Originally published in the Proceedings of APEX/EXPO 2004, Anaheim, CA

Practical Lead-Free Implementation

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Abstract

Environmental regulations are forcing the elimination of lead (Pb) from electronic equipment. 2005 will be the year that many electronics assemblers will be transitioning their soldering processes from traditional tin-lead alloys to lead-free alloys. Many alternatives to tin-lead have been proven to be technically viable in relatively small volumes, but the implementation of the new processes in high-volume manufacturing presents a series of new challenges to engineering and operations personnel. This paper reviews six major considerations for implementing lead-free soldering processes in a manufacturing operation: equipment evaluation, materials compatibility, separating and identifying the two separate processes, training, validating the process, and beginning continual improvement. Details of each consideration are discussed and summarized in a checklist format at the end of the paper.

Introduction

The transition to lead-free electronics is becoming a reality for more and more manufacturing operations. The RoHS and WEEE regulations, although still with a number of implementation questions, have final implementation dates. Many electronic manufacturers have some lead-free process capacity; others are making a significant effort to learn what is required, and some are in the beginning stages of understanding the lead-free process.

Numerous scientific studies have been published regarding lead-free concerns: equipment capability, solder alloy types, component metallization, process chemistries, PWB materials and surface finishes. The scientists and engineers have shown feasibility, and in some parts of the world, full-scale production of lead-free electronics is a reality. But many assemblers, particularly those in North and South America, are still formulating their transition plan. The scientific work that identified lead-free solutions must now be translated into practice on the shop floor. This is a considerable undertaking, given all the variables that exist in a production environment. The goal of this paper is to provide the framework for planning the transitions of individual factories. It combines the experience of several engineers who have supported lead-free transitions around the world.

Step One – Equipment: Verify that the production equipment in the factory is capable of supporting lead-free materials. It is important to consider all the equipment in a production facility. The obvious equipment considerations include the hot processes, like reflow and wave soldering. Less obvious include the data logging devices; rework systems, solder pallets, cooling apparatus, and other assembly equipment.

First of all, verify that the oven data logger is capable of operating at higher temperatures. It may need a better-insulated protective case. This should be easily verified by calling the device's manufacturer.

Once the high temperature capability of the data logger used to create heating profiles (recipes) for the reflow and wave soldering processes is verified, it's time to check the heating and cooling capability of the reflow and wave soldering systems. The most difficult to profile board under tin-lead temperatures is likely to be the most difficult to profile under lead-free temperatures also. Situations with large delta T's will probably require longer soak zones and perhaps longer Times Above Liquidus (TAL's).

Peak temperatures and TAL's will be traded off in the profiling process. Early profiling is important not only to understand equipment capability, but also to aid in selecting solder pastes and other materials later in the implementation process.

Some tricks to achieving appropriate profiles have been introduced. They include the "reverse spike" and "double spike" recipes. In the reverse spike scenario shown in figure 1, the second-to-last zone is used for the spike, and the last zone is set below spike temperatures. The double spike recipe, which is sometimes seen in 10-zone tin-lead processes, simply uses the last two zones to spike, at equal but lower setpoints. These types of recipes can help to control high peak temperatures while trying to achieve recommended Time Above Liquidus (TAL) on thermally challenging boards.

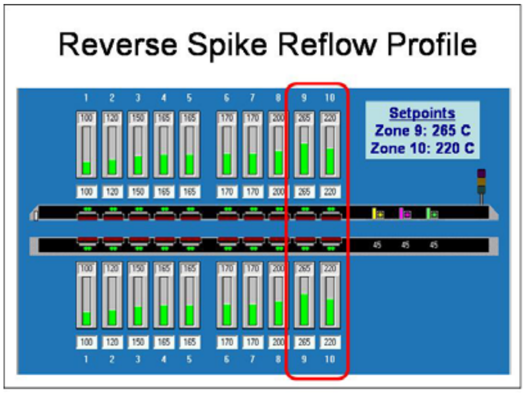

Figure 1. Reverse spike reflow profile may help some assemblies achieve good TAL's without exceeding peak temperatures.

The heaviest board that runs at slow belt speeds is likely to cool the slowest upon exit, and is the most likely to present handling issues depending on conveyor configuration. If boards are fed to operators directly from the reflow oven, they should be profiled all the way to the operators' area to assure they are at appropriate handling temperatures when they arrive.

Wave soldering equipment must also be verified. Since wave soldering temperatures are not very different between tin-lead and lead-free, the wave solder machine's thermal capability may not be as serious a consideration as its construction. Lead-free soldering alloys have very high tin contents. Tin-rich alloys rapidly corrode stainless steel components (fig. 2); so all machine components that make contact with molten solder should be reviewed. The list includes the solder pot interior surface, nozzles, flow ducts, pump hardware and conveyor fingers.

Figure 2. Stainless steel flow duct corroded by tin-rich solder alloy. Stainless steel will degrade after 6 – 12 months exposure to lead-free solder.

Another consideration is the configuration of the wave nozzles themselves. Tin-lead solder is typically processed at approximately 60°C above its melting point. To avoid excessive thermal strain on the assemblies and to ease the transition, lead-free solders are processed at temperatures closer to their melting point – 30° to 40°C above liquidus. Solder nozzle configurations that work well on tin-lead may not be optimum for lead-free. The distance between the turbulent and smooth wave nozzles can become a critical factor. Figures 3 and 4 show typical tin-lead nozzles and lead-free nozzles.

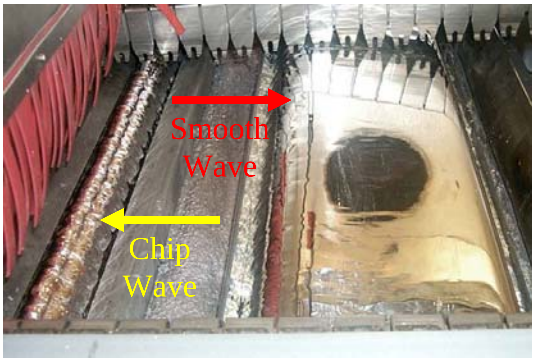

Figure 3. Typical tin-lead wave solder nozzle for air environment. Notice the distance between the waves.

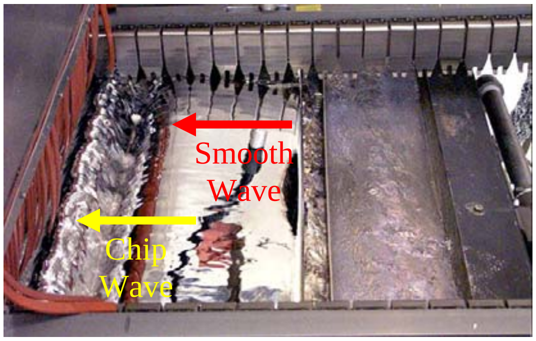

Figure 4. Lead-free wave solder nozzle for air environment. Notice the shorter distance between waves.

After passing through the chip wave, solder joints cool and begin to solidify. When they reach the smooth wave, they are reheated and re-melted. Once the solder again becomes molten, its wetting forces can act on the lead and the barrel to fill the hole. The shorter distance between nozzles gives the lead-free solder less time to cool, and requires less energy to re-melt the solder in the barrels, thus providing more contact time on the smooth wave for wetting. The net result of closer nozzles is better hole fill.

Thermal profiles comparing the two nozzle types can be seen in figure 5. The solid traces represent lead-free nozzles; the dashed traces represent tin-lead nozzles. Both were processed at lead-free temperatures (250^{o}C) without preheat. Notice the dramatic difference in the joint temperatures with the closer nozzles.

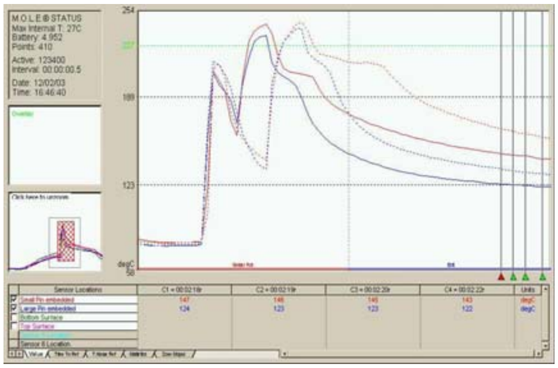

Figure 5. Thermal profiles for traditional tin-lead and lead-free nozzles. The lead-free nozzles do not allow as much cooling between waves, resulting in better hole fill.

Solder pot maintenance will have a few new considerations when compared to tin-lead soldering. Solder analysis should be performed more frequently to monitor the levels of lead (coming from components that are not yet lead-free) and copper (coming from circuit boards). This is extremely important on selective solder or mini-wave machines, which have smaller pots that get saturated faster. Lead levels of greater than 0.1% limits a solder joint's ability to be called "lead-free" [1] and can also contribute to fillet lifting in through-hole devices. Copper levels greater than 0.9% can make tin and SAC alloys more sluggish, causing solder bridges. Removal of copper from the alloy also presents a new challenge, as the copper-tin intermetallic compound is denser than tin, tin-copper, or tin-silver-copper alloys, and cannot be floated to the top of the pot and skimmed, as was the typical practice with tin-lead. The lower density of lead-free alloys also means that hand tools which are erroneously dropped into the solder pot will no longer float to the top, as they did with tin-lead.

If pallets are used in the wave soldering system, they should be part of the material considerations. The pallets will be exposed to longer thermal cycles with slower conveyor speeds and longer contact times in the wave. They may need more frequent cleaning. Many different materials are available for wave pallets. It is best to check with the pallets' supplier to verify the material's stability, to understand if they have any experience with the specific material and lead-free soldering, or if protective coatings are available to prolong their service life.

Rework stations will require verification also. Although most stations will be able to reach the proper temperatures, boards may become more difficult to profile. As with the reflow process, it is advisable to check both heavy and light boards to understand the process window and the higher temperature's impact on warpage and handling. Component body temperature should also be monitored, as the reflow temperature of the solder approaches the maximum allowable temperature of the component.

Soldering irons are typically located throughout the factory – at inspection stations, rework stations, test stations and sometimes at final assembly. The location of all irons should be recorded, so that if new tips are needed, they can be deployed to all appropriate places. These locations will also require spools of lead-free solder, and operators and technicians will need to be trained on how to identify lead-bearing from lead-free products.

Non-soldering processes will also be affected. Some factors will change in stencil printing; others will not. Printability of solder pastes depends heavily on flux formulation but not at all on alloy type. Experience has proven that there is no difference in the actual printing of lead-free solder paste from printing tin-lead solder paste. Formal testing by Speedline Technologies has verified that the printed volume of several lead-free solder pastes and tin-lead solder paste was statistically the same using the same stencil, printing equipment, and boards. The results are shown in figure 6.

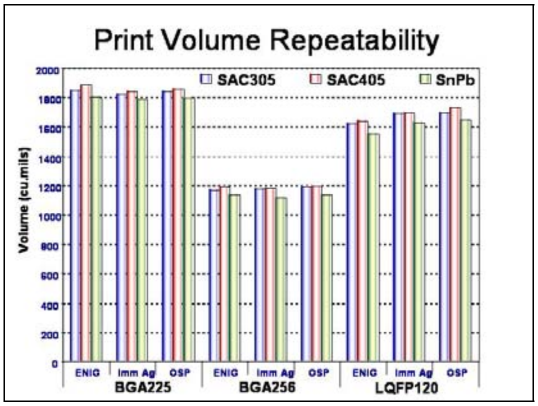

Figure 6. Print volumes of three different alloys on three different surface finishes for three different devices showed that volumes for all alloys were statistically the same.

Lead-free solder paste's printability will not change, but its spread during reflow will, which may require a tightening of the stencil printing process.

One issue that is of concern is the print accuracy, or the alignment of the printed solder paste to the printed circuit board pad. Since the lead-free alloys do not spread or wet as well as tin-lead, any solder paste that is not accurately printed onto the printed circuit board will stay close to where it was printed after the reflow soldering process. Figures 7 and 8 depict the same deposits before and after reflow for QFP's and for passives.

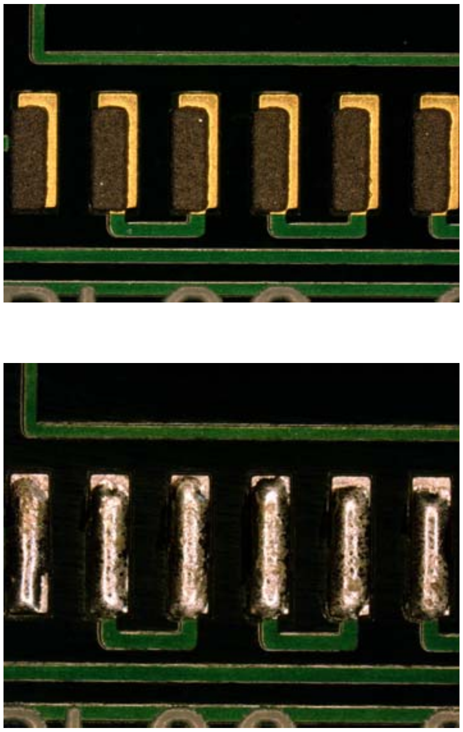

Figure 7. Lead-free QFP print before and after reflow. Notice the lack of spread during reflow process.

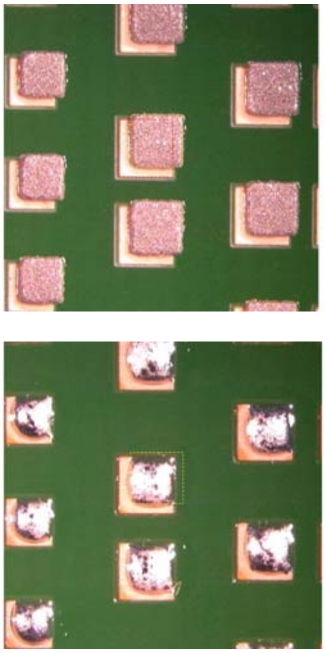

Figure 8. 0603 and 0805 pads before and after reflow process. Again notice the lack of spread.

The major concern in this situation is the accuracy of the printing equipment to align the stencil apertures to the printed circuit board pads. When addressing the variation in stencil to PWB alignment, several sources must be considered. They include the variation of the positional accuracy of the PWB, the variation of the alignment capability of the printer, and the variation in the stencil itself.[2] If the variation of the stencil is contained, and the variation of a calibrated printer is known to be +/- 1 mil at 6 sigma[3], then the remaining factor is the positional accuracy of the PWB itself. The PWB variation is by far the largest contributor to misalignment. PWB's are known to "shrink" from CAD data as a result of their fabrication process. They also experience some shrink in their first reflow process, exacerbating the misalignment issues when printing the second side of the board.

To address the variation in the PWB, it can be measured and mapped; so that a stencil can be generated to custom fit the PWBs. Generally, all PWBs in a manufacturing lot shrink by the same proportion if oriented in the same direction on the vendor panel. For large volume production, it is economically advantageous to request the PWB manufacturer to measure the circuit boards and provide positional data so a customized stencil can be cut to match them. The improvement in yields far offsets the cost of the stencil. Measuring and mapping the board brings the added benefit of programming the pick and place equipment with actual location data, thereby reducing the defects typically associated with pick and place: misplacements, tombstones, and soldering defects like solder balls or bridges that result from paste smears[4].

Work has been performed to identify the optimum aperture for chip components (0402 – 1206) that will allow for good pad coverage while limiting defects like mid-chip solder balls (MCSB) and tombstones[5]. Three experimental apertures were compared to industry standard rectangular and home plate apertures. The experimental apertures are shown in figure 9.

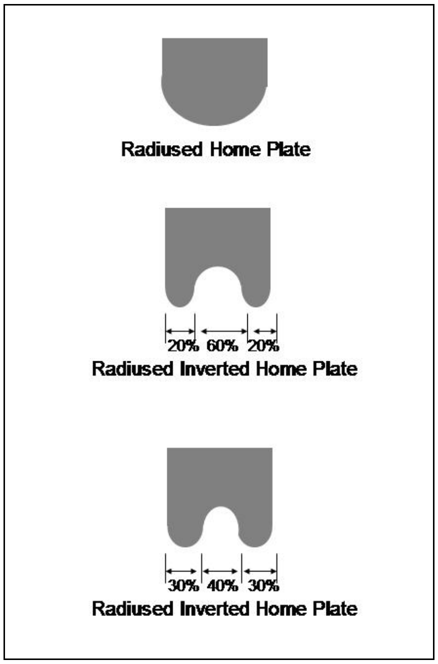

Figure 9. Experimental apertures designed for lead-free paste printing.

The best aperture that limited both MCSB's and tombstones was the radiused-inverted homeplate with the radii set at proportions 20%-60%-20%. This aperture design allowed for full pad coverage (1:1 printing at corners) but limited the amount of paste under the component that contributes to MCSB defects. The test compared multiple factors; the results can be viewed in the interaction plots in figures 10 and 11.

Figure 10. Mid-Chip Solder Ball interaction plot

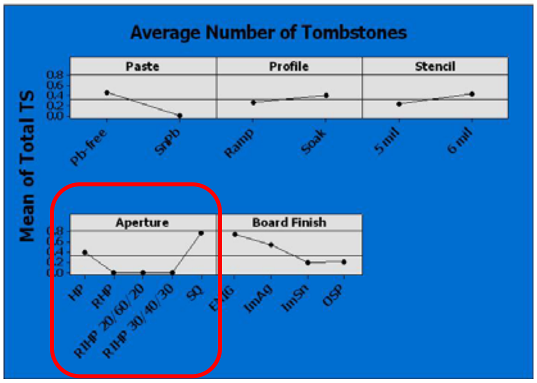

Figure 11. Tombstone interaction plot. Notice all of the experimental apertures minimized tombstones, but the 20-60-20 aperture also minimzed MCSB's.

The final consideration in the assembly line is the pick & place system. With the exception of component vision files, lead-free processing has little impact on the placement process. Components will have the same size and shape, but have a lead-free finish on their leads or bumps. Finishes may include matte tin, tin-copper, tin-bismuth, tin-silver-copper, nickel-palladium or nickel-gold. Whatever finish is applied to the leads, there is a chance that it will appear differently to the vision processor than its tin-lead predecessor did. Depending on how a facility manages its vision files, the best option may be to test lead-free devices as they become available and have separate files for tin-lead and lead-free components until the transition is complete.

Another area of concern in the component placement process is placement accuracy. Several formal studies, including one performed by Speedline Technologies, showed that component self-centering during reflow is not as robust in lead-free processes[6]. Components that will center back to the printed circuit board pads in a tin-lead process will not center back to the printed circuit board pads as well in a lead-free process. Placement processes should be monitored to insure proper component orientation after reflow.

The majority of equipment considerations can be reviewed well in advance of running lead-free processes. In fact, some of them *must* be reviewed in advance. Conversely, many can be performed without lead-free materials, but others must wait until the lead-free materials are available and in stock. Any preparation or evaluation that can be performed in advance should be done in advance. This will not only help to smooth the workload during the transition, but certain aspects (like tightening up stencil printers and pick & place machines) may also bring some immediate improvements to the current tin-lead process.

Step Two: Investigate material compatibility. Obviously the solder paste will change when a lead-free formulation is used. Many factors influence solder paste selection, including printability, stencil life, pin testability, tack, reflow window, and joint cosmetics. Regardless of alloy, each assembler must determine which factors are most important to them and prioritize their selection accordingly. When moving to lead-free solder paste, however, the difference in surface appearance should be considered early, as it will affect inspection and yields.

When evaluating a solder paste, reference the profiles generated in Step One. The solder pastes under evaluation should be processed at similar time and temperatures. These assemblies can then be used to assess worst-case residue cosmetics (if no-clean) or cleanability (if water-soluble). If water-soluble paste is used, it is advisable to clean after each reflow pass, but if this is not possible, cleaning after two reflow cycles should be checked.

Long, hot thermal excursions present a worst-case scenario for flux residues. Fast, cool thermal excursions present a worst-case scenario for solder joint cosmetics. An assembly should also be tested under an anticipated fast thermal excursion, using a shorter time above liduidus and lower peak temperature. This assembly can then be assessed for wetting, surface appearance, and fusion of fine features.

Will the current wave flux be compatible with lead-free alloys in wave soldering? It could be, depending on the vintage of the formulation. Most modern liquid fluxes developed in the past few years are likely to work well with lead-free solders. The manufacturer probably tested the flux with lead-free solders during its development.

If a more mature flux formulation is used, the likelihood of lead-free compatibility is lower. A water-soluble flux is more likely to stand up to the demands of a lead-free process than a no-clean, which is designed to become benign after the thermal exposure of a tin-lead process. It is best to check with the flux manufacturer before beginning testing.

Changes in paste and potentially flux chemistries may require changes in cleaning chemistries, for both wet paste (stencil & misprint cleaning) and post-assembly cleaning, when applicable. A further consideration to misprint cleaning is second-side misprints on double-sided SMT boards. In this case, it is important to characterize the interaction of the misprint cleaning chemistry with the reflowed flux residues.

In a manufacturing process using tin-lead soldering materials, a high-level understanding of the components was all that was required. Basic concerns focused on component geometry and process capability in the areas of solder paste printing, component placement, and reflow soldering, with the goal of reliably and repeatably assembling these components.

Rarely were the components' temperature tolerances or maximum ramp rates (degrees/second) a consideration. These factors have always been important, but the tin-lead reflow temperatures almost never exceeded the maximum allowable temperature and seldom exceeded the maximum allowable ramp rate. Lead finish was not a large consideration either, because all components were specified to be compatible with the tin-lead soldering process – the biggest consideration on lead finish was if it was "solderable" or not due to aging or other environmental conditions.

The introduction of lead-free materials requires process engineers to read and understand the specification of each and every component used on each and every product manufactured. Simply assuming that a component's temperature tolerance, lead finish, or Moisture Sensitivity Level (MSL) is compatible with a lead-free manufacturing process can be a costly mistake. An overheated or popcorned component may fail during assembly and test, or even worse, it may fail later on in service.

Of extreme importance in lead-free soldering is the circuit board material. Depending on the performance level required of the final assembly, traditional FR-4 may need to be replaced with more thermally robust materials. The glass transition temperature (T_g) of resin systems used in circuit boards is defined as the temperature at which the material transforms from a relatively rigid or "glassy" state to a more deformable or softened state[7]. The general view of T_g is "the higher the better," it is important to understand it in a little more depth, because properties like thermal expansion are different above T_g than below T_g. The coefficient of thermal expansion (CTE) above T_g is much greater than below. Furthermore, T_g cannot predict expansion rates. A low T_g material may have a low CTE, while a higher T_g material may have a higher CTE. A high T_g material may actually exhibit greater net expansion at reflow temperatures than its low T_g counterpart.

Thermal expansion, especially in the Z-axis, is an important factor in long-term reliability. Plated vias and through holes experience a great deal of stress during thermal excursions. The higher the Z-axis expansion, the more stress gets placed on the plated holes, thereby affecting the assembly's service life. **Higher T_g materials do not necessarily mean lead-free compatibility or improved reliability.** If not selected carefully with other considerations in mind, a high T_g laminate can make a bad situation worse. Figure 12 shows the total Z-axis expansion of three different laminates.

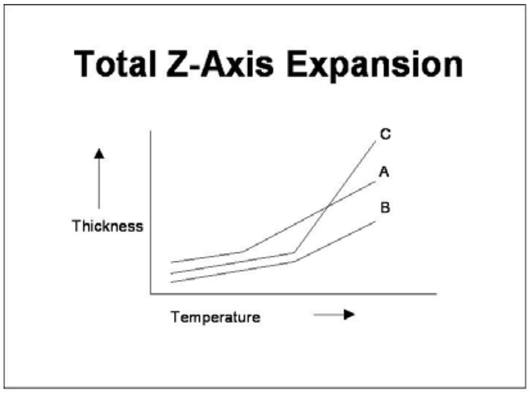

Figure 12. Expansion of three different base laminates. Notice that *all* post-T_g CTEs are higher than pre-T_g CTEs. Material A exhibits more total Z-axis expansion than B because of a lower-T_g, but material C, even with a higher T_g, exhibits more total Z-axis expansion than A because it has a high post-T_g CTE.

An equally or even more important consideration when selecting a lead-free compatible circuit board material is the decomposition temperature, T_d. T_d is the temperature at which 5% of the mass of the material sample is lost to decomposition. Any mass lost during heating is not recovered. Even 2-3% loss, especially when exposed to multiple thermal cycles, can significantly degrade reliability. Materials with lower T_d's can decompose and become permanently altered during the reflow cycle. Figure 13 shows the decomposition curves for two different FR-4 materials with the same T_g – 175^{o}C, as measured with thermogravimetric analysis (TGA).

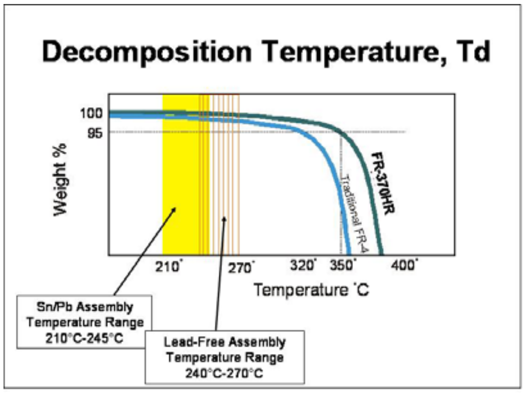

Figure 13. TGA of two laminate materials showing weight % loss during heating.

Solder mask may be a consideration during the lead-free transition, as new flux and paste chemistries and higher processing temperatures may attack masks that perform well in the tin-lead environment. As there are many brands and types of solder mask available, it is best to check with the board supplier in advance. It is also advisable to perform close visual inspection of the solder mask during the paste and flux evaluation cycles.

If peelable or temporary solder mask is used in wave soldering, it should be verified to hold up with lead-free fluxes and thermal excursions. Since the alloy has little effect on peelable mask, compatibility can be verified by running the current tin-lead solder process with the anticipated lead-free process parameters.

Some SMT adhesives are heat-reworkable. In other words, they are cured and hardened by heat (typically 125-150^{o}C), but can be softened by applying more heat after the cure is complete. Because alloy metallurgy has little bearing on adhesive performance, adhesive compatibility can be checked in a method similar to that described for peelable solder mask.

Underfills should be tested for compatibility with new solder paste chemistries. Ideally, capillary underfill materials should demonstrate the same adhesion to the lead-free solder paste residues as it did with the tin-lead residues. This can be evaluated visually by cross sectioning, but thermal cycle and drop or vibration test data is preferable. No-flow underfills require more careful consideration. Because the cure rate of the underfill is matched to the reflow profile, it is likely that the cure characteristics of the material will need to be changed by the material's supplier.

Rework flux is usually the same flux used in the assembly process. If fluxes are changing, any defluxers used in test areas should be tested for compatibility with the new assembly process chemistries.

Step Three: Prepare to segregate

Cross-contamination of lead-bearing and lead-free solders in the assembly process can be a costly mistake, as it holds the possibility of rendering all assemblies that are suspected of cross contamination to the scrap pile. Segregation efforts should be diligent and highly visible. If possible, during the transition period, designate assembly lines as lead-bearing or lead-free ONLY. If this is not possible, separate setup kits should be stocked for each line. The setup kit should include squeegee blades, spatulas, dispenser nozzles, soldering iron tips, rework materials, and any other components of the assembly process that offer potential for cross contamination. Each component of the kit should be individually labeled as lead-bearing or lead-free for identification purposes, in case they do not get returned to the kit immediately during line changeover.

Solder pastes should be stored in separate locations (refrigerators or cabinets) to prevent operators from taking a wrong container by mistake. Solder bar and dross should also be stored separately and be clearly labeled. Many solder manufacturers are taking steps to aid operators in recognizing the difference between the two products by changing the colors, shapes, or legends on their products' containers. In early stages of transition, it is wise to keep solder materials secure, giving only line leaders or supervisors access until the labor force becomes accustomed to the segregation systems.

Stencils bring an opportunity to cross-contaminate two alloys if they are shared between the two processes. Manual stencil cleaning does not remove all the particles from the apertures. Many automatic stencil cleaners leave some paste residue behind, also. If an assembly is transitioning to a lead-free process forever, the stencil can be thoroughly cleaned and inspected under magnification to assure its cleanliness, then labeled and moved to a separate storage location designated for lead-free. If an assembly will be transitioning with some runs in lead-free and some in tin-lead (eg. during qualification runs), the best option is often to purchase a second stencil. This practice will eliminate the concern of cross contamination from stencils and bring the added benefit of having apertures optimized for lead-free paste[5]. Most stencil manufacturers can aid in the identification of lead-free stencils, by etching “Lead-Free Only” in the foil, and some even offer different color frames to provide a visual cue to the production personnel.

Step Four: Effectively communicate the change before it happens.
Train the inspectors and rework operators before running lead-free product. A contributing factor to yield loss during a lead-free transition is “false failures.” Often, solder joints that do not need touch up are touched up anyway. Solder joints that are touched up are typically logged as a defect in the factory data collection system. There are several possible reasons operators touch up solder joints unnecessarily:

- The operator is not properly trained in visual inspection of lead-free joints.
- The operator doesn’t *think* it is a problem but diligently opts to err on the safe side, since he or she is responsible for final quality of the assembly.
- The operator confuses the characteristics of lead-bearing and lead-free because he or she is being moved between assembly lines during the shift.

Lead-free surface mount solder joints look different than tin-lead solder joints. Their surface is generally duller, their wetting angle is shallower, and they can resemble what’s referred to as a “cold joint” in tin-lead processes.

Lead-free wave solder joints can also look different from their tin-lead counterparts. Often, the surfaces appear rough and cracked; this is normal and usually dependent on the cooling rate of the joint. The joints can resemble the tin-lead defect referred to as a “disturbed joint” for alloys with a pasty range. Even operators who are unfamiliar with disturbed joints can be tempted to touch them up, based solely on the different appearance.

The best approach to avoiding unnecessary rework is to train the operators early, provide plenty of visual references in the work area, avoid moving operators from lead-bearing to lead-free lines during a shift, and appoint an “expert” on each shift that the operators can ask regarding whether or not the joint needs touch up. This expert can be an experienced solderer, a line supervisor, or someone from the training department.

Training and education does not stop with rework operators and inspectors. Every person in the factory who judges solder joint quality and uses a soldering iron must be trained. This can include personnel in test, final assembly, or warranty/repair areas. For CEM’s, customers will also need training in order to avoid unnecessary questions and/or returns.

Visual indicators are critically important. Board labeling should be different, e.g. different color backgrounds for bar code lables or an extra label identifying the product as lead-free. This will prevent mix-ups downstream. Examples of the labeling conventions should be posted throughout the factory. Photographic examples of good quality lead-free solder joints should also be posted throughout the facility.

Once an assembly line is dedicated to lead-free processing, the line should have plenty of visual indicators. The words “Lead-free only” should be on all equipment and tools used on the line. Operators should be prevented from trading equipment or tools between lines whenever possible. Some materials suppliers provide stickers or labels to their customers assist them in the transition.

Line leaders or supervisors should be included in the formulation of a communication plan. They can best advise the most effective means of communication to the labor force. Prior to the launch of a lead-free transition, all levels of operations supervision should be briefed on the communication plan prior to its rollout.

Step Five: Validate the process. The equipment is ready, the soldering chemistries have been selected, and the factory floor has been prepared for the transition. The only thing left to do now is run the process and validate it. Unforeseen issues are bound to arise during the first few runs, so a few short "shakedown" runs are suggested to flush them out and address them. Next, it's time for validation. An assembly with multiple types and surface finishes of components should be selected to run through the lead-free process and undergo the appropriate scrutiny:

- Full visual inspection of solder joints, residues, and wetting properties
- Full visual inspection of the substrate for signs of blistering, measling, delamination or solder mask peeling
- Full visual inspection of all components and connectors, with particular emphasis on the plastics
- Inspection of through-hole connectors for solder balls (solder side for wave solder or topside for intrusive reflow)
- Cleanliness analysis
- Cross-sectional analysis of assembly
- Joint integrity testing, when applicable
- Any non-conforming defects or process indicators are recorded and resolved

Since the rework is a fact of life, some reworked joints should be included in the validation phase. One or more devices on the assembly, preferably including a BGA, should be reworked prior to the validation review.

Process validation can take place internally, or be sent to an independent laboratory for an objective review. Whichever option is exercised, the party reviewing the assembly should be notified which devices were subjected to rework cycles.

Step Six: Refine the process. Assuming the validation assembly passed all testing, the process is ready for production. But like any change in the fundamental structure of a process, a learning curve follows the initial implementation. Since lead-free alloys behave somewhat differently than their lead-bearing counterparts, parameter settings that were optimized for lead-bearing may be suboptimal lead-free.

In surface mount technology, rates of midchip solderballing, tombstoning, skewing, and random solderballing and pull back (e.g. when printing on mask for intrusive reflow) will be different with lead-free alloys. Voiding properties can also be expected to change, as the lead-free solderpastes use different flux chemistries than tin-lead pastes. Self-centering properties of lead-free paste will not be as strong as their tin-lead counterparts, so placement tolerances and end-of-line defects will require monitoring.

In wave soldering, the slower wetting of the lead-free alloys can cause more skips and less hole fill. The different surface tension can cause more bridges and micro solderballs.

Essentially, the processes must be re-optimized as production volumes come up to a level where significant sample sizes can be obtained. Some of the process inputs that may require re-optimization include stencil aperture design, reflow profile style, and placement pressure and accuracy in surface mount assembly. Flux loading, wave contact, peel-off mechanics and cooling methods may need to be revisited in wave soldering.

The best place to start when seeking process refinements is not necessarily on the factory floor. *It should start with research.* There are a multitude of resources available that describe the new generation of tricks of the trade. Many organizations have published results of optimization procedures at international conferences. Proceedings are usually available on-line to organization members. The on-line libraries are more convenient to scan than individual proceedings that are published on CD. Local professional society meetings offer opportunities to share findings with other local assemblers on a one-to-one conversational level, or to learn from visiting experts. Bulletin board type websites offer excellent exchanges of opinions and information free of charge from the engineers that visit them[8]. Spending an hour reading the postings of other engineers can answer a lot of questions and provide excellent guidelines when setting up DOE's. Specific questions can be asked of the worldwide panel of experts by simply posting them on the website and reviewing the subsequent responses.

Suppliers of both materials and equipment should be a prime resource in providing guidelines to process optimization. Suppliers' engineers support numerous lead-free implementations in a variety of assembly areas, build their knowledge bases quickly, and should be able to provide credible opinions on what works and what doesn't.

Conclusion

2005 will be the year that most assemblers begin building with lead-free processes. There are a multitude of factors to consider when planning the transition to lead-free. This paper provides a listing of the factors deemed most important by engineers from material and equipment suppliers who have been working on lead-free transitions throughout the world. It is intended to provide a starting point for assemblers who are now planning the transition. Appendix A is a synopsis of the considerations in checklist form. Assemblers using the checklist as a planning tool can easily add considerations unique to their situation or delete considerations that do not apply to their process.

The single most important thing for an assembler to keep in mind during the transition is that they do not have to embark on the process alone. Materials suppliers, equipment suppliers, professional organizations and websites are great resources. The first step in the transition plan should be researching the work that has been done and is readily available. The up-front time investment will bring considerable payoff when the implementation actually occurs.

References

[1] RoHS (Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment)

[2] Mendez, D., Clarke, R., "Statistical Model of Printed Wiring Board and Stencil Alignment Issues", Proceedings of Surface Mount Internantional Conference, April, 1997.

[3] Eagle-Eyed One, an independent engineering firm that characterizes stencil printer performance.

[4] "Reducing Variation in Outsourced SMT Manufacturing Through the use of Intelligent Stencil Systems", Chrys Shea, Valentijn Van Velthoven, Ron Tripp and Ranjit S Pandher, Proceedings of the SMTA International Conference, Chicago, Illinois, 2003

[5] "Optimizing Stencil Design for Lead-Free Processing", Ranjit Pandher, Chrys Shea, Proceedings of the SMTA International Conference, Chicago, Illinois, 2004

[6] "Self-Centering of Offset Chip Components in a Pb-free Assembly," Belmonte et al Proceedings of IPC Lead-free Conference San Jose 2004.

[7] "An Assessment of the Impact of Lead-Free Assembly Processes on Base Material and PCB Reliability." Ed Kelly, Polyclad, Proceedings of APEX International Conference, Anahiem, California, 2004

[8] www.SMTnet.com, an industry portal site bringing together providers and users of the products, services, and information related to electronics manufacturing.

Appendix A

Lead-Free Implementation Checklist

	Date Verified	Verified by			
		Engineering	Production	Supplier	Other
1) Equipment					
Can the current profiling tool handle the elevated temperatures of the reflow oven?					
Spot check reflow profiles					
High thermal mass boards					
Can oven reach lead-free reflow temps and maintain line throughput?					
Exit temp - will boards be cool enough to handle at inspection station?					
Do cooling zones(s) allow for control of cooling rate?					
High Delta T boards					
Can oven maintain reasonable delta T's?					
Record hottest and coldest cycles for subsequent paste evaluation					
Thin, light boards					
Will these warp exesssively, causing issues at test or final assembly?					
Is the wave solder machine ready for tin-rich solder?					
Solder pot					
Flow ducts, pumps, impellers, bearings, other solder pot hardware					
Conveyor fingers					
Spot check wave profiles					
High Delta T boards					
Can the wave maintain a reasonable delta T?					
Heavy ground plane/poor thermal relief boards					
Can the wave get good hole fill? (Need to test with specific wave alloy)					
What is the exit temperature of the assembly?					
Will the boards be cool enough to handle when they get to the inspectors?					
Is there a cooling system at the exit of the wave? (may provide better joint cosmetics)					
Wave solder pallet materials					
Will the material break down faster, requiring more maintenance?					
Will they need more frequent cleaning?					
Are the rework stations capable?					
Are new soldering iron tips needed?					
Will AOI programs need modification?					
Will AXI programs need modification?					
If cleaning boards, is the assembly line configured to clean after each reflow pass?					

2) Materials

	Date Verified	Verified by			
		Engineering	Production	Supplier	Other
Solder paste qualification plan					
Prioritization of characteristics and pass/fail criteria					
Run under high and low profile extremes from Step 1					
Flux qualification plan					
Run under high and low profile extremes from Step 1					
Run with and without turbulent wave					
Board cleaning chemistry					
Compatible with paste					
Compatible with flux					
Does cleaning take place in process (post-reflow) or after all soldering is complete?					
Misprint cleaning chemistry					
First side, paste only					
Second side, paste & flux residues from prior reflow					
Stencil cleaning chemistry					
SMT Adhesive compatibility					
Peelable solder mask compatibility					
Rework flux and defluxer					
PWB Card materials					
RoHS compliance					
Laminate temperature compatibility					
Solder mask temperature and chemistry compatibility					
Rework thermal cycle compatibility (of board)					
Surface finish					
Component materials - understand for every component					
Metallization					
Lead-free finish					
Compnents tested in pick & place vision system?					
Plastics					
Maximum Time & Temperature					
Moisture Sensitivity Level					

3) Shop Floor Segregation

	Date	Verified by			
	Verified	Engineering	Production	Supplier	Other
Materials storage					
Separate refrigerator for lead-free paste					
Visual indicator? (Color of tube or jar)					
Separate storage area for lead-free bar					
Visual indicator? (Color of box, shape of bar)					
Separate storage area for dross					
Visual indicator? (Color of cans, labelling of area)					
Limited access to materials during transition?					
Stencils					
Separate stencils for lead free?					
Visual identification method? (etched in foil, painted frame)					
Separate stencil cleaning method?					
Separate storage areas?					
If same stencil, is manual cleaning & inspection procedure in place?					
Will a line be dedicated to Lead-Free or change back and forth from tin-lead?					
SMT Line changeover lead-free setup kits					
Squeegee blades					
Spatulas					
Paste dispenser nozzles					
Soldering iron tips					
Cored wire solder					
Cleaning and inspection procedure for support tooling					
Board identification					
Label changes					
Visual indicators of label changes in all areas that may touch up solder joints					
Add-on					
Test					
Final Assembly					
Other					
Lead-free solders & irons available in above areas					

4) Training

	Date Verified	Verified by			
		Engineering	Production	Supplier	Other
Solder joint inspection					
Line operators					
Inspectors/rework areas					
Quality assurance					
In-circuit test					
Field return/repair					
Customers					
Material handling					
Operators					
Material handlers & stockroom/tool crib					
Receiving & incoming inspection					
Visual indicators for lead-free					
Product identifiers - labelling differences on boards					
Process identifiers					
Manufacturing equipment labels					
Process chemistry labels					
Personnel labels (diff color smocks)					
Dedicated line labels (diff color mats)					
Mass communication of visual indicators & transition plan					
Program overview to line leaders, supervisor, managers					
Posters in break areas, cafeterias, common areas, etc					

5) Process Validation

	Date Verified	Verified by			
		Engineering	Production	Supplier	Other
Shakedown runs					
Board selection					
Component types, surface finishes, amount of data on tin-lead process for comparison					
Production					
Rework					
Visual inspection					
Wetting & spread					
Solder joints - quality, wetting and residues					
Circuit board - delamination, blistering, soldermask peeling					
Plastics on components and connectors					
Record of non-conforming defects and process indicators					
Voiding analysis					
Cleanliness analysis					
Cross-sections					
Final Approval					

6) Process refinement and yield enhancement

Compare defect rates between tin-lead and lead-free

Areas to Investigate

Surface Mount	Print Parameters	Stencil Design	Placement Parameters	Reflow Parameters
BGA, MLF, leadless IC's				
Opens	X	X		
Shorts	X	X		X
Voids		X		X
Chips				
Opens	X	X		
Shorts	X	X	X	X
Tombstones		X	X	X
Mid-chip solder balls		X	X	X
Skews		X	X	
QFP, J-Lead, other SMT				
Opens	X	X		
Shorts	X	X		

Areas to Investigate

Wave Solder	Flux Loading	Preheat time & temp	Wave Contact	Peel Off	Cooling Rate
Through-hole					
Insufficients	X				
Bridges	X		X	X	
Hole fill	X	X	X		
Solder balls		X	X		
Joint surface appearance					X
Fillet lifting					X
Wave soldered SMT					
Skips	X		X		
Bridges	X			X	