Are Lead-Free Solder Joints Reliable?

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Judge for Yourself. A NEMI team found that lead-free manufacturing can be implemented without degrading solder joint reliability.

The National Electronic Manufacturing Initiative (NEMI, Herndon, VA) formed a project in 1999 to help North American electronics manufacturers develop the capability to produce lead-free printed circuit board assemblies (PCBAs). Realizing that choosing a single solder alloy would significantly benefit the industry, effort was put into reviewing the research that had been done with lead-free solders in the United States, Europe and Japan. Finding no drop-in replacement for tin-lead (SnPb) solder, the NEMI group recommended a tin-silver-copper alloy of Sn3.9Ag0.6Cu±0.2 percent as the best available option for surface-mount reflow solder applications.

Once this single replacement alloy was identified, several NEMI project teams then focused on activities that would enable timely implementation of lead-free PCBAs, including enhancing basic understanding of the material and assuring its reliability. As part of this effort, the NEMI Reliability Team tested selected solders, components and board finishes using a series of test vehicles to compare the reliability of lead-free PCBAs with standard tin-lead PCBAs.

The Test Plan

The team's focus was on the solder joint, comparing the tin-silver-copper alloy to eutectic tin-lead. This process involved defining the reliability test requirements, designing and fabricating the test vehicles, performing a 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, and documenting results. The reliability plan was developed in fall 1999, based on published information available at that time and on the anticipated availability of resources (components, boards and testing facilities). Because the predominant failure mechanism expected for the solder joint was thermal fatigue, the reliability plan was centered around thermal cycle testing. The activities included:

- Design and procure test boards.
- Identify and procure components.
- Conduct pre-assembly acoustical scanning of components.
- Assemble the test vehicles (partnering with the NEMI Assembly Process Team).
- Collect post-assembly/pre-test information.
- Perform accelerated thermal cycling (ATC).
- Analyze failures, determine root causes and characterize solder joints.
- Analyze failure data.
- Perform bend testing on assemblies (no ATC).
- Partner with solder paste suppliers to assess electrochemical migration resistance of the SnAgCu alloy.

The team also focused on modeling for reliability. Test results are intended to provide a complete set of critical information needed for modeling.

Component/paste/board finish combinations

Six component types were selected for testing. These components featured lead-free and lead-containing termination finishes and 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 and the companies that provided them were:

- TSOP: thin small-outline package, type 1, 48 pin, nickel-palladium (NiPd) and SnPb finishes, provided by AMD
- R2512: zero ohm chip resistor, pure Sn and SnPb finishes, obtained from KOA Speer Electronics
- 169 I/O CSP: chip-scale package, 0.8-mm pitch, SnAgCu and SnPb balls, provided by Lucent Technologies
- 208 I/O CSP: 0.8-mm pitch, SnAgCu and SnPb balls, provided by ChipPAC

Feature	Composition	Notes
Lead-free balls	Sn4.0Ag0.5Cu	Provided by Heraeus
Tin-lead balls	Sn37Pb	
TSOP finish	Sn10Pb	
R2512 finish	Sn10Pb	
Solder pastes	Sn37Pb	
	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.

- 256 I/O PBGA: plastic ball grid array, 1.27-mm pitch, SnAgCu and SnPb balls, provided by Amkor
- 256 I/O CBGA: ceramic BGA, 1.27-mm pitch, SnAgCu and SnPb balls, vendor part, ball attach by IBM.

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 and the solder alloy was lead-free
- 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 extrapolate results from other components, in effect increasing the total number of components evaluated.

Test vehicles

Six different boards, one for each component type, were used. The boards for the area array packages, designed by StorageTek, had four components per board. These boards were eight-layer, 0.062-in. FR-4 with a glass transition temperature (T_g) of approximately 170°C. The TSOP and R2512 boards, provided by Motorola, had 16 components per board and were four-layer, 0.062-in. 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) performed by Sonoscan, to establish a baseline. After assembly, these packages were again analyzed 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 equipment from Agilent and automatic optical inspection equipment from Orbotech. Cross sections of one component per component type were made by the National Institute of Standards and Technology (NIST), characterizing intermetallics and determining standoff heights.

CTE determination – components and boards

Moiré interferometry, performed by StorageTek, was used to determine the coefficient of thermal expansion (CTE) of each area array package. Perkin-Elmer and Lucent Technologies are currently determining the CTEs of the test boards using thermomechanical analysis (TMA). CTE values are needed for modeling purposes.

Thermal cycling

Accelerated thermal cycle (ATC) testing was performed at six facilities: Celestica, Kodak, Lucent, Motorola, Sanmina-SCI and Solectron. The boards were tested under one of two temperature conditions:

- -40°C (+0,-5) to 125°C (+5,-0)
- 0°C (+0,-5) to 100°C (+5,-0).

These conditions were taken from JEDEC Standard *JESD22-A104B, Temperature Cycling* (July 2000). 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 Standard *IPC-SM-785, Guidelines for Accelerated Reliability Testing of Surface Mount Solder Attachments*.

Post-cycling failure analysis

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

- visual inspection (10× to 30×)
- C-SAM analysis (Sonoscan)
- layout dye staining/dye penetrant analysis (Compaq, IBM and Motorola)
- cross-sectioning to identify failure modes, voiding, joint height (NIST, Celestica and IBM)
- scanning electron microscopy (SEM) analysis of intermetallics (Celestica and NIST)
- compositional gradient mapping of the solder joints (Motorola and NIST).

Initial findings from the 169CSP test vehicles, for all three material combinations in both ATC conditions, indicated that no pronounced differences in joint geometry occurred. The thermal cycling caused microstructural changes, and failure always occurred first in the solder on the component side. The failure mechanism in the lead-free/lead-free cell is the same as that in the tin-lead/tin-lead cell: bulk solder fatigue. This result is important in that failure models based on tin-lead systems can be extended to new lead-free alloys, as long as critical material properties and new constitutive equations are available.

Analysis of failure data

The failure data were analyzed at four facilities, using different analysis packages. Solectron used JMP Discovery statistical software package (Version 4.0.5) by SAS Institute. Intel used MINITAB Release 13.1 (Intel version). At Lucent, WinSmith Weibull 1.0F by Fulton Findings was used, and Agilent ran ReliaSoft Weibull++ 5.0. In all cases, no significant differences existed between the analysis packages. Results from the Weibull analyses of the 169CSP failure data are shown in Table 2.

Comparing the values for the characteristic life (η), performance of the lead-free/lead-free cell, when cycled 0 to 100°C, is statistically better than the performances of the other two cells. When cycled -40°C to 125°C, both the lead-free/lead-free and tin-lead/lead-free cells performed statistically better than the benchmark tin-lead/tin-lead 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.

ATC Relative Performance

The relative ATC performance of all cells completed to date is shown in Table 3. Using 95 percent 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.

Three-point bend testing

ATC testing probes fatigue failures. Three-point bend testing was performed by Compaq on 256PBGA and 208CSP components to simulate the damage that occurs from out-of-plane deformation during drop, test or assembly. A schematic of the test configuration is shown in Figure 1.

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.

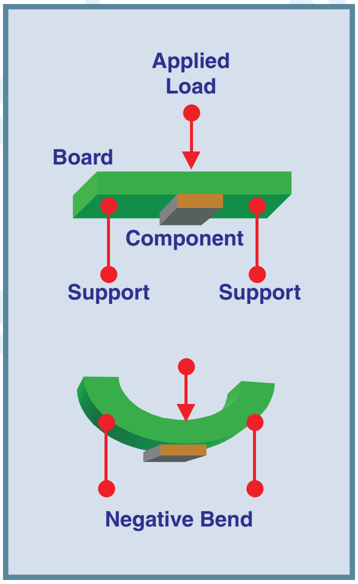

FIGURE 1: Three-point bend test configuration.

Electrochemical migration testing

Solder pastes were assessed for electrochemical migration resistance using *IPC-TM-650 Method 2.6.14.1*, 65°C/85 percent RH/10V, 500h. The test pattern used was IPC B25A, Pattern D (0.0125-in. lines/spaces). Four paste suppliers (Alpha, Heraeus, Indium and Kester) performed the testing, using the NEMI-recommended Sn3.9Ag0.6Cu alloy, with Sn37Pb as the benchmark. All lead-free and tin-lead samples passed, indicating that no electrochemical migration issues are inherent in the SnAgCu alloy when evaluated using the IPC test method described above.

	-40°C to 125°C			0°C to 100°C		
Weibull Parameter	**Pb-Pb**	**Pb-LF**	**LF-LF**	**Pb-Pb**	**Pb-LF**	**LF-LF**
η (N63)	1944	3071	3254	3321	3688	8343
β	6.6	10.6	7.5	7.5	2.9	4.1

TABLE 2: 169CSP Weibull analysis results.

	-40°C to 125°C			0°C to 100°C		
Component	**Pb-Pb**	**Pb-LF**	**LF-LF**	**Pb-Pb**	**Pb-LF**	**LF-LF**
TSOP	0	-	0	----------Not tested---------		
R2512	0	0	0	----------Not tested---------		
169CSP	0	+	+	0	0	+
208CSP	0	0	+	----------Under test---------		
208CSP (JEITA)	------Not tested------		0	----------Not tested---------		
256PBGA	0	0	0	----------Under test---------		
256CBGA	-------------Not tested------------			0	-	+

TABLE 3: Relative ATC performance.

Conclusion

Results from ATC testing using both temperature conditions showed 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. The results are not as clear with tin-lead/lead-free combinations; most performed equivalent to the tin-lead/tin-lead benchmark, two combinations performed worse than the benchmark, and one combination performed 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* (Figure 1).

All results obtained to date demonstrate that the solder joint reliability of lead-free solder joints is equivalent or superior to that of the benchmark tin-lead systems. Although the reliability analysis has not been completed as of this writing, we have not found any unexpected impediments that will prevent the successful manufacture of lead-free products.

Much work still remains to be done with process optimization, such as flux formulations and reflow conditions. Also, higher reflow temperatures require new 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. Other important areas under research and development 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.

The NEMI Reliability Team found that lead-free manufacturing can be implemented without degrading solder joint reliability. This important conclusion has led to a follow-on NEMI project, Advanced Lead-Free Hybrid Assembly and Rework Development, which began in May 2002. ■

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INDUSTRY TERMS IN THIS ISSUE

ATC	Accelerated thermal cycling
Btu	British thermal unit
CBGA	Ceramic ball grid array
C-SAM	C-mode scanning acoustic microscopy
CSP	Chip-scale package
CTE	Coefficient of thermal expansion
dB	Decibel
G	Giga (10^9)
GSM	Global system for mobile
k	Kilo (10^3)
M	Mega (10^6)
m	Milli (10^{-3})
μ	Micro (10^{-6})
n	Nano (10^{-9})
OSP	Organic solderability preservative
p	Pico (10^{-12})
PBGA	Plastic ball grid array
RF	Radio frequency
RMS	Root mean square
SEM	Scanning electron microscopy
ΔT	Temperature differential
Tg	Glass transition temperature
TSOP	Thin small-outline package
TMA	Thermomechanical analysis
UV	Ultraviolet
VHF	Very high frequency
WCDMA	Wideband code division multiple access
WLAN	Wireless local area network

NOTE: Some of these industry terms are from the 2000 *NEMI Technology Roadmap*. For further information, contact the National Electronics Manufacturing Initiative at www.nemi.org.