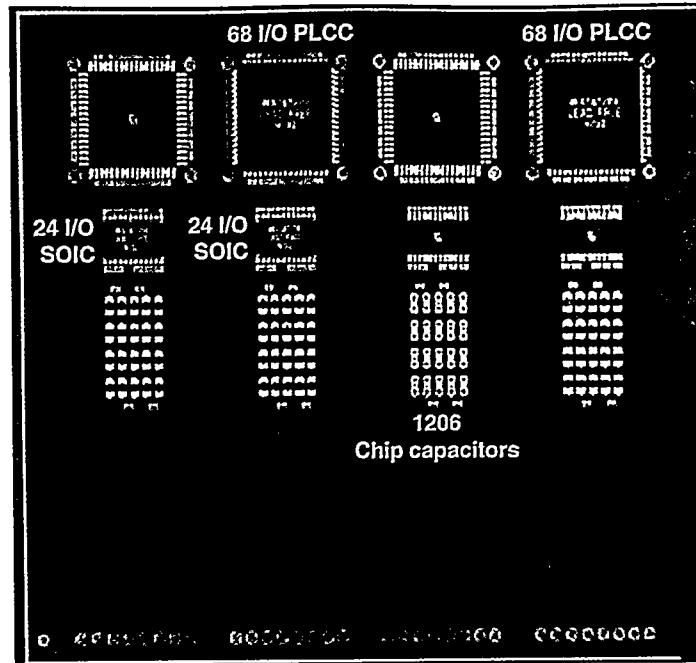


Fig. 3 Photograph of the prototype circuit board used to evaluate the reliability of surface mount, Sn-Ag-Bi solder joints.

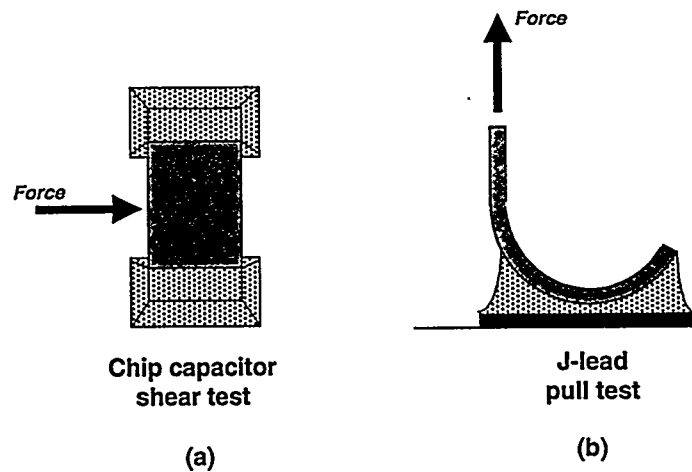
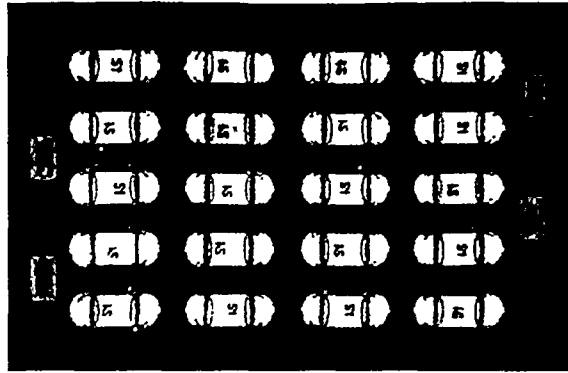


Fig. 4 Schematic diagrams of the mechanical testing modes used to evaluate the solder joints from (a) the leadless chip capacitor solder joints and (b) the J-leaded, PLCC package.



(a)

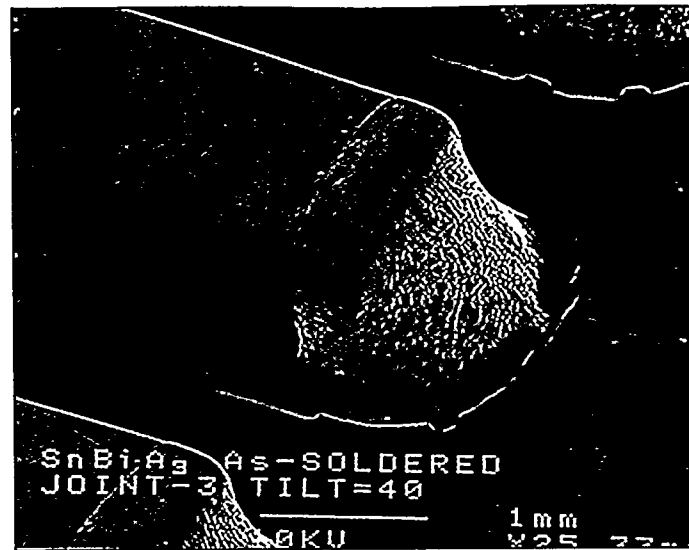


(b)

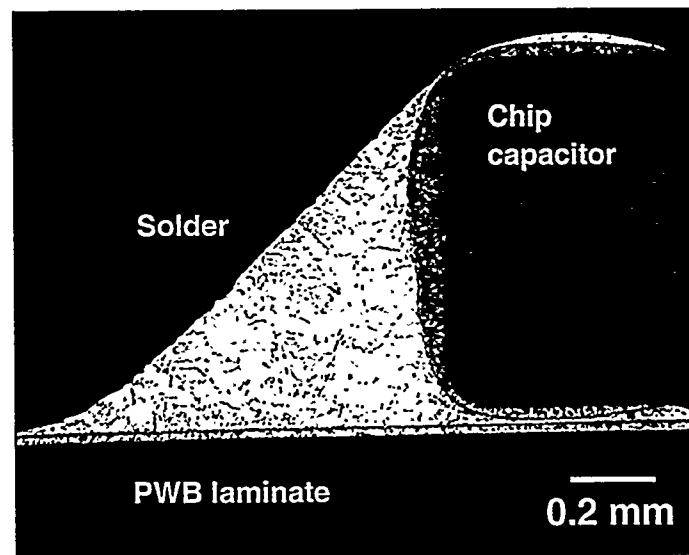


(c)

Fig. 5 Photographs of views of each of the package types on the test vehicle after assembly: (a) chip capacitors, (b) SOIC, and (c) PLCC.

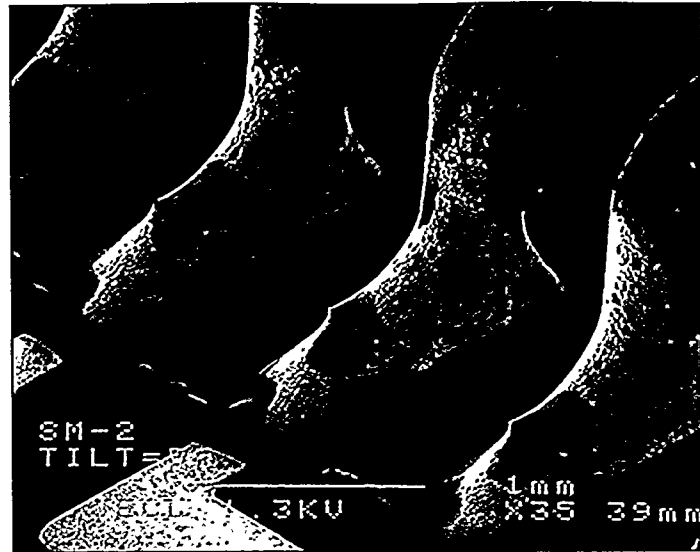


(a)

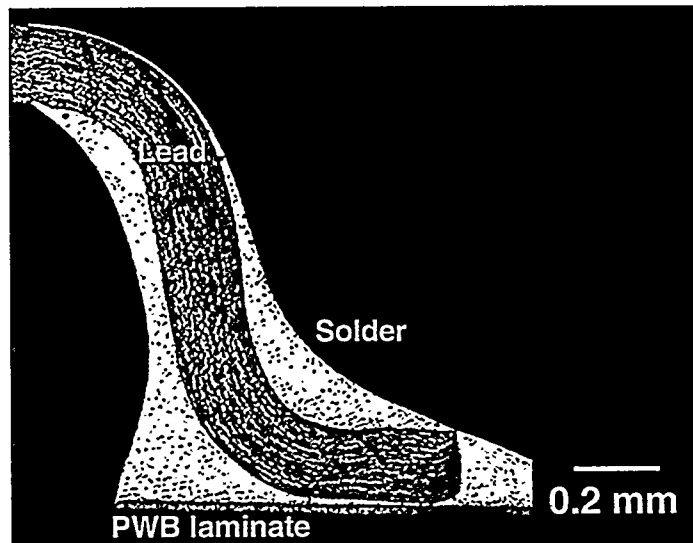


(b)

Fig. 6 SEM photographs and cross sectional optical micrographs are presented of the three solder joint configurations: (a, b) chip capacitor; (c, d) SOIC gull wing; and (e, f) PLCC J-lead. (*con't*)

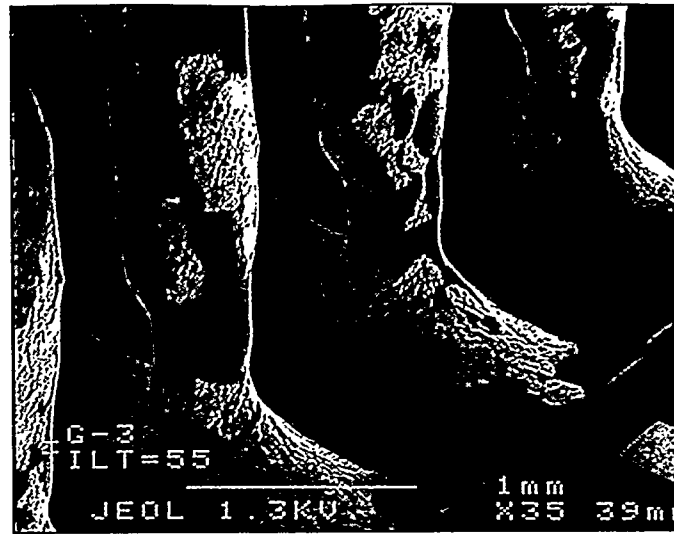


(c)

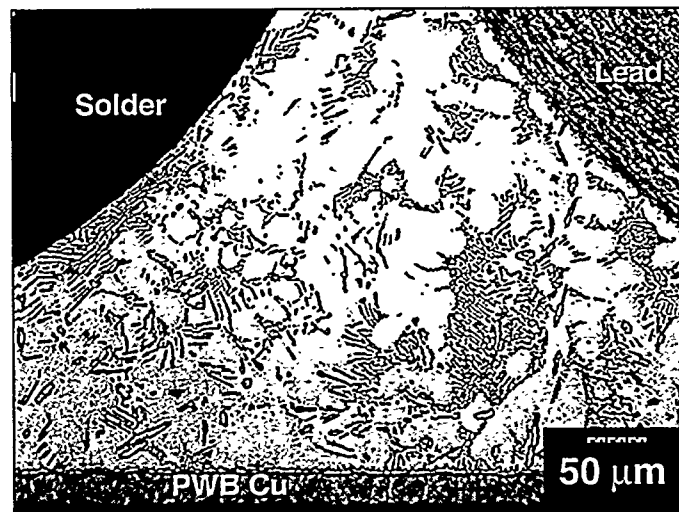


(d)

Fig. 6 SEM photographs and cross sectional optical micrographs are presented of the three solder joint configurations: (a, b) chip capacitor; (c, d) SOIC gull wing; and (e, f) PLCC J-lead. (*con't*)

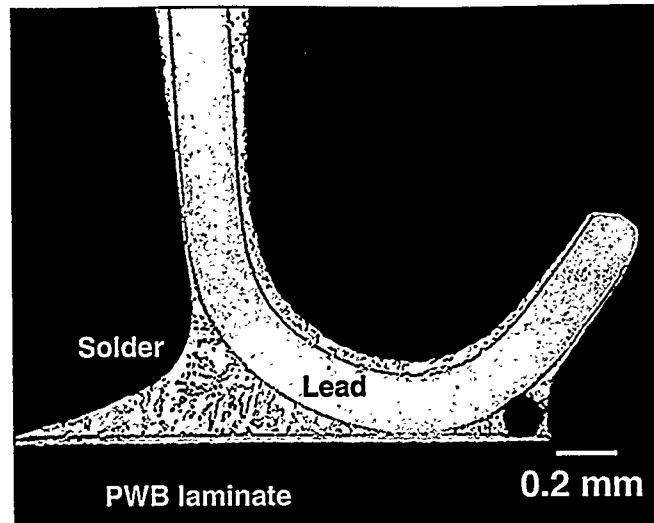


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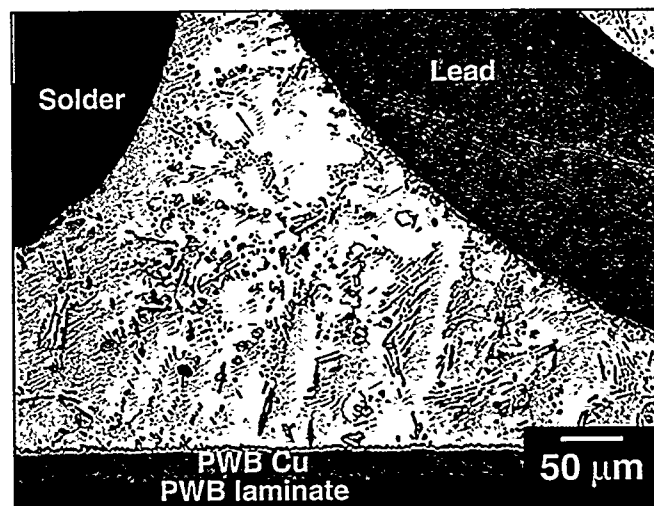


(f)

Fig. 6 SEM photographs and cross sectional optical micrographs are presented of the three solder joint configurations: (a, b) chip capacitor; (c, d) SOIC gull wing; and (e, f) PLCC J-lead.

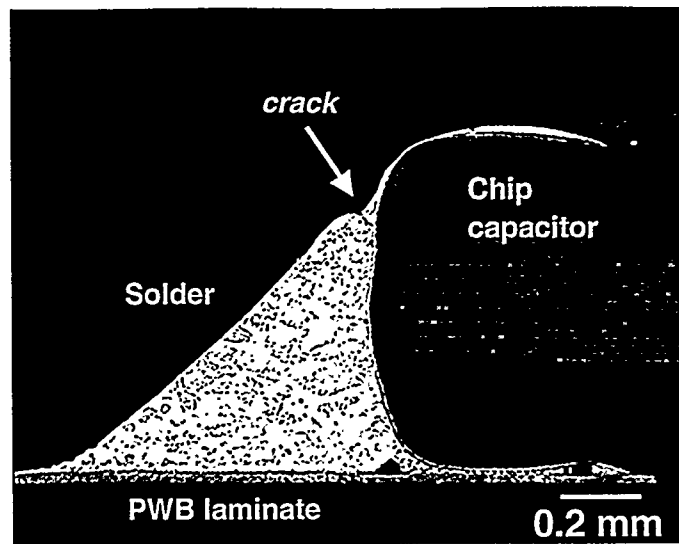


(a)

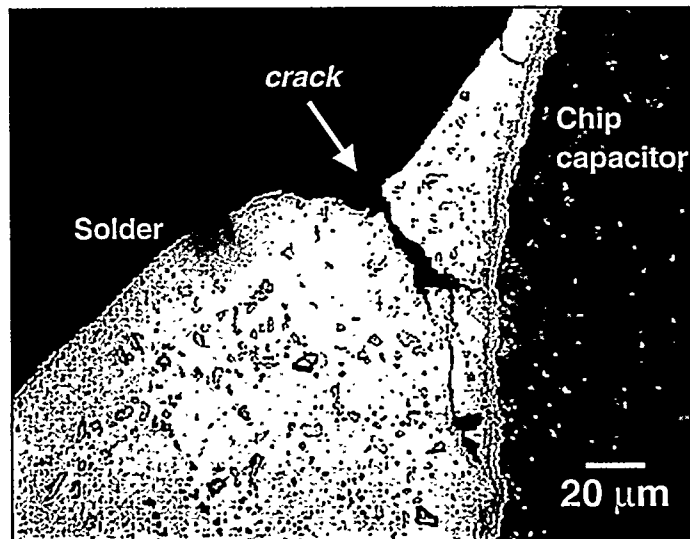


(b)

Fig. 7 Optical micrographs of a J-lead joint from a PLCC package after 1000 thermal cycles: (a) low magnification view of the whole joint and (b) high magnification view of the heel fillet.

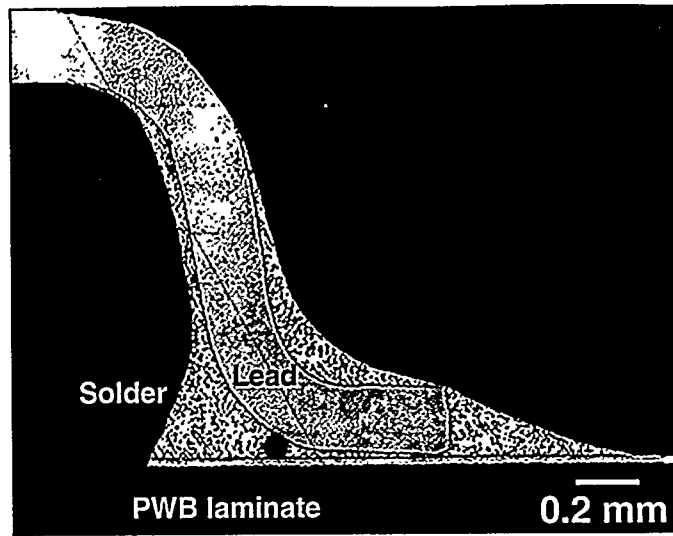


(a)

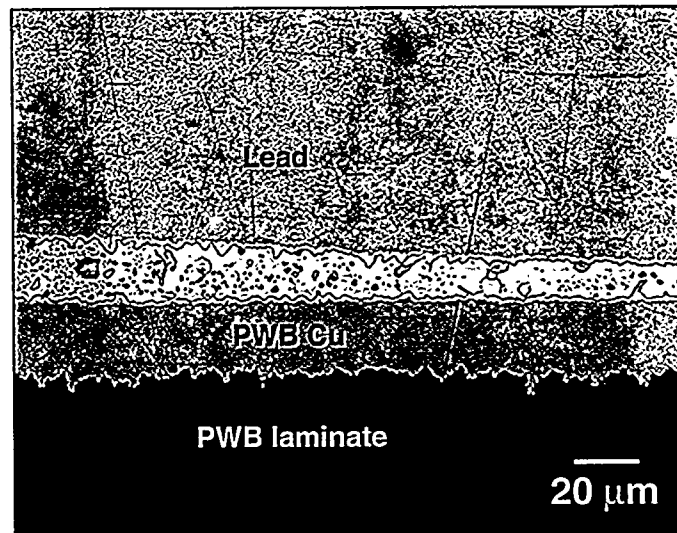


(b)

Fig. 8 (a) Chip capacitor solder joint after 2500 thermal cycles. (b) High magnification image of the crack formed at the top of the fillet.

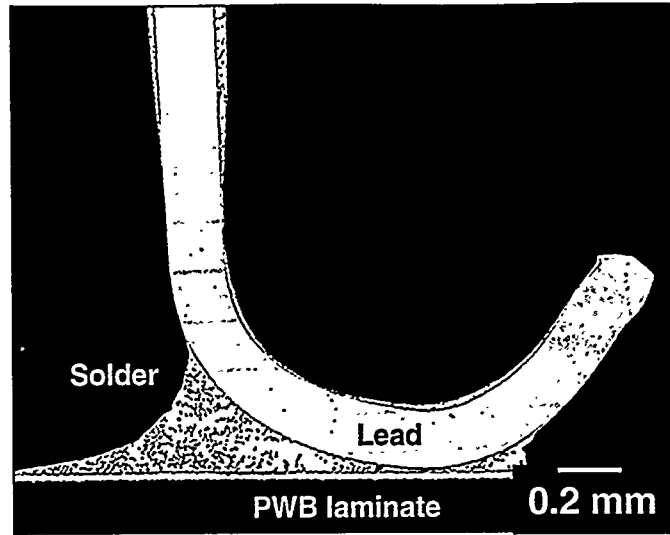


(a)

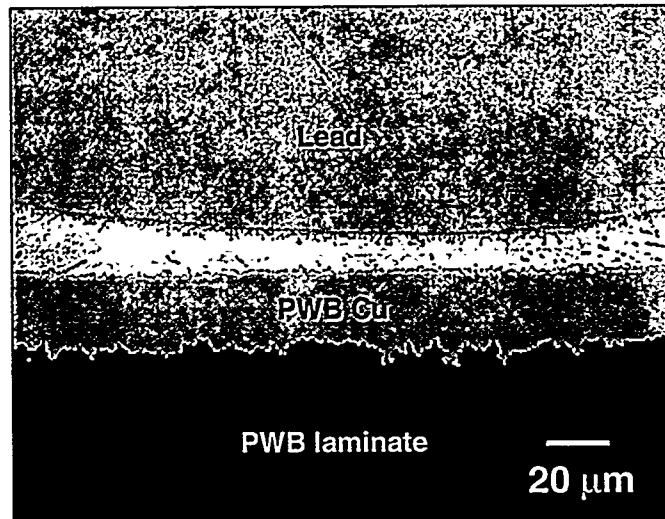


(b)

Fig.9 (a) SOIC solder joint after 2500 thermal cycles. (b) High magnification image of the gap region between the gull-wing lead and circuit board pad.

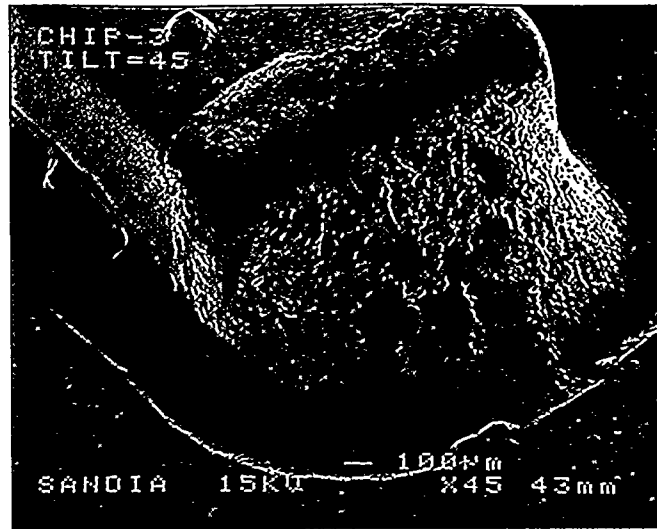


(a)

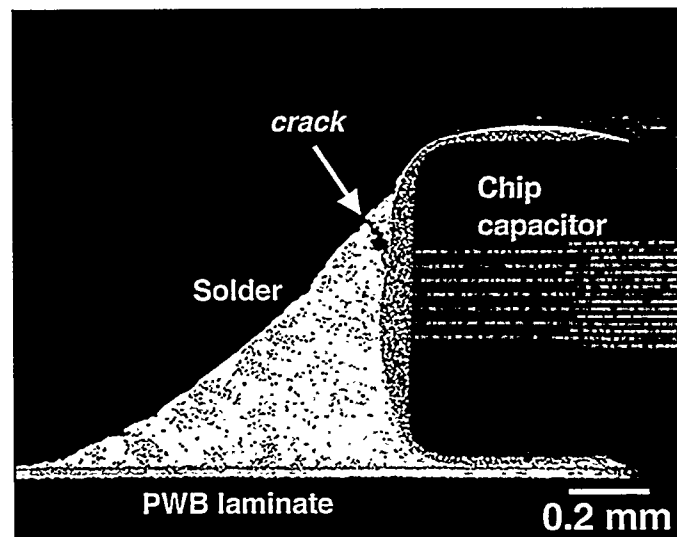


(b)

Fig. 10 (a) PLCC solder joint after 2500 thermal cycles. (b) High magnification image of the gap region between the J-lead and circuit board pad.

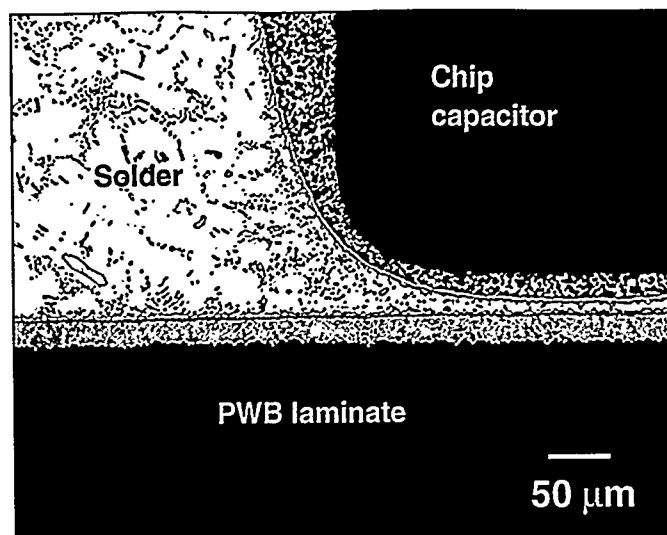


(a)



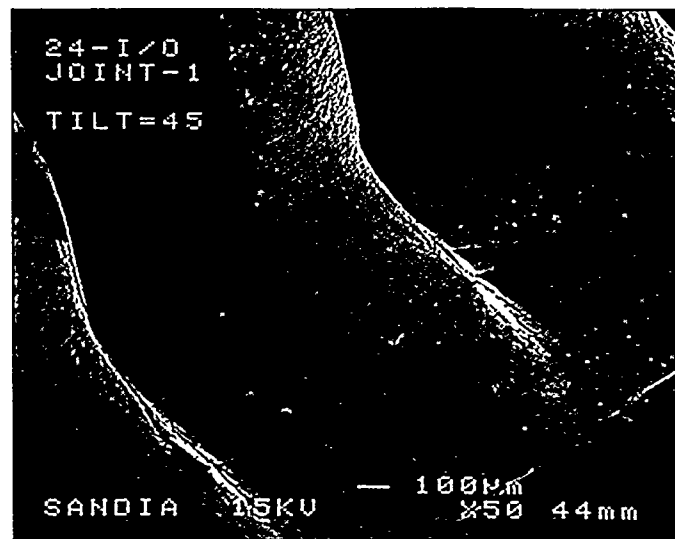
(b)

Fig. 11 Chip capacitor solder joint after 5000 thermal cycles: (a) SEM image of the solder fillet, (b) optical micrograph showing the cross section of chip capacitor joint, and (c) high magnification, optical micrograph of the gap region of the solder joint. (*con't*)

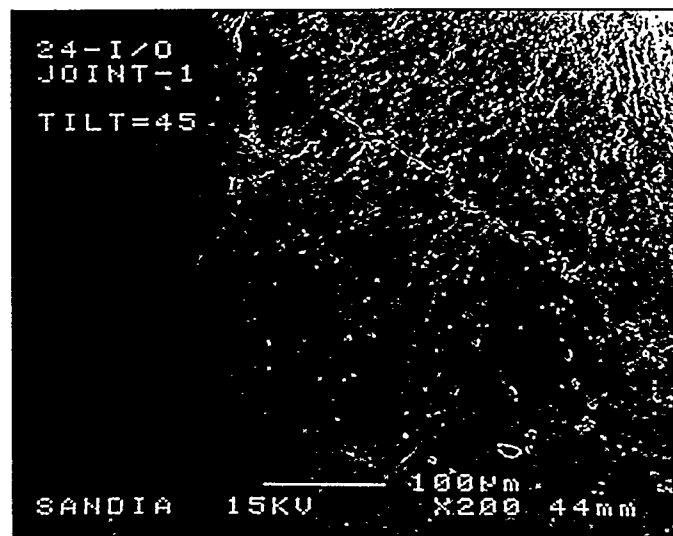


(c)

Fig. 11 Chip capacitor solder joint after 5000 thermal cycles: (a) SEM image of the solder fillet, (b) optical micrograph showing the cross section of chip capacitor joint, and (c) high magnification, optical micrograph showing the gap region of the solder joint.

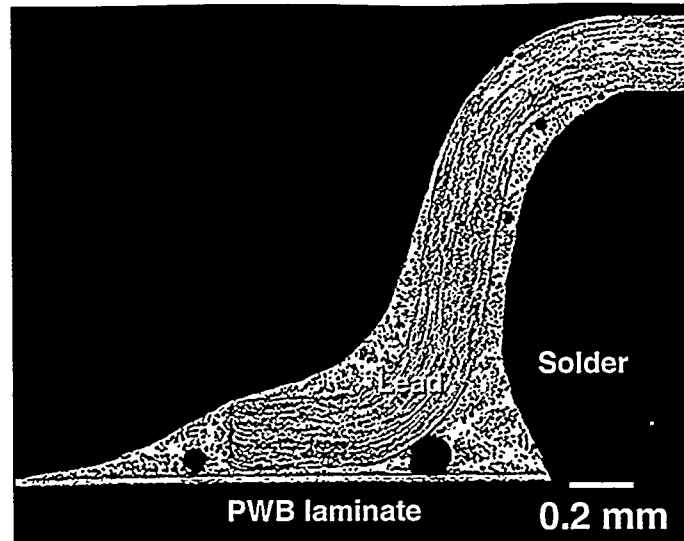


(a)

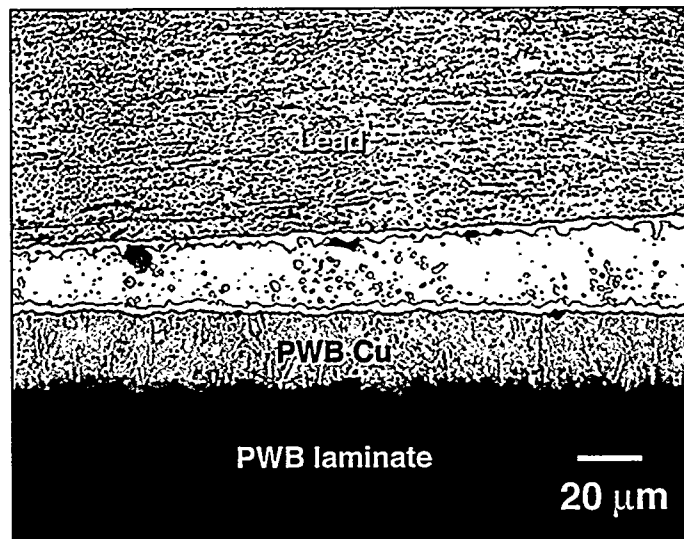


(b)

Fig. 12 SOIC solder joint after 5000 thermal cycles: (a, b) SEM images of the solder fillet, (c) optical micrograph showing the cross section of gull-wing lead joint, and (d) high magnification, optical micrograph showing the gap region of the solder joint. (con't)

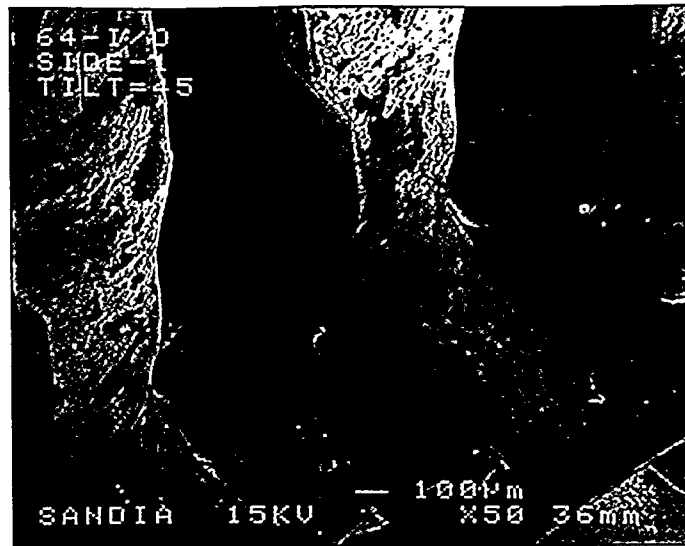


(c)

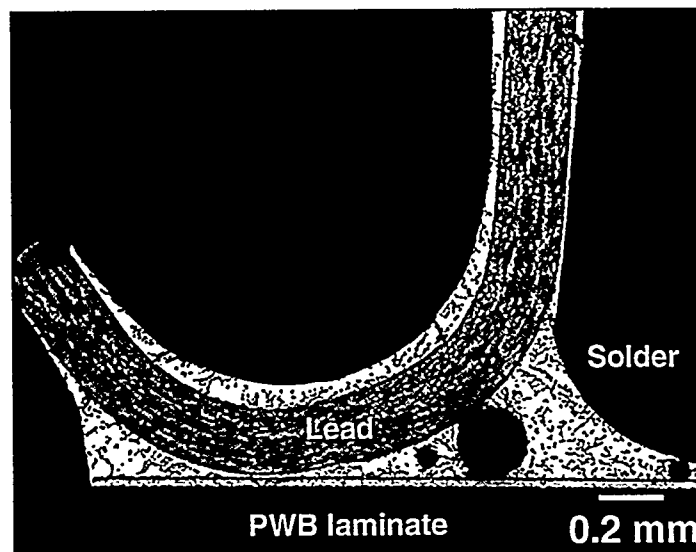


(d)

Fig. 12 SOIC solder joint after 5000 thermal cycles: (a, b) SEM images of the solder fillet, (c) optical micrograph showing the cross section of gull-wing lead joint, and (d) high magnification, optical micrograph showing the gap region of the solder joint.

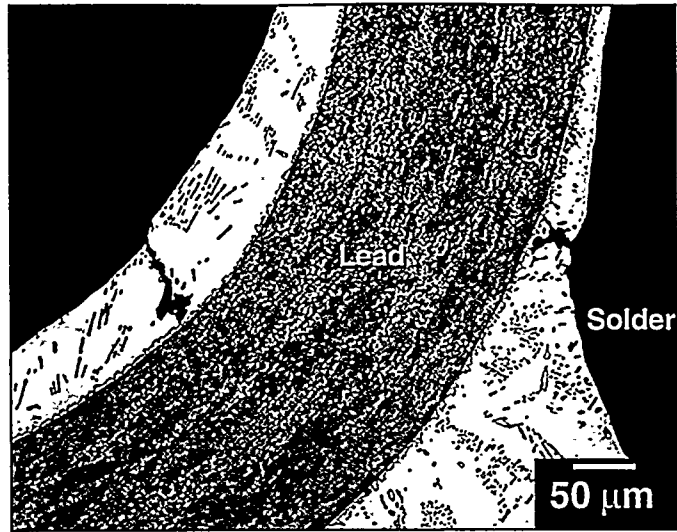


(a)

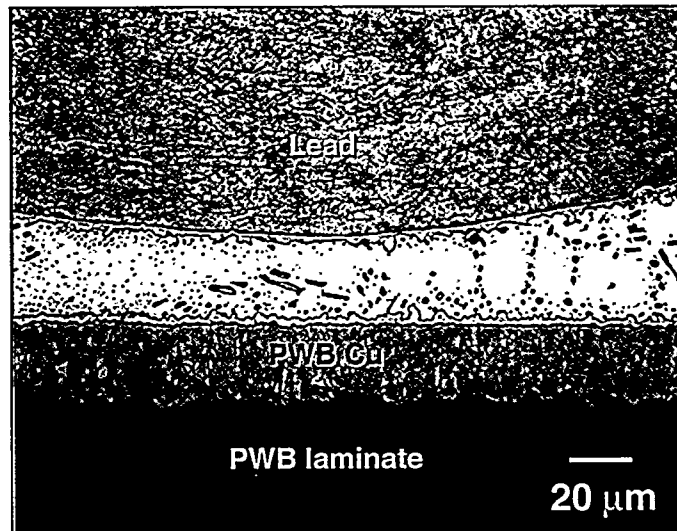


(b)

Fig. 13 PLCC solder joint after 5000 thermal cycles: (a) SEM image of the solder fillet, (b) optical micrograph showing the cross section of J-lead joint, (c) high magnification, optical micrograph showing cracks in the solder film on the lead surface, and (d) optical micrograph of solder in the gap region of the joint beneath the lead. (con't)



(c)



(d)

Fig. 13 PLCC solder joint after 5000 thermal cycles: (a) SEM image of the solder fillet, (b) optical micrograph showing the cross section of J-lead joint, (c) high magnification, optical micrograph showing cracks in the solder film on the lead surface, and (d) optical micrograph of solder in the gap region of the joint beneath the lead.

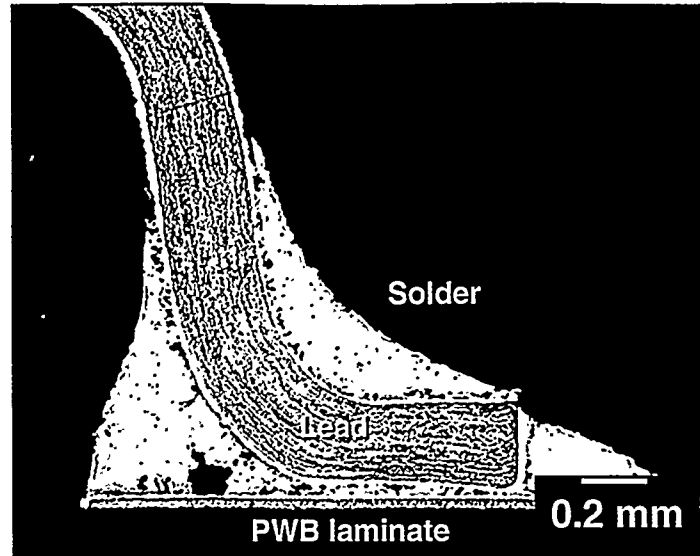
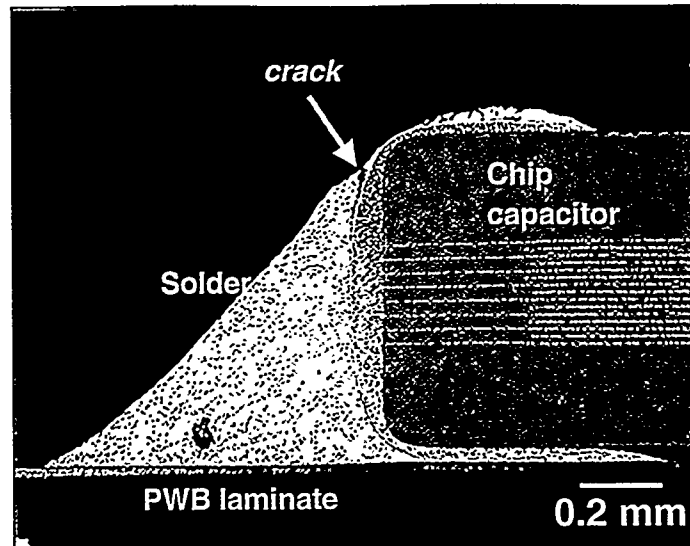
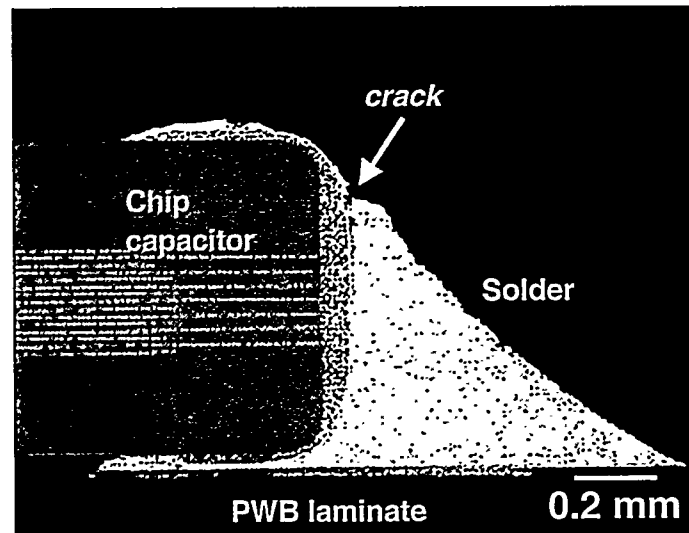


Fig. 14 Optical micrograph of the a 58Bi-42Sn, SOIC solder joint after 5000 cycles. Severe deterioration has taken place.

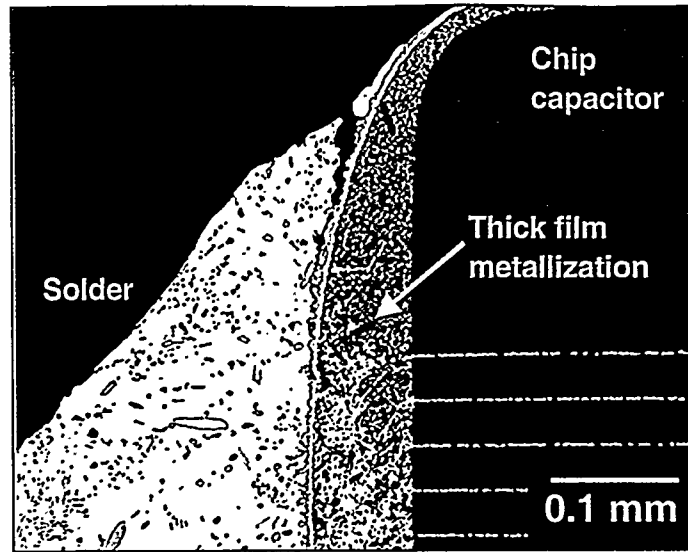


(a)

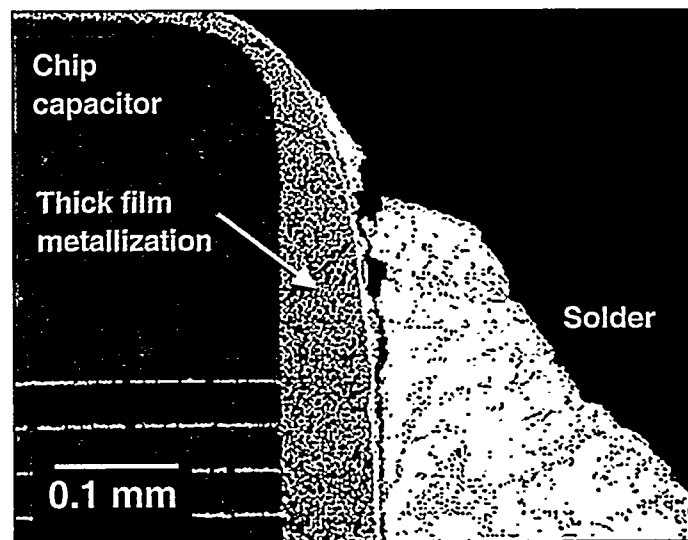


(b)

Fig. 15 Optical micrographs of Sn-Ag-Bi solder joints on the chip capacitors that were exposed to 10,000 thermal cycles: (a, b) low magnification views and (c, d) high magnification views of the tops of the solder fillets. (*con't*)

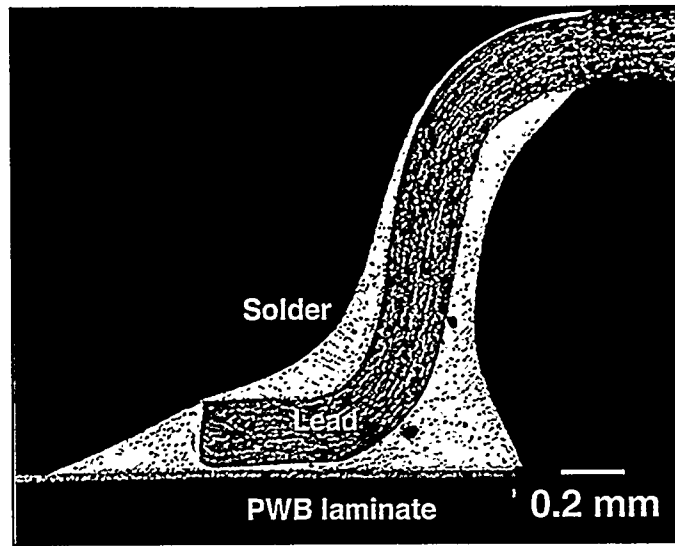


(c)

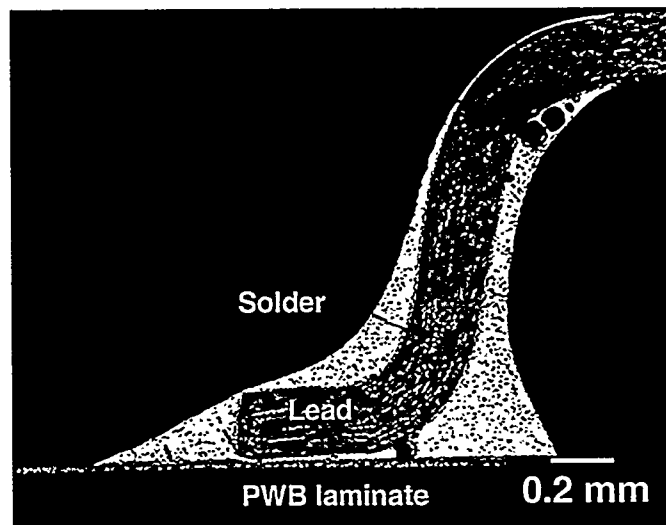


(d)

Fig. 15 Optical micrographs of Sn-Ag-Bi solder joints on the chip capacitors that were exposed to 10,000 thermal cycles: (a, b) low magnification views and (c, d) high magnification views of the tops of the solder fillets.

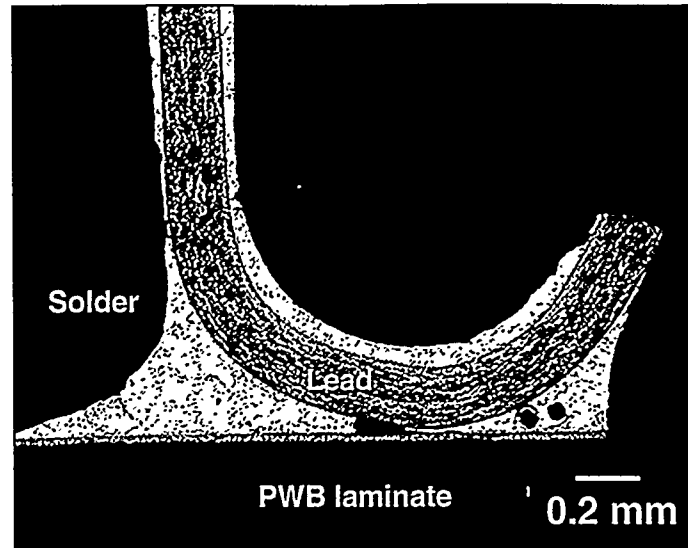


(a)

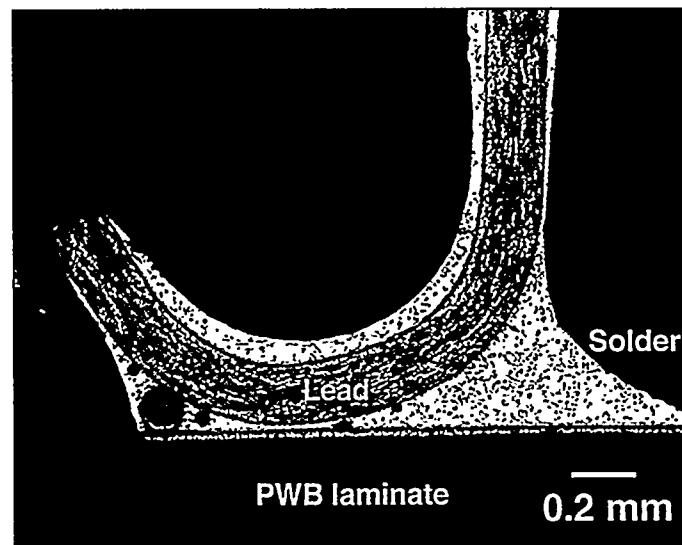


(b)

Fig. 16 Optical micrographs of the SOIC gull-wing solder joints after 10,000 thermal cycles. The case in (a) was typical with an absence of damage while that in (b) shows the formation of some surface cracks.

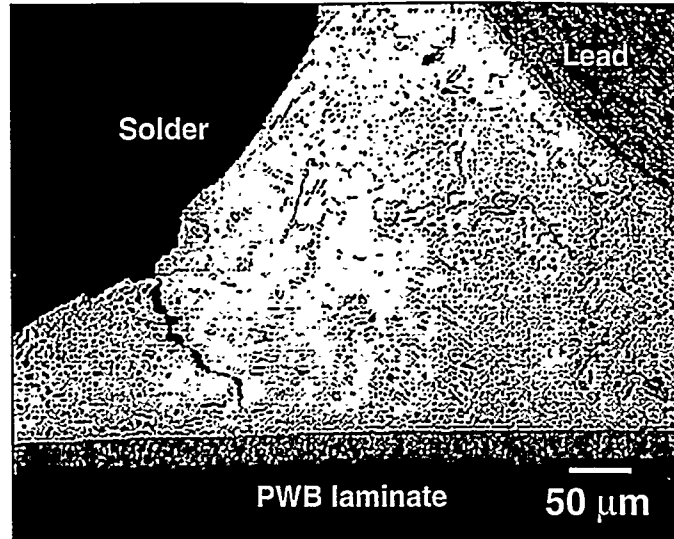


(a)

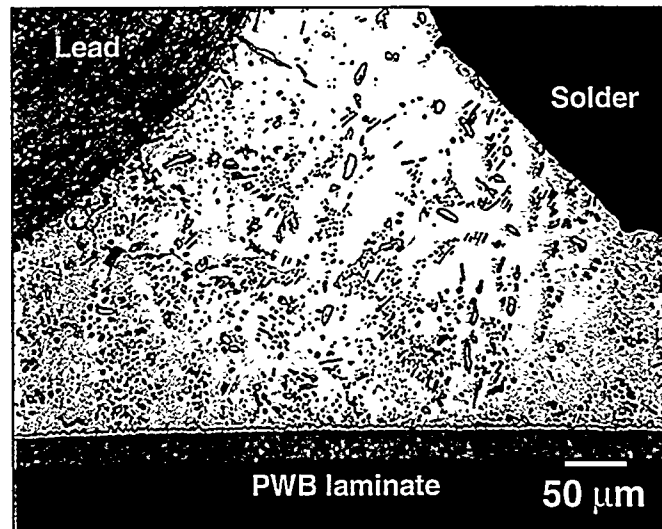


(b)

Fig. 17 Optical micrographs of the PLCC J-lead solder joints after 10,000 thermal cycles: (a, b) low magnification images and (c, d) high magnification images of the solder joint fillets. (*con't*)



(c)



(d)

Fig. 17 Optical micrographs of the PLCC J-lead solder joints after 10,000 thermal cycles: (a, b) low magnification images and (c, d) high magnification images of the solder joint fillets.

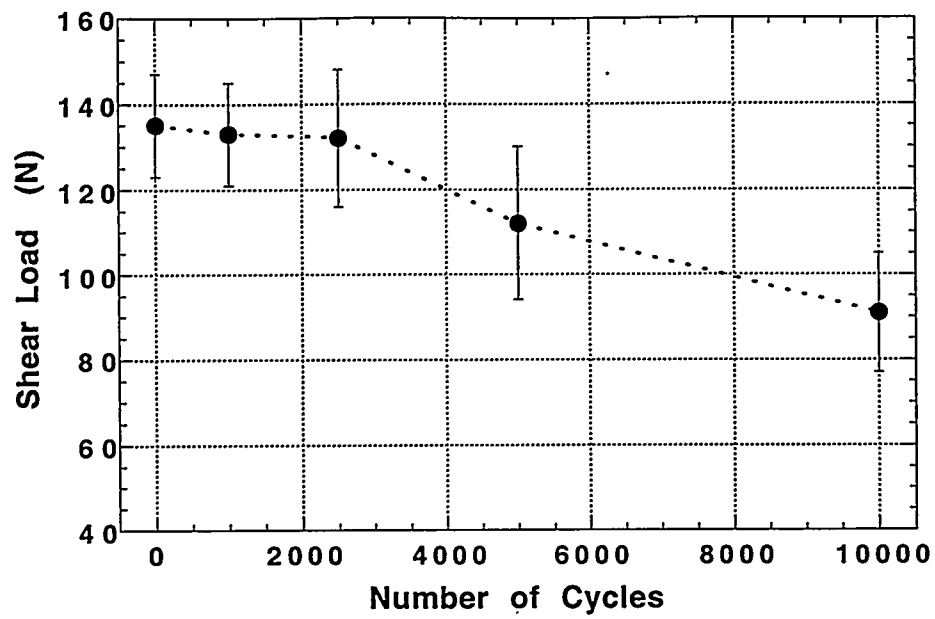
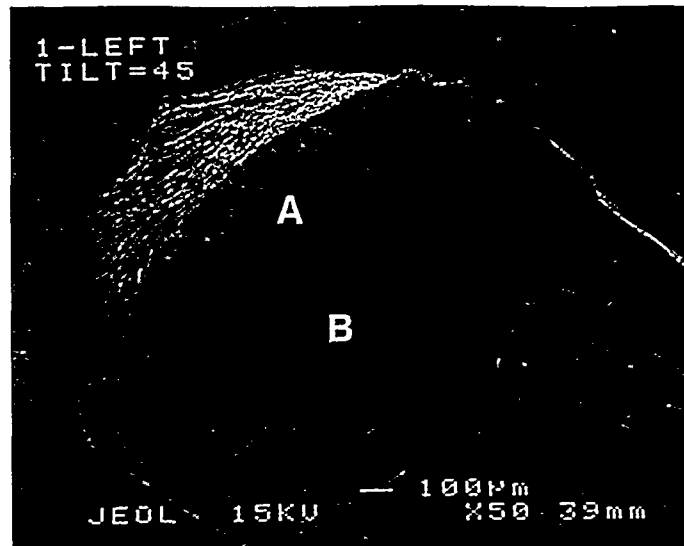
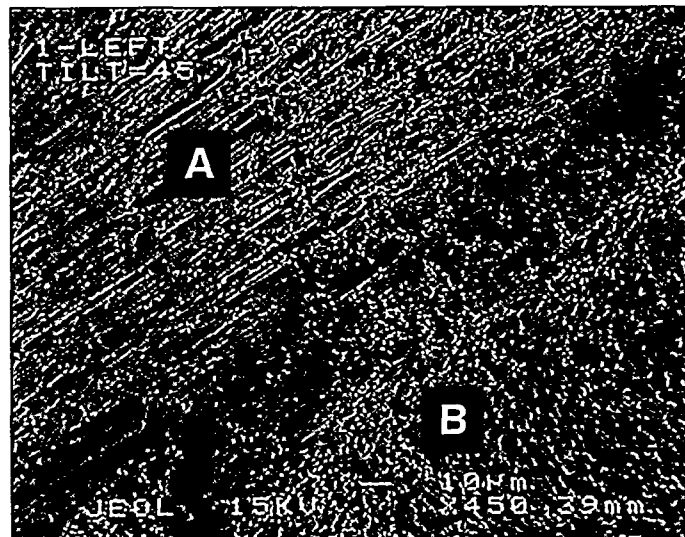


Fig. 18 Shear strength as a function of the number of thermal cycles for the chip capacitor solder joints.



(a)



(b)

Fig. 19 SEM photographs of the fracture morphology of a chip capacitor solder joint after exposure to 5000 thermal cycles: (a) low magnification view of the remaining fillet. Location "A" is the vertical wall of the termination and "B" is the surface where the gap was located; (b) high magnification view of the fillet surface "A" showing the solder shear and "B" where failure of the Ag-frit metallization off of the capacitor ceramic had occurred.

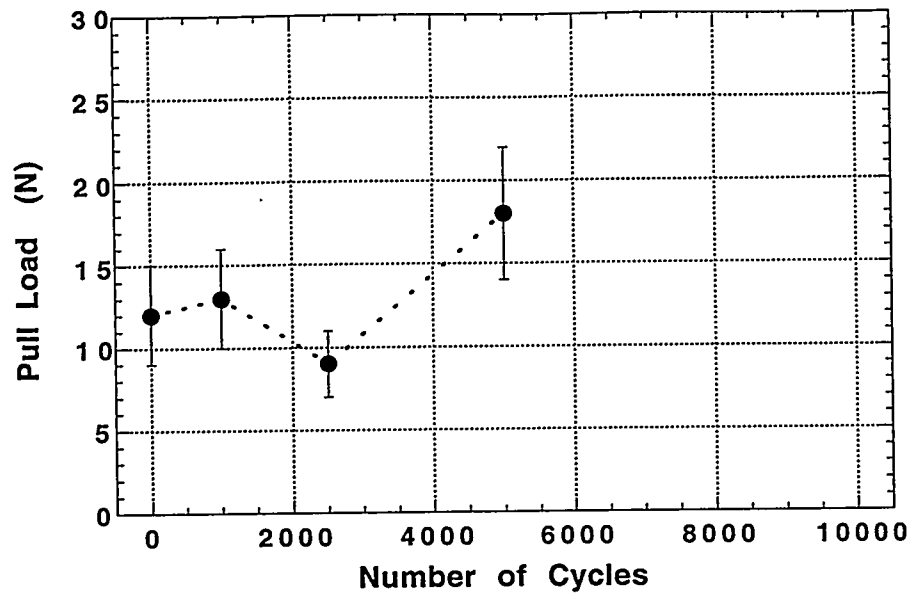


Fig. 20 Pull strength as a function of the number of thermal cycles for the J-lead solder joints on the PLCC package.