# NEMI LEAD-FREE ASSEMBLY PROJECT: COMPARISON BETWEEN PbSn AND SnAgCu RELIABILITY AND MICROSTRUCTURES

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**ABSTRACT**
The National Electronics Manufacturing Initiative (NEMI) Lead-Free Assembly Project had the following priorities:

- to down-select an alloy from the SnAgCu families to be recommended as the main standard lead-free solder;
- to demonstrate production-ready parts, materials and processes for lead-free soldering printed wiring board (PWB) assemblies, with an eye to total lead elimination by 2004;
- to cooperate with component, board and equipment manufacturers to allow for the smooth transition to components with higher exposure temperature limits of around 260°C; and
- to develop criteria for the industry to evaluate lead-free processes and reliability in order to assist industry with timely implementation of lead-free assemblies.

This article presents qualitative thermal cycling results for all the components and alloy combinations tested and provides a quantitative comparison of the failure data and microstructures for the CSP169 components for NEMI tin-silver-copper alloy, eutectic tin-lead, and a mixed tin-silver-copper paste with Pb-containing surface finish.

## INTRODUCTION

The National Electronics Manufacturing Initiative (NEMI) formed its Lead-Free Task Force in 1999 with the goal of helping the North American electronics industry develop the capability to produce lead-free products. Realizing that choosing a single solder alloy would significantly benefit the microelectronics industry, the Task Force put substantial effort into reviewing the research that had been done with lead-free solders in the U.S., Europe and Japan. In 2000 NEMI announced its recommendations for the "standardized" lead-free solder that would allow the microelectronics industry to implement a replacement sooner, avoid multiple manufacturing processes and enhance basic understanding of the material while assuring its reliability. The NEMI group recommended an alloy of Sn3.9Ag0.6Cu (+/- 0.2) as the best available option for surface mount reflow solder applications. (All compositions are expressed in terms of mass fraction*100.)

Following the selection, the NEMI Task Force began full-scale manufacturing trials and reliability testing. Reliability testing involved defining the reliability test requirements, designing and fabricating the test vehicles, performing a comprehensive matrix of tests, completing failure analyses to determine root cause of failures, performing statistical analyses of the failure data to provide for comparison between lead-free solder joints and those containing lead, documenting results, and developing databases of materials and board properties needed for finite element modeling of the solder joints. Since the dominant failure mechanism expected for the solder joint was thermal fatigue, the reliability plan focused on thermal cycle testing. The thermal cycling behavior of SnPb eutectic, SnAgCu alloy, and SnAgCu with SnPb component surface finishes were compared for a wide range of components and for two thermal cycling conditions. This article presents a comparison of the microstructures and the reliability of the solder joint, for the NEMI tin-silver-copper alloy and eutectic tin-lead

## RELIABILITY TEST PLAN

### Component-paste-board finish combinations

The six component types tested featured lead-free and lead-containing termination finishes/ ball compositions, based on the team's assumption that not all components would be available with lead-free finishes during start-up of a lead-free assembly line. The components used were:

- TSOP: type 1, 48 pin, NiPd and SnPb finishes
- R2512: zero ohm chip resistor, pure Sn and SnPb finishes
- 169 I/O CSP: 0.8mm pitch, SnAgCu and SnPb balls
- 208 I/O CSP: 0.8mm pitch, SnAgCu and SnPb balls
- 256 I/O PBGA: 1.27mm pitch, SnAgCu and SnPb balls

- 256 I/O ceramic BGA (CBGA): 1.27mm pitch, SnAgCu and SnPb balls

The specific lead-free and tin-lead compositions used for termination finishes, balls and solder pastes are shown in Table 1.

Three test cells were used for each component type:

- Tin-lead/tin-lead (Pb-Pb): both the component ball/termination finish and the alloy were tin-lead
- Tin-lead/lead-free (Pb-LF): the component ball/termination finish was tin-lead, the solder alloy was Pb-free (LF)
- Lead-free/lead-free (LF-LF): both the component ball/termination finish and the alloy were lead-free

Two of the components tested by NEMI — the 208CSP and 256PBGA — have also been investigated by lead-free projects conducted by the High Density Packaging User Group (HDPUG) and the National Center For Manufacturing Sciences (NCMS). The ability to correlate NEMI data for a specific component with the data from other groups allowed NEMI to examine the reproducibility of testing .

| Feature | Alloy | Notes |
|---|---|---|
| Lead-free balls | Sn4Ag0.5Cu | |
| Tin-lead balls | Sn37Pb | |
| TSOP & R2512 finish | Sn10Pb | |
| Solder pastes | Sn37Pb | Current standard solder |
| | Sn3.9Ag0.7Cu | NEMI-recommended alloy |
| | Sn3.0Ag0.5Cu | Alloy recommended by JEITA (Japan Electronics Information Technology Industries Assn.) |
| Board finish | immersion silver | Several of the boards used with TSOP and R2512 components had a nickel-gold finish |

**Table 1. Tin-Lead and Lead-Free Compositions Used**

**Test vehicles**

Six different boards, one for each component type, were used. The boards for the area array packages had four components per board. These boards were eight-layer, 0.062-inch FR-4 with a glass transition temperature ($T_g$) of approximately 170°C. The TSOP and R2512 boards had 16 components per board and were four-layer, 0.062-inch standard FR-4s. The circuitry in the six board types allowed each component to be monitored (one loop) during ATC testing. The boards had either connector fingers or terminals for hard wiring, depending on the fixturing at the different test facilities.

**Pre-test/post-assembly information**

Prior to assembly, the area array packages were analyzed by c-mode scanning acoustic microscopy (C-SAM) to establish a baseline. After assembly, these packages were again examined by C-SAM to document the effects of assembly on package integrity, and to provide reference points for use in post-ATC failure analysis. The assemblies were also characterized using x-ray and AOI . At least one component per cell and component type was cross-sectioned. These solder joint sections were used for analysis of the solder joint failures, intermetallic growth, and joint geometry.

**Thermal cycling**

Accelerated thermal cycle testing was performed at six Task Group members' facilities. The boards were tested under one of two temperature conditions:

- -40°C (+0°C,-5°C) to 125°C (+5°C,-0°C), with 5 minute minimum dwell at the temperature extremes
- 0°C (+0°C,-5°C) to 100°C (+5°C,-0°C), with 5 minute minimum dwell at the temperature extremes

These conditions were taken from JEDEC JESD22-A104B (July 2000), "Temperature Cycling". The NEMI team added requirements for tighter tolerances at the dwell temperatures in both duration time and temperature range. ATC profiles, which demonstrated the capability to meet the conditions and tolerances, were provided by each test facility.

Failure criteria were defined according to IPC-SM-785 ("Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachments").

## ANALYSIS OF FAILURE DATA

**Post-cycling failure analysis**

After ATC, both failed and surviving parts were characterized using several types of analyses:

- Visual inspection (10-30x)
- C-SAM analysis
- Layout dye staining / dye penetrant analysis
- Cross sectioning to identify failure modes, voiding, joint height
- SEM analysis of intermetallics
- Compositional gradient mapping of the solder joint

The relative ATC performance of all of the cells is shown in Table 2. As consistent with previous comparisons of other Pb-free with Sn-Pb eutectic [1-3], the NEMI results show that the relative performance of LF-LF, LF-Pb, and Pb-Pb solder combinations changes with component type and thermal cycling conditions. Using 95% confidence bounds, the characteristic life for a cell was compared to that of the tin-lead/tin-lead benchmark to determine equivalent (0), superior (+), or inferior (-) performance. As the table indicates, the lead-free/lead-free cells performed as well as, or better than, the tin-lead/tin-lead benchmark.

Weibull analyses of the 169CSP failure data are shown in Figure 1 (0°C to 100°C) and Figure 2 (-40°C to 125°C).

Using the values for the characteristic life (eta) for 0°C to 100°C (Figure 1), the performance of the LF-LF cell is statistically better than the performances of the other two cells. For thermal cycling from -40°C to 125°C, both the LF-LF and Pb-LF cells performed statistically better than the benchmark Pb-Pb cell. These results align with those from other studies that show equivalent to superior performance of lead-free systems as compared to the tin-lead benchmark.

Typical micrographs are shown in Figure 3. For all three material combinations and all component types and in both ATC conditions, there were no pronounced differences in joint geometry. The thermal cycling caused microstructural changes, with coarsening occurring in the solder joint and failure always occurring first in the solder on the component side. The failure mechanism in the LF-LF cell appears to be the same as that in the Pb-Pb and Pb-LF cells – bulk solder fatigue. This is an important result in that failure models based on tin-lead systems can be extended to new lead-free alloy systems, as long as critical material properties and new constitutive equations are available.

**Three-point bend testing**

ATC testing probes fatigue failures. Three-point bend testing was performed on 256PBGA and 208CSP components to simulate the damage that occurs from out of plane deformation during drop, test or assembly. All failures occurred between the board and the bonding pad on the board, for both the 256PBGA and 208CSP assemblies. No differences were observed between the various test cells, demonstrating that the lead-free systems provide equivalent performance when compared to the benchmark tin-lead/tin-lead system.

**Electrochemical migration testing**

Solder pastes were assessed for electrochemical migration resistance using IPC-TM-650 Method 2.6.14.1, 65°C/85%RH/10V, 500h. The test pattern used was IPC B25A, Pattern D (0.0125" lines/spaces). All samples, both lead-free and tin-lead, passed indicating that there are no electrochemical migration issues inherent in the SnAgCu alloy when evaluated using the IPC test method described above.

| Component (imAg board finish unless indicated) | -40°C to 125°C | | | 0°C to 100°C | | |
|---|---|---|---|---|---|---|
| | Pb | Mixed | LF | Pb | mixed | LF |
| 48 TSOP | 0 | - | 0 | | | |
| 48 TSOP, NiAu boards | 0 | + | + | | | |
| R2512 resistor | 0 | 0 | 0 | | | |
| R2512, NiAu boards | 0 | | | | | |
| 169CSP | 0 | + | + | 0 | 0 | + |
| 208CSP | 0 | 0 | + | 0 | + | + |
| 208CSP, JEITA alloy | | | 0 | | | |
| 256PBGA | 0 | 0 | 0 | 0 | 0 | 0 |
| 256CBGA | | | | 0 | - | + |

**Table 2. Relative ATC Performance**

**CONCLUSIONS**

ATC testing (-40°C to + 125°C and 0°C to 100°C) shows that solder joints formed from combinations using lead-free balls, component finish and paste alloy performed equivalent to or better than the tin-lead/tin-lead benchmark. Results are not as clear with tin-lead/lead-free combinations, where most performed equivalent to the tin-lead/tin-lead benchmark, with two combinations performing worse than the benchmark, and one combination performing better.

Three-point bend testing showed no differences between the different combinations across both component sets evaluated.

No electrochemical migration issues were seen with the NEMI-recommended SnAgCu alloy when evaluated per IPC-TM-650 Method 2.6.14.1.

All of the results obtained to date demonstrate that the solder joint reliability of lead-free solder joints is equivalent to, or superior to that of the benchmark tin-lead systems. From the NEMI testing and analysis, the reliability of Sn-3.9Ag-0.6Cu solder joints should be acceptable and allow for the successful manufacture and use of lead-free products.

Much work must still be done with process optimization (*e.g.* flux formulations and reflow conditions). Higher reflow temperatures require new component materials to overcome increased moisture sensitivity with some component families, and may require redesign of some components that currently will not function as designed if exposed to the higher temperatures. This project described in this paper examined surface mount assembly only. A follow-on NEMI project — Advanced Lead-Free Hybrid Assembly and Rework Development — is underway to examine similar temperature issues during wave soldering and rework. Other important R&D areas include environmental impact of the new alloys, suitability/upgrading of manufacturing equipment, compatibility with test fixtures, and workmanship standards. Individual companies must still qualify the new technologies to their own standards and requirements.

**NEMI Reliability Team Participants**

Contributing significantly to the work of the Reliability Team: Jay Bartelo (IBM), Rick Charbonneau (StorageTek), Richard Coyle (Lucent), Mike DiPietro (IEEC), Ken Fallon (Kodak), Charlie Fieselman (Solectron), David Godlewski (NEMI), Frank Grano (Sanmina-SCI), Angela Grusd (Agilent), Brian Hunter (StorageTek), Keith Johnson (Kodak), Kevin Knadle (IBM), Thomas Koschmieder (Motorola), John Manock (Lucent), Jack McCullen (Intel), Rich Parker (Delphi Delco), Swami Prasad (ChipPac),

Marianne Romansky (Celestica), Leonard Smith (NIST), Terri Womack (Sanmina-SCI), and Adam Zbrzezny (Celestica).

## References


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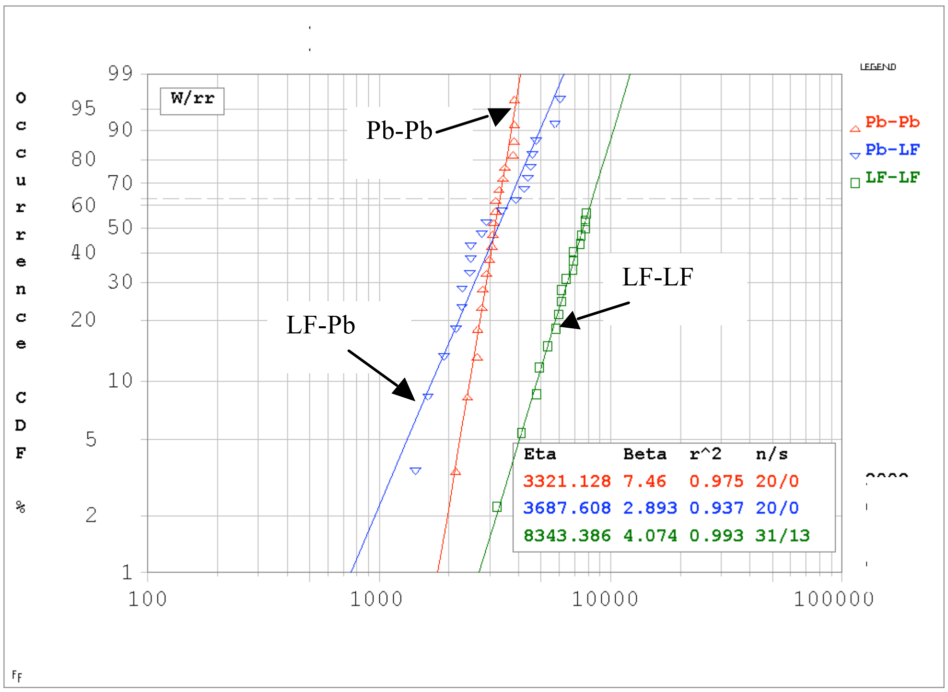


**Figure 1** 169CSP, 0°C to 100°C Cycling

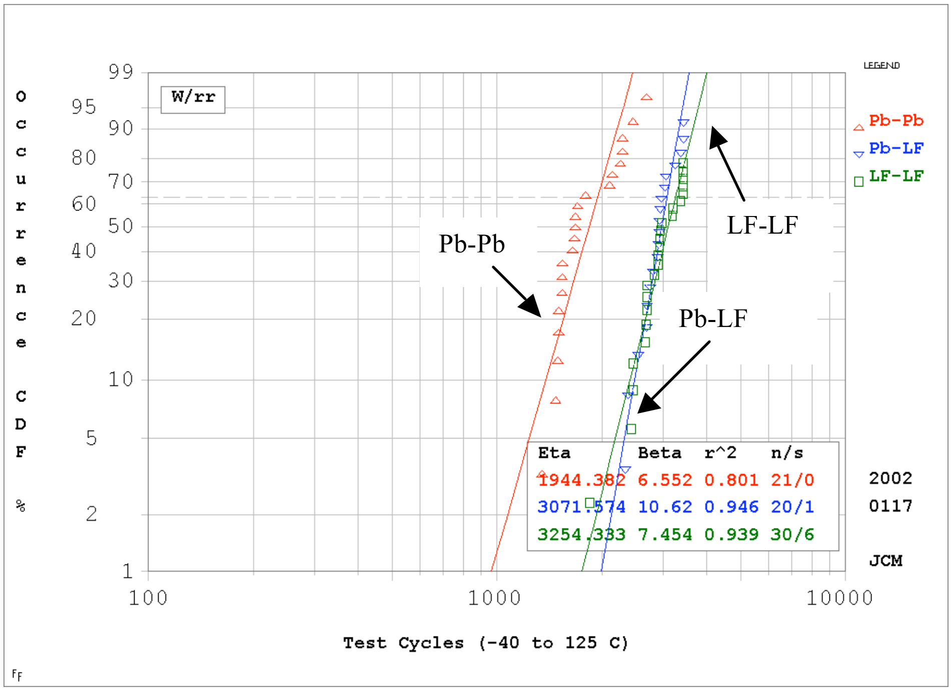


**Figure 2.** 169CSP, -40°C to 125°C Cycling

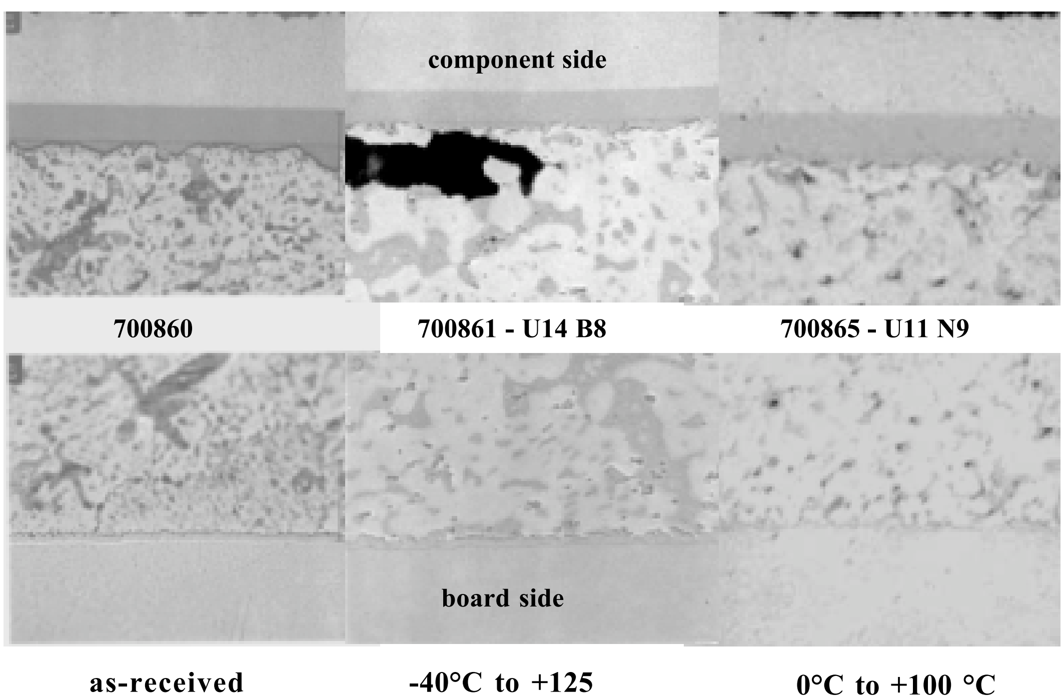


**Figure 3a.** 169CSP, Typical microstructures of the interface between the Pb-Pb solder and the connections on the component side (top) and board side (bottom) before and after thermal cycling at the conditions listed.

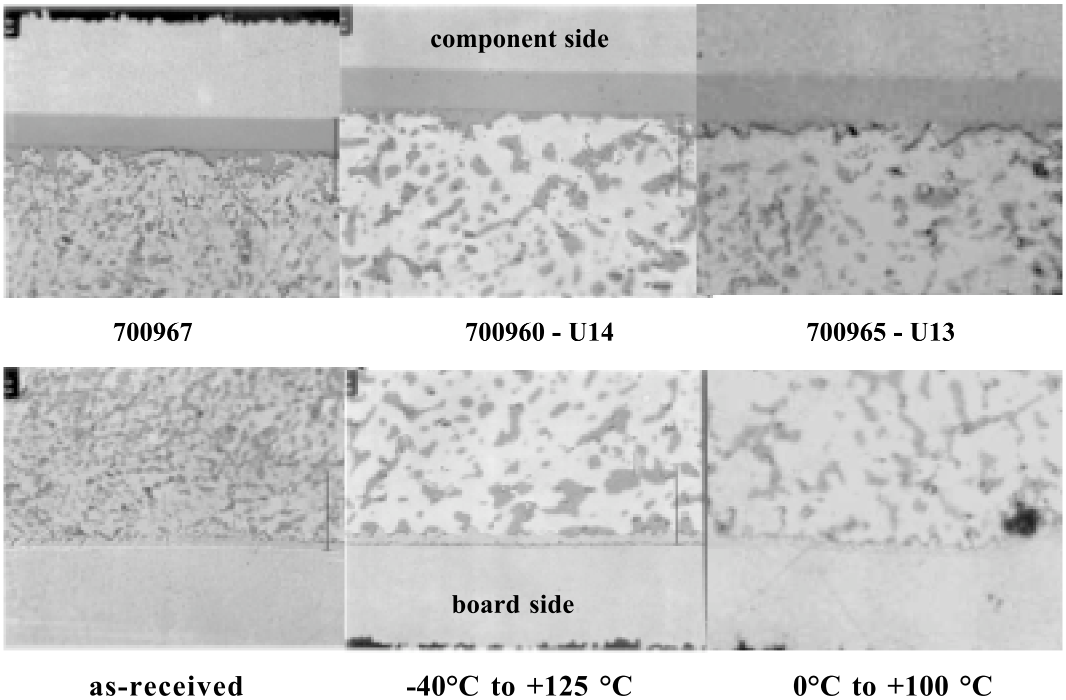


**Figure 3b.** 169CSP, Typical microstructures of the interface between the LF-Pb solder and the connections on the component side (top) and board side (bottom) before and after thermal cycling at the conditions listed.

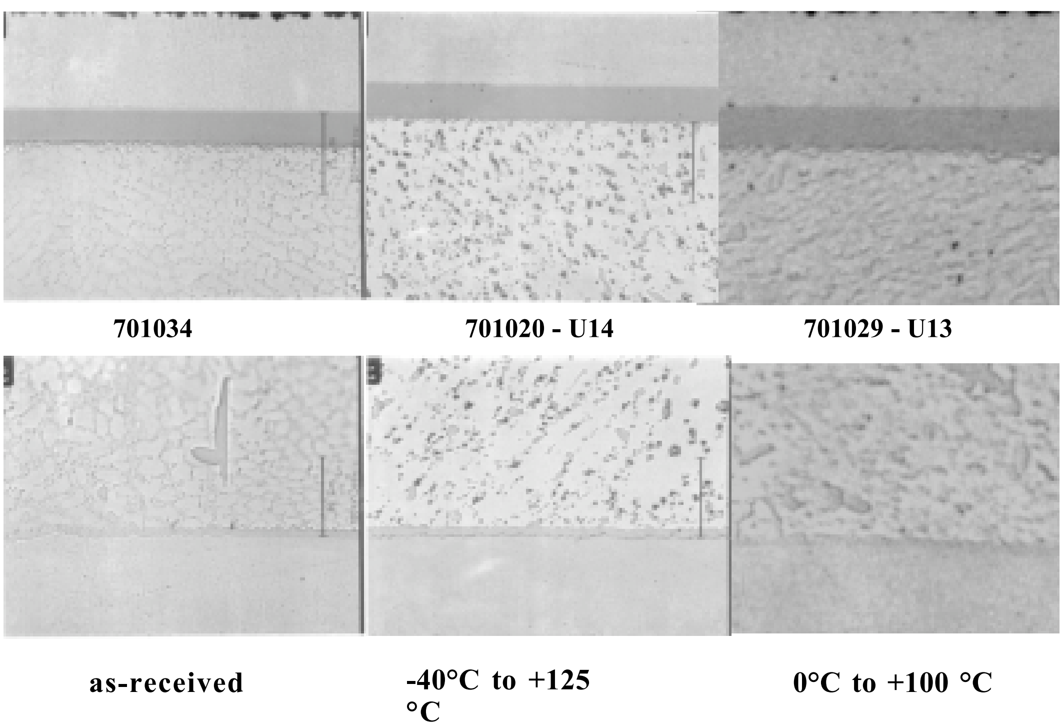


**Figure 3c.** 169CSP, Typical microstructures of the interface between the LF-LF solder and the connections on the component side (top) and board side (bottom) before and after thermal cycling at the conditions listed.