TEXAS INSTRUMENTS

Application Report

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Evaluation of Nickel/Palladium-Finished ICs With Lead-Free Solder Alloys

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ABSTRACT

A nickel/palladium (Ni/Pd) lead finish for integrated circuits (IC) was introduced in 1989. In 1998, solderability test results were published on Ni/Pd-finished components using a Sn/Ag/Cu/Sb lead-free (Pb-free) solder paste and printed wiring board (PWB) pads coated with organic solderability preservative (OSP). Since then, a number of other Pb-free solder alloys have been introduced.

This evaluation shows soldering and reliability performance of Ni/Pd-finished components with the leading Pb-free solder alloys now being considered by the electronics industry. The ICs tested were 20-pin small-outline integrated circuit (SOIC) and 56-pin shrink small-outline package (SSOP) gull-wing leaded devices finished with four-layer Ni/Pd. The solder alloys were Sn/Pb/Ag (control), Sn/Ag/Cu, Sn/Bi, Sn/Ag/Cu/Sb, Sn/Zn/Bi, and Sn/Zn. The land pads on the test PWB were coated with an OSP. Using Pb-free Ni/Pd-finished components, a Pb-free solder alloy, and an OSP coating, a Pb-free assembly was achieved and evaluated. Additionally, Ni/Pd/Au-finished IC leads were soldered using the Sn/Ag/Cu paste.

Evaluations of each alloy included visual appearance, lead pull before and after 1000 temperature cycles, and cross-sections of solder joints before and after temperature cycling.

Results of the evaluation indicate good wetting performance of the Ni/Pd-finished ICs, with all of the Pb-free solder alloys tested. In only one case (Sn/Zn/Bi alloy), a slight negative wetting angle was noted at the heel. Lead-pull data shows higher average pull forces for all of the Pb-free alloys versus the Sn/Pb/Ag paste used as a control, with the exception of Sn/Bi. Voiding in a few of the solder joints occurred, but did not impact lead-pull strength. Ni/Pd/Au-finished IC leads show good wetting performance with the Sn/Ag/Cu alloy.

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Introduction

An Ni/Pd finish for ICs was first introduced in the late 1980s.[1,2] As of September 2000, more than 35 billion Ni/Pd-finished IC packages are in the field.

With the interest in Pb-free processing that developed during the mid-1990s, the need for Pb-free package terminations was evident.[3,4,5,6,7,8,9] Because Ni/Pd is a Pb-free finish, use of Ni/Pd-finished components with a Pb-free solder alloy and PWB pad finish can yield a lead-free solder joint. A study was performed[10] in 1998 to evaluate a Pb-free solder joint formed by using four-layer Ni/Pd-finished IC components (as well as Ni/Pd/Au-finished components and Sn/Pb plated components as a control), Sn/Ag/Cu/Sb Pb-free solder paste, and an organic solderability preservative (OSP) as the PWB surface finish. Contact-angle measurements and lead-pull testing were done. Temperature cycling was performed to evaluate the package integrity. The wetting-balance test was used to determine the solder wetting-times characteristic of the Ni/Pd and Ni/Pd/Au finishes.

That study showed that contact angles increased with Ni/Pd and Ni/Pd/Au finishes. However, Ni/Pd and Ni/Pd/Au finishes achieved equivalent or better lead-pull and temperature-cycle results versus Sn/Pb-plated component leads (control). This indicated that any difference in performance of the different lead finishes (Sn/Pb, Ni/Pd, Ni/Pd/Au) was merely visual. By using either Ni/Pd- or Ni/Pd/Au-finished IC components, Sn/Ag/Cu/Sb Pb-free solder paste and the OSP PWB surface finish, it was possible to achieve a Pb-free solder joint.

Proposed European legislation and existing Japanese legislation[11,12,13] intensified interest in Pb-free processing in late 1999 and into 2000. This interest in Pb-free processing sparked this evaluation of Ni/Pd-finished components with the industry-preferred Pb-free solder alloys.

Experiment

Pb-free solder alloys chosen for this evaluation were based upon input from customers, industry consortia, and standards organizations. These are shown in Table 1.

Table 1. Solder Alloys Included in This Evaluation

RUN	ALLOY	MELTING POINT (°C)	PEAK TEMPERATURE (°C)
1	62Sn/36Pb/2Ag	179	225
2	95.5Sn/3.9Ag/0.6Cu	217	235
3	95.5Sn/3.9Ag/0.6Cu	217	260
4	42Sn/58Bi	139	170
5	96.2Sn/2.5Ag/0.8Cu/0.5Sb	215–217	240
6	89Sn/8Zn/3Bi	187–197	225
7	91Sn/9Zn	199	225

Sn/Pb/Ag solder alloy was the control paste. The Sn/Ag/Cu alloy was chosen because this alloy has been recommended by the National Electronics Manufacturing Initiative (NEMI) as a standardized Pb-free solder alternative.[14] The Sn/Ag/Cu class of alloys also has been recommended or suggested by IPC, ITRI, and NCMS.[15,16,17] The Sn/Bi alloy was chosen, based on interest by some end users, to develop a process utilizing a lower-temperature melting alloy. The Sn/Ag/Cu/Sb (Castin™) has been available since 1993. This is the alloy evaluated in 1998[10] and is included here for direct comparison to the other alloys. The Sn/Zn/Bi and Sn/Zn alloys are being evaluated by the Japanese market, and this warranted their inclusion in the study.

For the Sn/Ag/Cu alloy, two peak reflow temperatures were used. NEMI has indicated that “use of the recommended alloys will raise the melting point by as much as 40 degrees, which obviously has an impact on a number of the materials and steps in the assembly process, and affects companies throughout the supply chain.”[14] The peak reflow temperature of 260°C has been mentioned as worst case across the industry for the Sn/Ag/Cu alloy. The run using a peak reflow temperature of 235°C was to characterize performance of the Sn/Ag/Cu alloy at a lower peak reflow temperature. Skidmore reported that best results were obtained using a linear profile at 235°C peak when evaluating the factors of solder alloy, flux chemistry, and profile.[18]

To evaluate Pb-free solder joints, an OSP, ENTEK™ PLUS CU-106A, was used to coat the PWB pad. This coating is a substituted benzimidazole that preserves the solderability of Cu through multiple soldering operations. During reflow, most of the OSP is displaced by the wetted solder and becomes a negligible constituent of the solder-paste residue. Some of the OSP (<25%) volatilizes at reflow temperatures.[19]

Reflow Profiles

Reflow profiles used were based on inputs from the solder-paste vendors. For runs 1, 6, and 7 (Sn/Pb/Ag, Sn/Zn, Sn/Zn/Bi alloys), the profile shown in Figure 1 was used. This profile has a preheat range of 140°C to 180°C for approximately 100 seconds, before rising to a peak of 225°C.

For run 2 (Sn/Ag/Cu alloy), the profile is shown in Figure 2. This profile has a preheat range of 140°C to 180°C for approximately 100 seconds, before rising to a peak of 235°C.

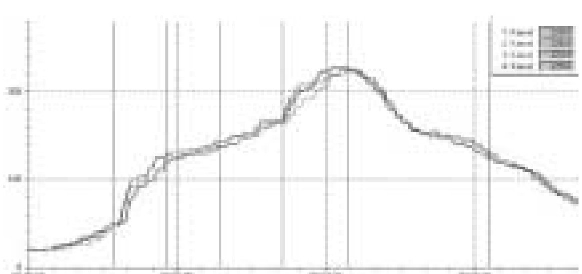

Figure 1. Profile for Runs 1, 6, 7

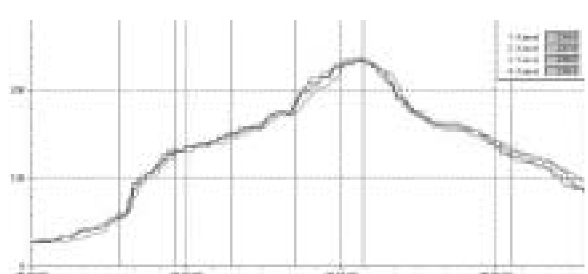

Figure 2. Profile for Run 2

For run 3 (Sn/Ag/Cu alloy), the profile is shown in Figure 3. This profile has a preheat range of 140°C to 200°C for approximately 100 seconds, before rising to a peak of 260°C.

For run 4 (Sn/Bi alloy), the profile is shown in Figure 4. This profile has a preheat range of 100°C to 130°C for approximately 100 seconds, before rising to a peak of 170°C.

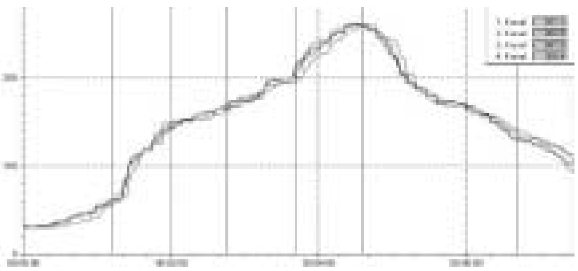

Figure 3. Profile for Run 3

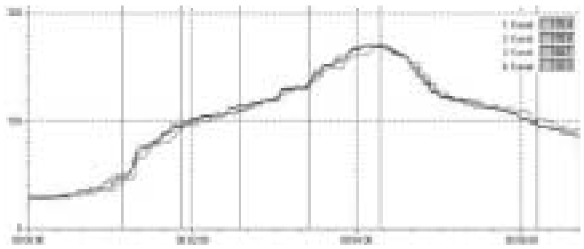

Figure 4. Profile for Run 4

For run 5 (Sn/Ag/Cu/Sb alloy), the profile is shown in Figure 5. This profile has a preheat range of 140°C to 180°C for approximately 100 seconds, before rising to a peak of 240°C.

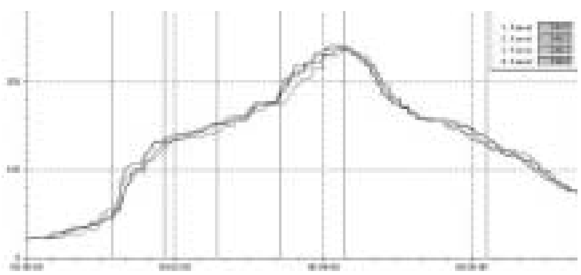

Figure 5. Profile for Run 5

Test Equipment and Procedure

The solder-paste stencil was a 150-mm stainless-steel stencil, laser cut and polished. Solder paste printing was done manually. An optical alignment tool for manual component placement was used to position the device leads to the solder paste prints. Optical inspection of the printed solder paste on the board was done to ensure adequate paste height and complete printing. For reflow, a Rehm full-convection oven was used with N_2 and O_2, 500 ppm to1000 ppm.

Performance Measures and Results

We used visual, mechanical, and reliability-test methods to judge the performance of the solder joints. Methods used and results obtained are discussed in the following paragraphs.

Visual Appearance

Solder-joint appearance was used to assess the wetting performance of each paste alloy with the Ni/Pd-finished components. Samples were judged using criteria in IPC-A-610C.[20] Photographs of representative solder joints (either SOIC or SSOP, as noted) are shown in Figures 6 through 12. Note the coarse, grainy appearance of the Sn/Zn/Bi alloy in Figure 11 and, to a lesser extent, similar graininess in Figure 12 for the Sn/Zn alloy. This has been reported by others who have evaluated Sn/Zn-based solder pastes.

All solder joints exhibited a heel-fillet height at least 1× the lead thickness and wetting to the sides of the leads. This performance is acceptable for all three classes of products identified in IPC-A-610C (general electronic products, dedicated-service electronic products, and high-performance electronic products). Variations in side-fillet height were noted for the different solders; however, side-fillet height did not correspond to any difference in lead-pull strength (see Figures 13 and 14), except in the case of the Sn/Bi solder that showed extremely low solder-joint strength. We do not have a good explanation for this behavior, although it contradicts what has been reported elsewhere.

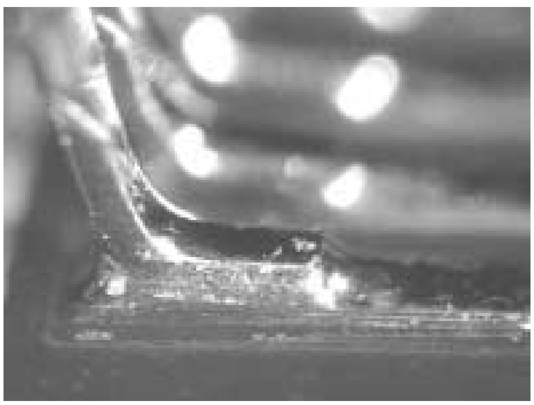

Figure 6. Sn/Pb/Ag Control Paste, SSOP Package

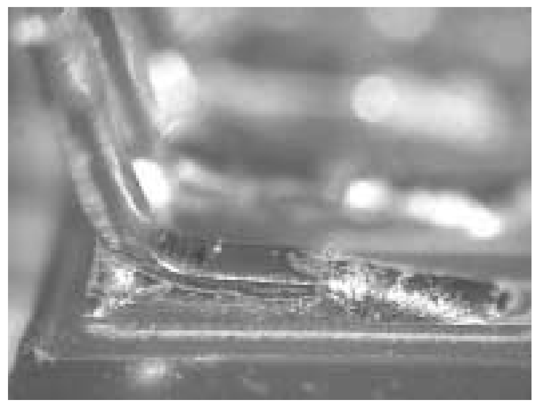

Figure 7. Sn/Ag/Cu Paste (235°C Peak), SSOP Package

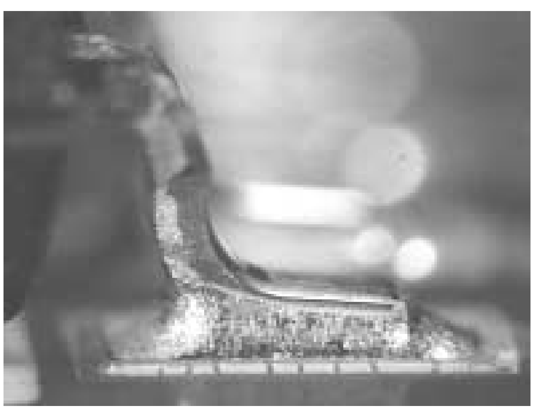

Figure 8. Sn/Ag/Cu Paste (260°C Peak), SOIC Package

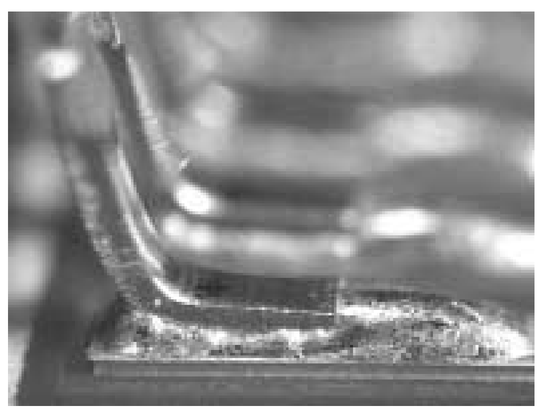

Figure 9. Sn/Bi Paste, SSOP Package

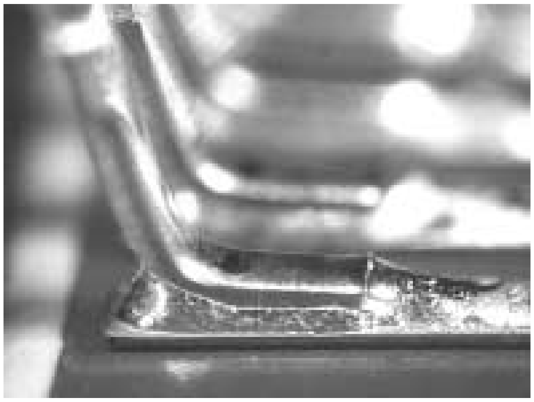

Figure 10. Sn/Ag/Cu/Sb Paste, SSOP Package

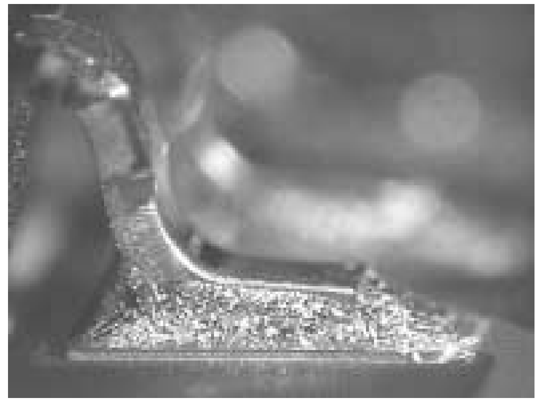

Figure 11. Sn/Zn/Bi Paste, SOIC Package

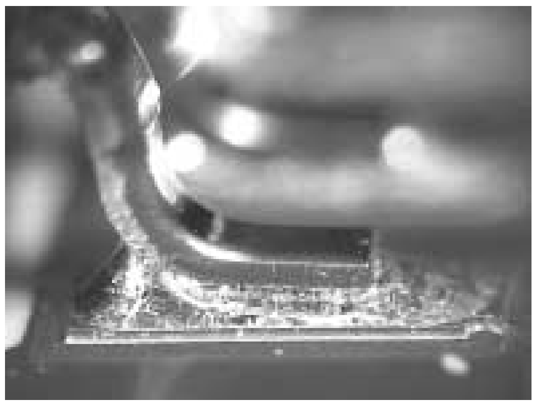

Figure 12. Sn/Zn Paste, SOIC Package

Lead-Pull Data

Lead-pull testing determined the force needed to pull an individual IC lead from the PWB pad after soldering. First, to allow access to an individual lead on the PWB, the leads were cut near the package body. Next, with the leads separated from the package body, the PWB was fastened in a test fixture. Finally, the lead was pulled perpendicular to the PWB surface until it separated from the PWB. The rate of movement of the test device was 0.4 mm/s vertically to the board surface. The force needed to pull the lead from the PWB was measured and recorded. Lead-pull data were taken before and after exposure to temperature cycling.

Lead pull was performed on 20-pin SOIC packages. A sample size of 40 leads for each group was pulled to define an average pull force. Figure 13 gives the average and the range of lead-pull values for the Ni/Pd-finished packages with each solder alloy. Lead-pull force is measured in newtons.

Results of lead pull prior to temperature cycling indicate that all Pb-free alloys showed a higher average pull force than the Sn/Pb/Ag control.

Figure 14 gives the average and range of lead-pull values for the Ni/Pd-finished leads after temperature cycling.

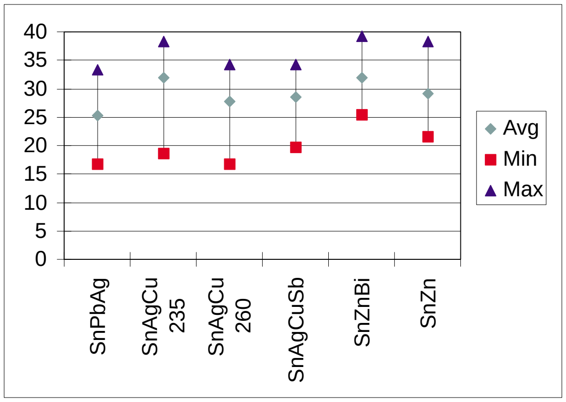

Figure 13. Lead-Pull Results Prior to Temperature Cycling

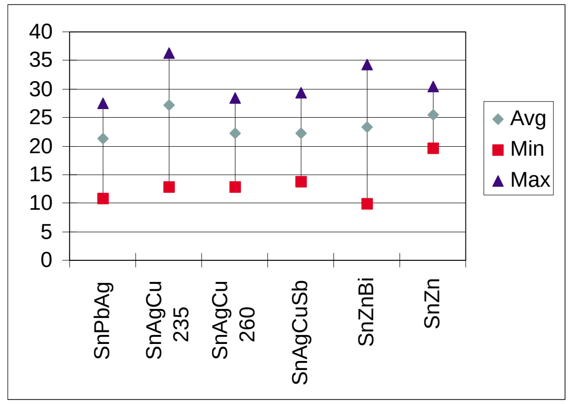

Figure 14. Lead-Pull Results After Temperature Cycling

The temperature cycle excursion was –40°C to 125°C in 10-minute cycles. This was a thermal-shock test, with the boards being moved from a –40°C to 125°C chamber. There was no ramp between the temperature extremes.

Results of lead pull after exposure to temperature cycling again indicate that all lead-free alloy pastes showed a higher average pull force than the Sn/Pb/Ag control paste. The Sn/Ag/Cu alloy reflowed at 235°C gave the highest average lead-pull result. In general, 10% to 30% lower values for lead pull were seen for all solder alloys after temperature cycling.

Pull-strength values for the Sn/Bi paste are not included. This alloy is under further study because results we obtained were anomalous and not well understood.

Cross Sections of Solder Joints

Figures 15 through 21 show visual cross-section results for the lead-free alloys after 1000 temperature cycles of –40°C to 125°C.

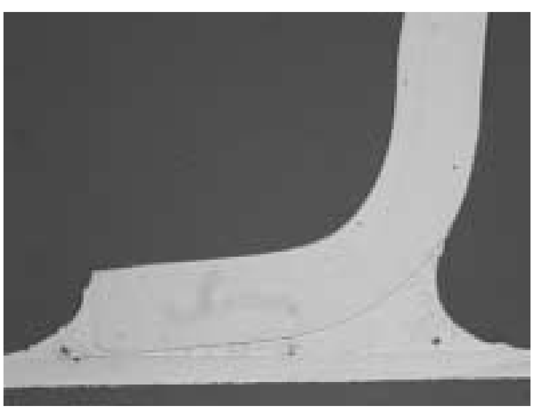

Figure 15. Sn/Pb/Ag Solder, 1000 Temperature Cycles

Figure 16. Sn/Ag/Cu Solder (235°C Peak), 1000 Temperature Cycles

Figure 17. Sn/Ag/Cu Solder (260°C Peak), 1000 Temperature Cycles

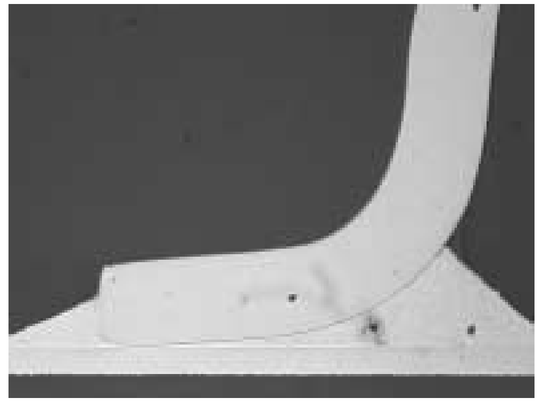

Figure 18. Sn/Bi Solder, 1000 Temperature Cycles

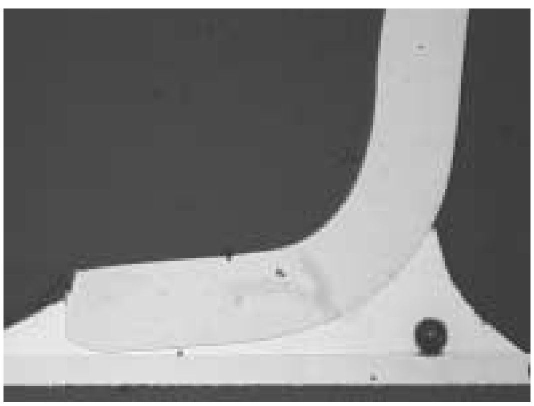

Figure 19. Sn/Ag/Cu/Sb Solder, 1000 Temperature Cycles

Figure 20. Sn/Zn/Bi Solder, 1000 Temperature Cycles

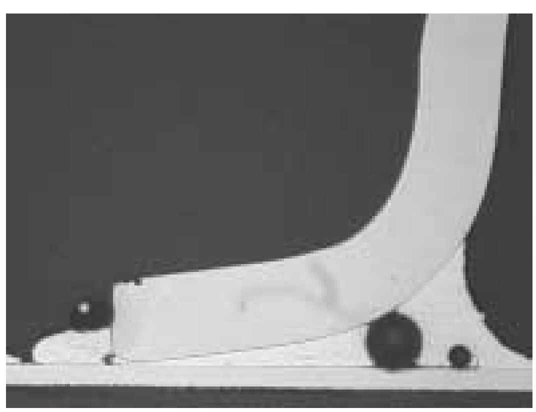

Figure 21. Sn/Zn Solder, 1000 Temperature Cycles

Cross-Section Results

All solders show good wetting (fillet height at least 1X lead thickness) at 0 hour. For this reason, only sections after temperature cycling are shown. Slight voiding was seen on Sn/Ag/Cu solder (0 hr) at 235°C and 260°C. The largest amount of voiding occurred with Sn/Zn/Bi and Sn/Zn solders (Figures 20 and 21). In these cases, the flux chemistry might not have been optimal for the alloy/paste being tested. These two alloys are relatively new solder pastes. Voiding amounts did not correlate with lead-pull strength because all Pb-free solders showed average lead-pull strengths better than Sn/Pb/Ag solder at 0 hour. Additionally, a very slight negative wetting angle was noted at the top of the heel region of the Sn/Zn/Bi alloy sample. These cross sections are the subject of further work. One area for investigation is the solder/lead interface. The paste properties, i.e., solder alloy, particle size and distribution, and flux type, seem to need further development and can influence the performance of the different alloys.

Intermetallic Results on Cross Sections

Cross sections showing intermetallics before and after 1000 temperature cycles are shown in Figures 22 through 35. In all cases, the PWB pad is at the bottom and the Ni/Pd-plated Cu lead is at the top.

As shown previously, the mechanism of soldering to an Ni/Pd-plated Cu lead is the formation of Ni_3Sn_4 intermetallic at the surface. The Pd, present at a very small thickness – 0.075 µm – spalls off the surface as a ternary Pd-Ni-Sn intermetallic and moves into the bulk of the solder.[21,22] This indicates that the Pd does not play a role in intermetallic formation in the bulk solder joint for these Sn-rich systems.

Figures 22 and 23 show the rather coarse grains that develop in the Sn/Pb/Ag system when subjected to thermal cycling. At the top of the section, the Ni plating at ~1 µm and the Ni_3Sn_4 intermetallic at the Ni interface can be seen, and, at the base, the Cu_6Sn_5 intermetallic at the Cu board-pad interface. Figures 24 and 25 show virtually no general grain coarsening, but do show large needle-like structures at widely spaced intervals. Also, there is Ni_3Sn_4 and Cu_6Sn_5 at the interfaces. Figures 26 and 27 show properties similar to those shown in Figures 24 and 25, but with possibly thicker Ni_3Sn_4 and Cu_6Sn_5 intermetallics at the interfaces. Figures 28 and 29 show very thick intermetallic formation at the Ni interface and at the Cu interface. Within the bulk solder, very coarse grains develop with temperature cycling. This may contribute to the anomalous lead-pull data we obtained for the Sn/Bi solder. Identification of the intermetallics present would help explain what was observed. Figures 30 and 31 show results similar to Figures 24 through 27, but with no needle-like structures. For Figures 32 through 35, there appear to be some isolated inclusions that form after temperature cycling. The interfacial intermetallic formations at the Ni and Cu surfaces increase with temperature cycling, which is consistent with results seen in the preceding figures.

Figure 22. Sn/Pb/Ag Solder, 0 Temperature Cycles

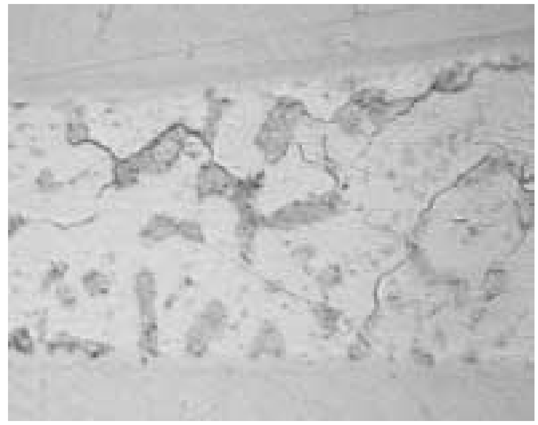

Figure 23. Sn/Pb/Ag Solder, 1000 Temperature Cycles

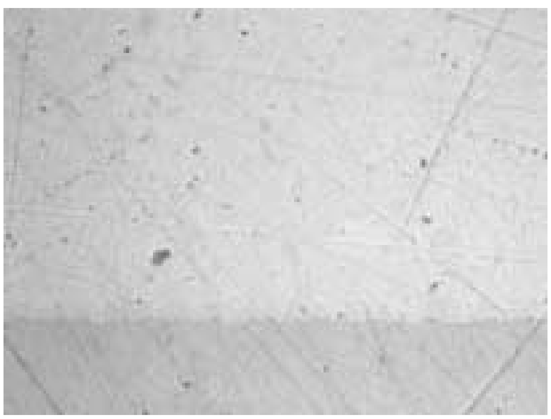

Figure 24. Sn/Ag/Cu Solder (235°C Peak), 0 Temperature Cycles

Figure 25. Sn/Ag/Cu Solder (235°C Peak), 1000 Temperature Cycles

Figure 26. Sn/Ag/Cu Solder (260°C Peak), 0 Temperature Cycles

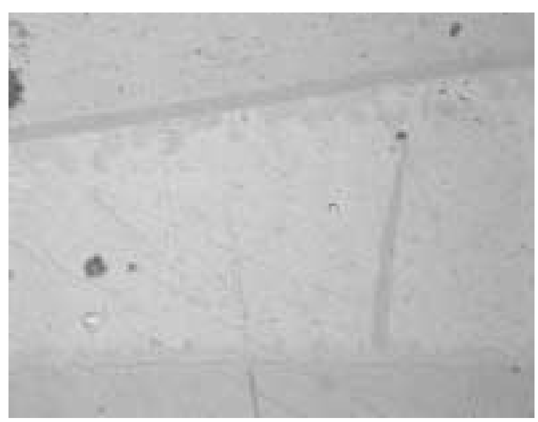

Figure 27. Sn/Ag/Cu Solder (260°C Peak), 1000 Temperature Cycles

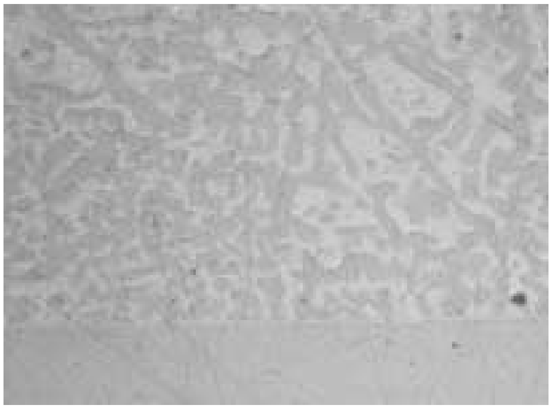

Figure 28. Sn/Bi Solder, 0 Temperature Cycles

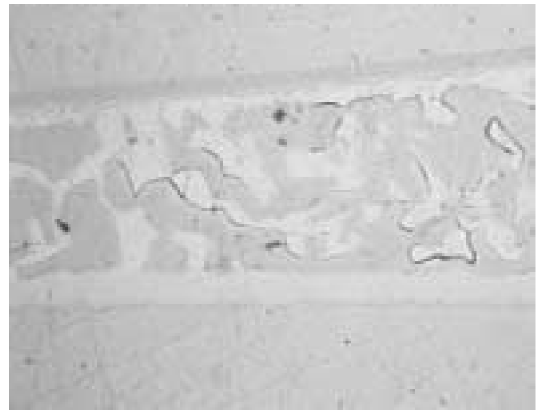

Figure 29. Sn/Bi Solder, 1000 Temperature Cycles

Figure 30. Sn/Ag/Cu/Sb Solder, 0 Temperature Cycles

Figure 31. Sn/Ag/Cu/Sb Solder, 1000 Temperature Cycles

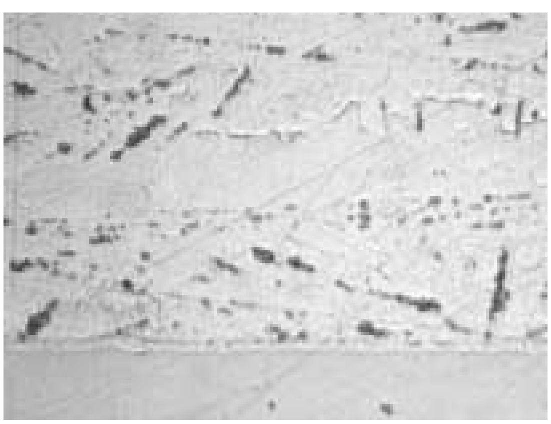

Figure 32. Sn/Zn/Bi Solder, 0 Temperature Cycles

Figure 33. Sn/Zn/Bi Solder, 1000 Temperature Cycles

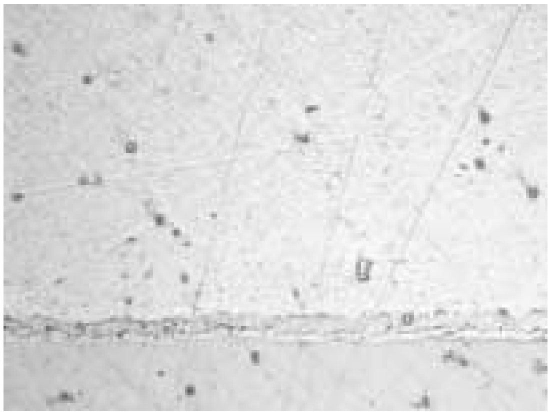

Figure 34. Sn/Zn Solder, 0 Temperature Cycles

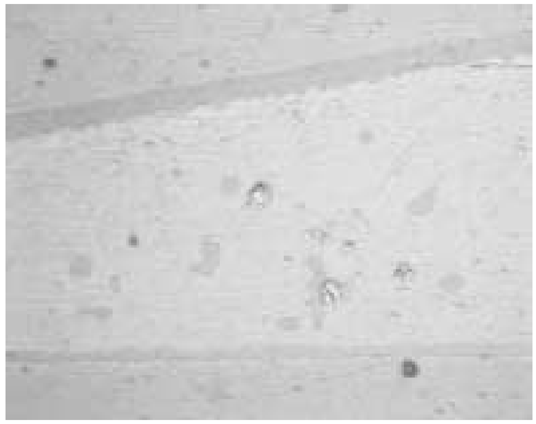

Figure 35. Sn/Zn Solder, 1000 Temperature Cycles

Ni/Pd/Au Finish

As mentioned previously, the Ni/Pd leadframe finish was introduced in 1989. About seven years later, in Japan, an Ni/Pd/Au finish was proposed as an alternative to the original Ni/Pd finish. In previous evaluations, the Ni/Pd/Au finish showed improved performance in wetting-balance tests and equivalent, sometimes better, performance in visual appearance of solder joints when compared to Ni/Pd finishes. With the move toward lead-free processing, renewed interest in the Ni/Pd/Au finish has developed.

In addition to evaluations performed with Ni/Pd-finished components, 14-pin SOIC packages built with Ni/Pd/Au-finished leadframes were evaluated with the Sn/Ag/Cu solder paste. Visual appearance of the Ni/Pd/Au-finished components can be seen in Figure 36 (235°C peak reflow) and Figure 37 (260°C peak reflow). We are continuing evaluation of this lead finish, and expect to publish an application report in the second quarter of 2001.

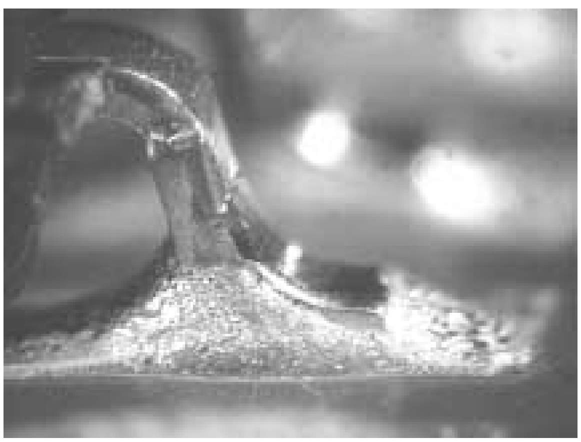

Figure 36. Sn/Ag/Cu Alloy Paste (235°C Peak), Ni/Pd/Au-Finished SOIC Package

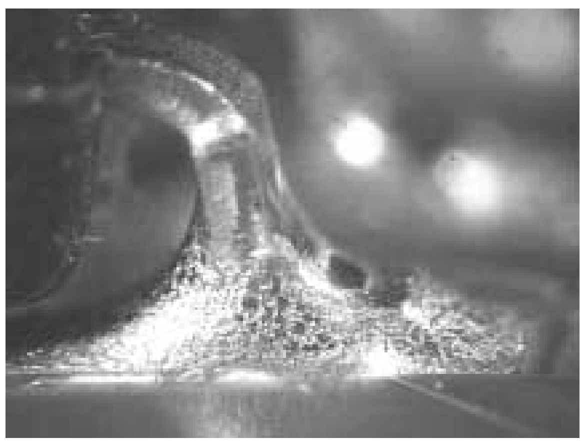

Figure 37. Sn/Ag/Cu Alloy Paste (260°C Peak), Ni/Pd/Au-Finished SOIC Package

Summary of Results

- Visual-appearance and cross-sections show acceptable heel fillets of at least 1X the lead thickness for all solders evaluated. Very slight negative wetting was noted only on the Sn/Zn/Bi sample. Sn/Bi appeared as expected.
- Lead-pull results, before and after temperature cycling, indicate higher average pull force for all lead-free alloys when compared to the Sn/Pb/Ag control. After temperature cycling, the Sn/Ag/Cu alloy, when reflowed at 235°C, gave the highest average lead-pull result. In general, 10% to 30% lower values for lead pull were seen for all solder alloys after temperature cycling. The exception was the Sn/Bi solder, which showed virtually no solder-joint strength (below the detection limit of our equipment).
- Voids in the solder were noted on a few of the Pb-free alloys, with the Sn/Zn/Bi and Sn/Zn alloys showing the greatest voiding. Voids in the solder may indicate that the flux chemistry is not optimum for the alloy/paste or, possibly, that the peak reflow temperature was not optimum. The amount of voiding did not correlate with any effect on lead-pull strength.
- The visual appearance of the intermetallics formed is consistent with that reported by other researchers. The intermetallic formation of Ni_3Sn_4 and Cu_6Sn_5 at the respective Cu and Ni interfaces is expected and fits well with the lead-pull data obtained.
- Visual appearance of the Ni/Pd/Au-finished leads soldered with Sn/Ag/Cu alloy paste show very positive wetting performance.

Acknowledgment

The authors wish to recognize Texas Instruments employees Kay Haulick and Martin Pauli for their board mount, visual documentation, and lead-pull testing.

The authors also wish to recognize the following solder-paste suppliers for their support with materials and technical information:

ALLOY	SUPPLIER
Sn/Pb/Ag	Multicore
Sn/Ag/Cu	Multicore
Sn/Bi	Multicore
Sn/Ag/Cu/Sb (Castin)	AIM
Sn/Zn/Bi	SDK
Sn/Zn	SDK

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