Pollution Prevention Case Study

Lead-free Solder Assembly

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In anticipation of the European Union's Restrictions of Hazardous Substances (RoHS) regulations for lead effective July 2006, Benchmark Electronics (Winona, Minn.) initiated a lead-free surface mount technology assembly option for their customers. This conversion to lead-free assembly was funded through a 2004 state pollution prevention grant and matching funds provided by the company. The results were immediate elimination of 50 pounds of lead per year and an anticipated elimination of 7,000 pounds of lead waste annually from the facility.

This case study describes the process used to successfully convert to lead-free surface mount technology assembly, including the sequence of steps, challenges encountered, and key findings.

Benchmark Electronics now uses rework equipment designed especially for lead-free assembly.

Overview of findings

All aspects of electronic solder assembly need to be considered during conversion to a lead-free process. A comprehensive evaluation process that includes selection of which solder, flux paste, printed circuit board surface finish, components, equipment (assembly and rework), and processes to use as part of an overall plan is essential for success.

Until non-lead solder conversion is mature, the evaluation of materials and components is likely to identify trade-offs. The performance of the no-clean andwater-soluble solder pastes that were tested varied widely. Ultimately each company will need to determine which attributes are most important for their product line. Also components needed for a product may not be currently available as lead-free or may command a higher cost.

Many aspects of conversion are interrelated, for example the higher assembly temperature needed for non-lead assembly increases the moisture sensitivity of components. At the same time, heating the printed circuit board to the required higher temperature needs to occur with a minimal effect on cycle times.

As differences in handling and processing are identified, the assembly process will need to be modified and optimized. For example, in contrast to the lead solder process, there is a narrower temperature range for prevention of heat damage to components while at the same time higher temperatures are needed to reflow lead-free solder. To satisfy both requirements simultaneously, improved controls are critical for maintaining the solder flow within a narrower temperature range. In the short run, solder defects may increase until all of the conversion process adaptations and modifications are complete.

Conversion steps: Lead-free solder assembly

Benchmark Electronics developed a series of steps along with a timeline for conversion to non-lead assembly. A variety of tests were included as the process progressed to ensure performance and quality. The initial focus was on establishing criteria and selection of the most optimal lead-free solder paste formulation to use. Then testing of the customer's fully populated circuit boards, modification of the Bill of Materials, and training of staff would follow.

Step 1: Selection of solder-paste formulation

Capitalizing on previous research done by the iNEMI, International Electronics Manufacturing Initiative, the solder alloy ratio range selected for testing was tin – silver (3-3.9%) – copper (0.5-0.6%) or the SAC 305 alloy. The initial focus of the project was to identify which solder formulation within this alloy ratio also had the accompanying best paste or flux formulation. Eight water-washable and nine no-clean solder-paste formulations with this alloy ratio from various vendors were tested. Performance of the paste is key to determining the integrity and quality of the joint or interconnection a soldered component makes with the surface of the circuit board.

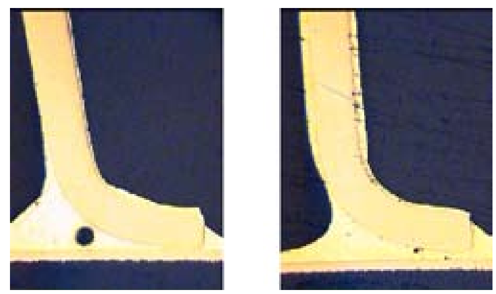
Printed circuit board and component surface finish

Three types of surface finishes on the commercially available test vehicle circuit boards that were used for testing were also evaluated: 1) Electroless nickel-immersion gold (NiAu), 2) immersion silver (ImAg) and 3) organic surface preservative (OSP). These surface finishes are expected to be the most prevalent for lead-free solder.

Lead-free components with tin over bare copper surfaces were used for populating the board tests. A nickel barrier is recommended to minimize tin whisker formation since tin plating over bare copper is very susceptible to tin whisker formation.

Evaluation criteria

Each phase of testing was designed to narrow the candidate solder-pastes. The majority of attributes, such as correct placement of solder (no solder balls or voids), were evaluated by visual examination of microscope or x-ray images. Scanning electron microscopy (SEM) was used to determine intermetallic bonds, grain structure, and morphology. Imaging was key to determining how robust the solder joints were.

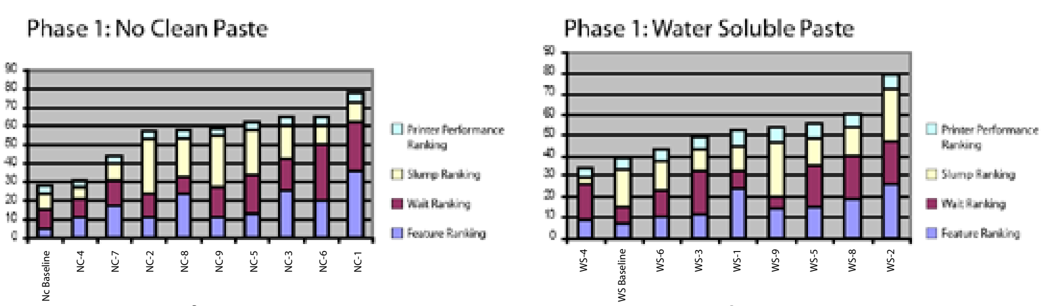


Lead-free joint Tin-lead joint
X-Ray cross section analysis of solder joints detects solder balls and voids.

In some cases, the defects were counted; for others, a 1, 2, 3 rating system was used, with one being the best and three the worst. Given criteria were assigned to each number using IPC-J-STD-610 standards (IPC – Association Connecting Electronic Industries). In instances where the attributes tested were not covered by industry standards, Benchmark developed their own criteria based upon priorities related to their processes. The solder-paste was tested for printing performance and for spreadability.

Printing performance tests The first test was for print performance, which determines how well the paste prints through a stencil onto the test circuit boards. During these tests, eight types ofwater-soluble and nine types of no-clean, lead-free solder pastes were evaluated. Each of the pastes was applied to the surface of an unpopulated circuit board containing various test patterns. Observations were made about how the deposits formed on the test board in a simulated production environment that included cooling and heating cycles. The test boards were evaluated for opens, bridges, paste and roll release, and unacceptable deposits. The results were averaged, compiled in a graph form for comparison to each other, with a water-soluble and no-clean tin-lead solder serving as the baselines.

The results showed baseline tin-lead pastes performed better than all lead-free pastes except one. Staff speculated that this was due to relative infancy of lead-free solder-pastes currently available.



Summary graphs of the print test comparing how well each of the pastes printed onto the test card.

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No one lead-free paste excelled in all four metrics that were compared; however five top pastes of each chemistry (no-clean, water-soluble) were selected for further testing.

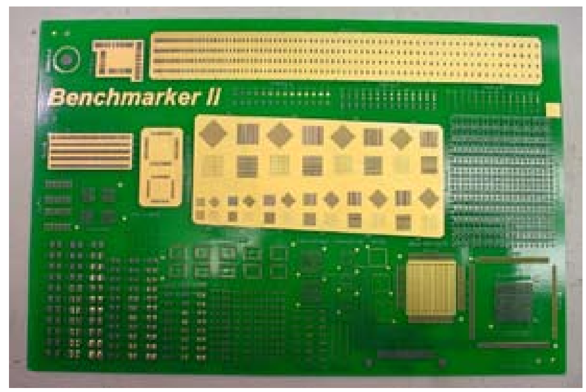
Spreadability tests The next evaluation step was a spreadability test to demonstrate how well the solder wets and spreads to the three selected surface finishes (NiAu, ImAg, OSP). Each card was preconditioned by one pass through the reflow oven to simulate a double-side reflow process. A water-soluble and no-clean tin-lead solder were used as the baselines.

The evaluation metrics for this test were formation of solder balls, wetting distance, solder quality and flux residue. None of the pastes outperformed the tin-lead pastes and no one paste excelled in all four metrics. Four out of the five water-soluble and no-clean solder-pastes tested were selected for further testing.

In terms of surface finishes, the electroless nickel-immersion gold finish (NiAu) performed the best for both the water-soluble and no-clean pastes.

Step 2: Testing of circuit board with components

The top four water-soluble and no-clean pastes were then tested with components. Non-lead components were attached to commercially available test circuit boards to evaluate performance with a variety of component types, including ball grid arrays (BGA), small outline plastic packages, quad flat packages, chip scale packages, and flip chip components.



Test circuit board that was used to evaluate performance.

In-circuit testing (ICT) determined how well spring-loaded probes could penetrate flux from non-lead solder to make contact with the pads and component leads to test for connectivity. This was performed on circuit boards assembled with the non-lead SAC 305 alloy to ensure that this ICT quality assurance test could still be performed effectively. The results of this test were a 75 percent first-pass yield. With a goal of achieving a 100 percent first-pass yield, Benchmark continues to work on improving the function of this test with the new solder paste.

Rework equipment was tested for use on ball grid arrays, surface mount technology, and through holes on circuit boards assembled with non-lead solder. The existing equipment proved inadequate so new hot air rework equipment, solder fountains, and solder irons designed for use with non-lead solder were purchased. This replacement equipment is currently being used with successful results.

Thermal cycling is accelerated lifecycle testing that includes heating, cooling and on/off cycles of the assembled non-lead circuit boards. One lead-free solder paste from each chemistry (water soluble, no-clean) actually outperformed the tin-lead baseline solder paste.

Run qualification lead-free builds includes assembling the customer product with the lead-free process to confirm results obtained on test circuit boards. Highly accelerated life cycle tests were performed. Evaluation metrics include opens and bridges on all components, tombstone and missing on all chip components, solder joint rating, and ball grid arrays void rating. Initial observations from this testing has documented positive results.

Step 3: Bill of materials revision

Revision of the current Bill of Materials is a key step that needs to occur early in the conversion process. Supply vendors are continuing to migrate toward stocking components compatible with non-lead assembly. It is even possible that components used with the traditional lead solder could eventually become scarce or unavailable in the future.

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The company worked closely with suppliers to source lead-free components. For the product assembled in this case study, currently 82 percent of components are lead-free (RoHS compliant), 6 percent are expected to be available in the near future, and it is not known if the remaining 3 percent are compliant or if the supply manufacturer plans to convert them. Inventory for lead-free and tin-lead components need to be kept separate so they are not mistakenly used interchangeably.

Step 4: Training

Training procedures were upgraded to reflect the characteristics of the lead-free assembly of circuit boards. For example, inspectors need to be trained for inspecting the lead-free solder joints which typically have a dull and grainy appearance yet function well. Training to ensure that necessary assembly, inspection, and handling procedures are implemented was provided to assemblers, quality assurance, and technical staff.

Challenges encountered, lessons learned

During the conversion process, the following are areas of focus were discovered to be key for ensuring success.

- **Materials selection criteria** for lead-free assembly materials and equipment need to be determined by each company based upon their priorities. As lead-free technology continues to emerge, an improved selection of lead-free pastes and equipment is becoming available. Until the process is mature, tradeoffs in product attributes may have to occur. Benchmark Electronics used a combination of industry standards and their own criteria based upon the processes used at their facility.
- **Process window for reflow** has a much lower tolerance range for lead-free solder assembly. Even though this was a known factor before conversion began, it continues to be a challenge. The temperature control of the reflow solder will be carefully monitored to prevent damage to components. This is because components can only withstand temperatures of 245 to 260 degrees C, while the reflow requirements of the non-lead solder are 240 to 250 degrees C; therefore the control temperatures are maintained in tight range of 240 to 245 degrees C. This dilemma is being addressed with data sharing and in-depth training of the entire organization.
- **Printed circuit board appearance changes** will need to be explained to customers since printed circuit boards assembled with lead free solder tend to look dull and grainy. Lead-free solder also tends to not wet or spread to the ends of the pads. Neither of these attributes affects the quality and performance of the circuit board, however it may be a cosmetic issue for some customers. In addition, customers that market internationally needs to be educated about the RoHS requirements.
- **Process cycle times** need to be maintained potentially with replacement equipment that is able to heat the PCB to the elevated soldering temperatures within acceptable time period.

Summary

Benchmark Electronics invested time in planning and implementing a comprehensive, multiphase approach to converting to lead-free solder assembly. The company has established all necessary process changes and continues to make improvements. Although the conversion required commitment and resource investment, once in place the benefits are many—from improved market position for products to decreased worker exposure and elimination of lead emissions to the environment along with decreased Toxic Release Inventory (TRI) reporting requirements.

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