

A Manufacturable Lead-Free Surface-Mount Process?

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NEMI demonstrates that lead-free manufacturing may be possible using existing production tools and equipment.

Printed wiring boards (PWBs) assembled with lead-free solders require higher processing temperatures than boards manufactured with standard tin/lead solders. This fact has been a major source of concern for the electronics industry as the transition to lead-free assemblies occurs. Component, board and equipment manufacturers are all potentially impacted by manufacturing processes that require reflow temperatures 30 to 40°C higher than the temperatures used currently.

Can existing manufacturing facilities be used, or will new equipment and tools be needed? Will lead-free solder joints be reliable? Can tin/lead components be mixed on boards with lead-free components? How will these tin/lead components work with lead-free solders? These questions, and more, were facing the industry more than three years ago when the National Electronics Manufacturing Initiative (NEMI, Herndon, VA) launched the Lead-Free Assembly Project.

Among the project's stated goals were the demonstration of materials and manufacturing processes for lead-free PWB assemblies and the comparison of lead-free and conventional solder

joints. Through the cooperation of component, board and equipment manufacturers—along with key original equipment manufacturers (OEMs) and electronics manufacturing services (EMS) providers—the NEMI group was able to demonstrate manufacturing processes for lead-free solders using existing tooling.

Reliability Test Board Build

The project recommended a single lead-free solder formulation for industry use—Sn3.9Ag0.6Cu. This tin/silver/copper alloy has a melting point roughly 35°C higher than eutectic tin/lead solder. The project's process group was charged with developing a new reflow process, identifying any new tools needed and transferring the process to a manufacturing location for building reliability test hardware. The group determined a new profile and found that, in most cases, existing manufacturing tools were adequate for handling the higher temperature solder. At that time (early 2000), existing lead-free pastes were produced only in laboratory testing quantities, and fluxes had not been optimized.

The team evaluated five tin/lead (Sn37Pb) and five lead-free, no-clean, Type 3 solder pastes. One tin/lead and one lead-free paste were used in the test vehicles (TVs) based on printability, visual solderability and x-ray defect inspection. All test boards were built at a single site, using standard manufacturing equipment. A total of 253 boards were built (Figure 1) using six TV designs: CSP169; CSP208; TSOP48; 2512 chip resistor; PBGA256; and CBGA256. Each board featured three distinct test cells: 1) tin-lead solder paste with tin-lead components; 2) lead-free Sn3.9Ag0.6Cu paste with tin-lead components; and 3) lead-free Sn3.9Ag0.6Cu paste boards with lead-free components.

Immersion silver was used as the board surface finish on all TVs with extra thin small-outline package (TSOP) and 2512 resistor boards built with a nickel/gold finish. All boards were

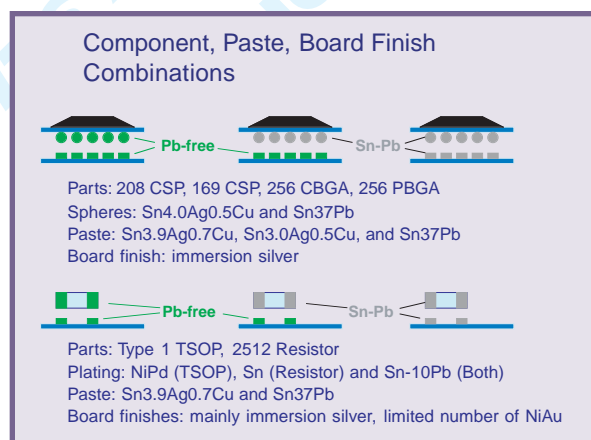


FIGURE 1: The test vehicle combinations built by NEMI's Lead-Free Assembly Project.

made from epoxy FR-4 material with a glass transition temperature (T_g) of 170°C, except TSOP and 2512 resistor boards, which had a T_g of 130°C.

Solder paste volumes were measured during the test board builds for all boards, and representative findings for paste volumes are listed in Table 1. Paste volumes for both the tin/lead and lead-free pastes were found to be acceptable, with lead-free paste having higher volumes using the same printer settings. This difference is due to the good printing characteristics of the selected lead-free paste and the relatively coarse pitch of the components being assembled.

The pick-and-place machine placement images were similar for the tin/lead and lead-free components.

A 10-zone convection oven, with a nitrogen atmosphere of less than 30 ppm O_2 , was used for all builds. Temperatures for the lead-free boards ranged from a high of 247°C on the 2,512 resistor board to a low of 239°C on the plastic ball grid array (PBGA) boards. Table 2 shows examples of the reflow profiles used in building the reliability test hardware.

The major difference between boards assembled with tin/lead and lead-free paste was the visual solder joint appearance. Visual images of the tin/lead- and lead-free-soldered ceramic ball grid array (CBGA) components are shown in Figure 2.

After the builds, the reliability test boards were subjected to electrical test, x-ray inspection, acoustical imaging and automatic optical inspection (AOI).

X-ray Inspection

X-ray inspection looked for process and solder-related defects. In addition to providing feedback about the TV assemblies, the task allowed the assessment of the suitability of x-ray equipment for inspection of lead-free assemblies.

X-ray images for lead-free- and tin/lead-soldered joints were found to be similar in appearance. The equipment required only slight adjustments for measuring solder joint thickness and diameter on lead-free assembled boards.

Overall, more defects were observed with the lead-free paste than with the tin/lead paste. Increased voiding for lead-free paste with tin/lead or lead-free ball grid array (BGA)/chip-scale pack-

Package	Paste	Avg. Paste Vol. (Cu. mils)	Paste Transfer Rate(%)	Avg. Paste Ht. (mils)
256PBGA	SnPb	2410	86%	6.7
	SnAgCu	2677	96%	6.5
169CSP	SnPb	552	56%	4.4
	SnAgCu	681	69%	5.5
208CSP	SnPb	522	53%	5.4
	SnAgCu	535	54%	5.1
256CBGA	SnPb	3836	95%	7.0
	SnAgCu	4037	100%	6.9
R2512	SnPb	30908	100%	7.2
	SnAgCu	32894	100%	7.9
TSOP48	SnPb	2312	79%	5.4
	SnAgCu	2373	81%	5.6

TABLE 1: Solder paste volumes and transfer rates for all board builds for the project.

Paste/Component Type	Specifications	Lead-Free Paste/Lead-Free Component	Lead-Free Paste/Tin-Lead Component	Tin-Lead Paste/Tin-Lead Component
256CBGA	TAL/Reflow Time	64 – 66 sec.		84 – 86 sec.
	Peak Temp.	240 - 241°C		209 - 210°C
256PBGA	TAL	61 – 69 sec.		84 – 88 sec.
	Peak Temp.	239 - 243°C		209 - 214°C
208 CSP	TAL	78 – 81 sec.		83 sec.
	Peak Temp.	244 - 246°C		217°C
169 CSP	TAL	80 sec.		88 sec.
	Peak Temp.	244°C		215°C
48TSOP	TAL	87 sec.		85 – 86 sec.
	Peak Temp.	247°C		217 - 218°C
2512 resistor	TAL	90 sec.		87 – 88 sec.
	Peak Temp.	247-248°C		217 - 220°C

Lead-free paste = Sn3.9Ag0.6Cu (mp. 217°C)
Tin-lead paste = Sn37Pb (mp. 183°C)
TAL= time above liquidus

TABLE 2: Reflow profiles used in building the reliability test hardware.

age (CSP) components was noted. Reduced wetting with lead-free SnAgCu paste and lead-free TSOP components was also indicated, as shown in Table 3.

Voiding was attributed to the use of the specific flux in the lead-free solder paste and the reduced solderability of the lead-free SnAgCu alloy (compared with tin-lead and the elevated temperatures used during lead-free solder paste processing). Accelerated thermal cycle (ATC) testing found no reliability problems with the voiding on boards that combined lead-free solder with lead-free components. More development work will

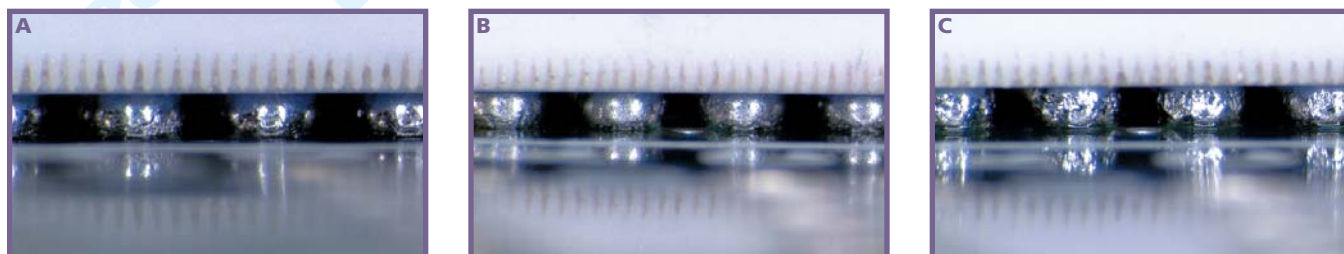


FIGURE 2: The solder joint made with tin/lead paste on a tin/lead/silver CBGA component (A) appears shiny; the lead-free paste used on the same component (B) appears dull; and the lead-free paste with a lead-free CBGA (C) has a cratered appearance. Despite differences in appearance, testing revealed no differences in reliability of the lead-free paste/component joints compared with tin/lead-tin/lead combinations.

Component Type	Test Cell		
	SnPb/SnPb	SnAgCu/SnPb	SnAgCu/SnAgCu
256CerBGA	No defects	22% V	3% V
256CBGA	0.1% In	4% V	3% V
208 CSP	0.2% In	0.5% In, 0.8% V	5% V , 0.2% In
169 CSP	5% V	18% V	8% V , 1% In
48TSOP	No defects	0.5% In	3% In, 0.3% Ex
2512 chip	No defects	No defects	No defects

In = insufficient solder
Ex = excess solder (bridging)
V = voids evident > 20% of the area of the solder joint and minimum void diameter of 10 mil at board-level solder joint slice or center of ball
V = voids with minimum diameter of 10 mil at board-level solder joint slice or center of ball

TABLE 3: X-ray defect summary (percent of total solder joints with a specific defect).

optimize the fluxes in the lead-free solder paste at higher reflow temperatures.

X-ray inspection found no difference in solder ball diameters and joint thickness for the various component types across the different tin/lead, lead-free test cells assembled.

AOI Inspection

The leadframe and chip components were evaluated using AOI inspection to determine the potential differences in visual solder joint appearance and shape of lead-free vs. tin-lead soldered joints.

Lead-free paste with the tin/lead 2512 resistor components were similar in appearance to the solder joints formed by the tin/lead paste with tin/lead resistors. When lead-free paste was used with pure tin resistors, a reduction in wetting on the board pad side and some surface cracking at the solder joint occurred—possibly due to the way the solder joint cooled. Nonetheless, ATC reliability testing found no mechanical integrity issues.

Acoustic Microscopy Inspection

The TSOP48, CSP169, CSP208, PBGA256 and CBGA 256 components were evaluated before and after reflow using acoustic microscopy to determine and compare any internal component damage. The 2037 components were evaluated with acoustical imaging prior to board assembly (Phase 1).

Component analysis was performed to the guidelines stipulated in IPC/JEDEC J-STD-020 Revision B. Prior to assembly, the components were baked at 125°C for 12 hours and then stored in a nitrogen

cabinet. After the components were assembled and reflowed on test boards using profiles shown in Table 2, the parts were tested again.

The TSOP48 components had some internal component damage before assembly. This damage was not sufficient to cause non-acceptance according to J-STD-020B. After reflow (Phase 2), internal component damage increased, but most of the damage was acceptable according to J-STD-020B criteria. Some parts assembled with the lead-free profile were not acceptable according to these criteria.

For the remaining component types, internal damage was observed pre-reflow. No significant increase in damage was found post-reflow for either tin/lead or lead-free processing temperatures. The minor internal damage noted for these components was found to be acceptable and within JSTD-020B criteria. After thermal cycle reliability testing, all parts were again analyzed with no indications of further increases in internal damage/delamination.

Rework Evaluation

Process steps for the rework of the CSP208 and PBGA256 test boards included component removal, board pad site preparation and placement/reflow of new components. For lead-free PBGA and CSP component test boards assembled with the lead-free paste, peak solder temperatures of 244°C and 246°C, respectively, were used for component removal. After site redressing, paste flux was applied to both component and board surfaces, and new lead-free components were placed and reflowed.

For lead-free rework, the peak solder joint temperature was 244°C for PBGA (time over 217°C of 66 seconds) and 246°C for CSP (time over 217°C of 68 seconds), respectively. The top of the lead-free component body would normally be around 15°C higher than the solder joint temperature. To preclude this, a method known as positive air flow was used to apply cooler air over the top of the component to reduce temperature while the component solder joints were heated from all four sides by the heater nozzle. With this technique, the peak temperature on top of the lead-free PBGA and CSP components dropped to 201°C and 231°C, respectively.

Despite the developmental nature of the rework and the small sample size, this effort provided a baseline of potential issues encountered during lead-free rework.

Conclusions

Little difference is found in the manufacture of boards assembled with eutectic tin/lead and lead-free SnAgCu solder paste. The only difference was reflow temperatures. In most cases, existing manufacturing tools and equipment may be utilized for these new processes.

X-ray, acoustic and AOI inspection equipment may be used successfully to evaluate lead-free assembly processes. Differences were observed between visual appearance for the lead-free and tin/lead soldered joints, but more work is needed to

test AOI inspection tooling. X-ray inspection showed increased voiding with the lead-free paste for CSP/BGA-type components and some reduced wetting with lead-free paste on TSOP components.

Components examined by acoustic microscopy showed internal component defects induced by the higher temperature lead-free reflow. Most of these defects, however, were well within component specifications. A method to lower the temperature at the top of the component during lead-free rework of CSPs and PBGAs was developed. More developments in the lead-free assembly and rework processes will be addressed in future projects. ■

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