Implementing Lead-Free Wave Soldering

Higher levels of copper and iron can change the alloy and require new guidelines.

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THE IMPLEMENTATION OF a lead-free wave soldering process will be successful only when multiple challenges are addressed. The International Electronics Manufacturing Initiative's (iNEMI's) Lead-Free Wave Soldering Project has identified specific materials, technologies and processes that are impacted by the conversion to lead-free wave soldering. When this article went to press, the team was completing Phase I of project activities, which focused on the impact of lead-free assembly on different process parameters and how to optimize the wave soldering process. This article provides a general overview of how lead-free impacts the wave soldering process, discusses the key challenges and looks at where the technology is going.

While the challenges of developing a wave-soldering process consist primarily of addressing how the lead-free transition will alter the conventional tin-lead process, other technical challenges will necessitate a comprehensive analysis of technology gaps (**TABLE 1**).

Decreasing component pitch will, for example, be a challenge. It becomes more difficult to solder through-hole layouts as the pitch decreases to 0.016-0.020″ from 0.060-0.075″. This is made more difficult by the wetting behavior of lead-free alloys. As a result, there is the need to determine whether wave soldering can deliver defect-free processes at these higher lead densities, or if an alternative technology exists.

Incorporation of palettes for an increasingly greater percentage of boards is another area where problems may arise. The trend to shift components to surface-mount and incorporate more press-fit components forces the use of palettes to protect the board and components from direct contact with the wave. This warrants an investigation into how the physical properties of lead-free alloys affect the palette design. Palette design guidelines for lead-free require a review of wave palette keep out areas, palette thickness, step/entry angle and wall thickness versus palette material selection, usage frequency and maintenance.

In optimizing the wave-solder flux process for lead-free processing, traditional preheat and atmosphere parameters must be revisited. For instance, as industry converts to lead-free alloys, it is possible that the fluxes of choice will shift from alcohol to those free of volatile organic compounds (VOCs). VOC-free fluxes have ramifications for fluxing technology as well as preheating technologies and required temperatures. From these two changes alone, a comprehensive analysis of each part of the process and profile is required. These parameters expose several technology gaps with regards to wave soldering that may only be addressed by converting to alternative soldering technologies, such as selective soldering.

TABLE 1. Technology Forecasts for Wave and Selective Soldering

PARAMETER	METRIC	2003	2005	2007	2009	2015	COMMENTS
Wave solder flux	VOC-free/halogen-free (%/%)	18/19	23/92	27/95	30/95	90/95	
Wave lead-free alloy	Utilization % (other/SAC)	SnPb	50/50	30/70	10/90	10/90	Low melting point alloys exist for various product types
Minimum feasible pitch	Mils	75	60	40	20	16	Selective soldering techniques may provide the alternative technology in PTH layout
Conversion costs – model changeover time	Hours in wave dynamic profiling	4	2	1	0.5	0.5	Drastic reduction once profile library is established
Conventional/selective wave soldering	Utilization % (conventional/selective)	90/10	75/25	60/40	60/40	60/40	
SMT paste in hole/ wave soldering	Utilization %	10/90	30/70	30/70	50/50	50/50	Potential conversion is needed to achieve hole fill for thinner PCBs. Reflow connectors need higher temperature capabilities
Pre-heat process temperature	°C	90-110	140-160	140-160	140-160	140-160	
Wave pot temperature	°C	250-260	260-270	260-270	260-270	260-270	
Environment process	N_2/air	50/50	80/20	80/20	280/20	90/10	

Source: iNEMI Roadmap, 2004

Two Factors

Ultimately, the development of a lead-free soldering process is dictated by two factors:

- **Impact of the various material specifications.** Alloy, flux, board laminate and finish, and component packaging and metallurgy exert specific restrictions on wave soldering that result in an overall window of opportunity. This window defines the process where a proper joint can be successfully formed while maintaining component and board integrity.
- **Flexibility and compatibility of soldering equipment.** Wave-soldering equipment must deliver a precisely controlled process that accommodates the tight material restrictions and also meets the product requirements for throughput. Additionally, the equipment must be compatible with the exposure to more extreme operating conditions and materials.

An in-depth analysis of the lead-free wave soldering process (**FIGURE 1**) illustrates the critical aspects to address in developing and implementing a reliable, robust lead-free process. Process development includes identifying the alloy and composition, flux type, preheating requirements and wave optimization. Also, the changes in materials and process results in increased electrical power demands. A separate but critical aspect is monitoring the alloy composition over time for elemental contamination as well as copper percentage increases. This last issue has significant ramifications for material behavior, process repeatability, equipment compatibility and safety and, ultimately, product defect levels.

The profile is broken into the three processes: fluxing, preheating and soldering. Characterizing the issues with the individual processes is critical to developing an overall repeatable and robust process. Flux selection and flux delivery will significantly influence the ultimate quality. Addressing the transition from alcohol-based fluxes to VOC-free fluxes requires an understanding of the differences in the behavior of the flux material.

The physical properties of isopropyl alcohol (IPA) versus water, **TABLE 2**, will significantly alter the required fluxing and preheating processes. For example, when compared to IPA, water demonstrates a 350% increase in surface tension and a 22% increase in boiling point. This behavioral change impacts the wetting of flux once applied to the assembly. Equally important is preheating the assembly. The use of VOC-free fluxes necessitates the use of higher temperatures equal to or greater than 130°C recorded on the topside laminate.

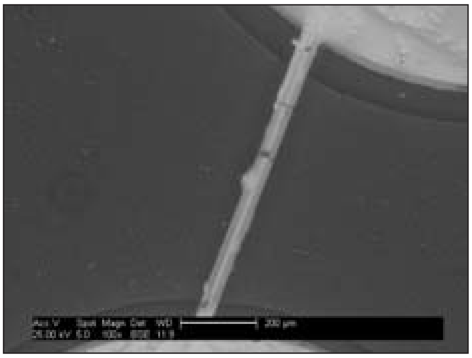

FIGURE 2. A 1 mm $FeSn_2$ bridge between two through-hole leads that formed as a result of iron from the solder pot dissolving and reaching sufficient mass to impact joint formation.

TABLE 2. Physical Properties of Water and IPA Used in Wave-Solder Fluxes

SOLVENT	BOILING POINT (°C)	FREEZING POINT (°C)	SURFACE TENSION AT 25°C (dynes/cm)	SPECIFIC HEAT (cal/gram°C)
Water	100	0	73	1
Isopropyl alcohol	82.3	-87.8	20.8	0.65

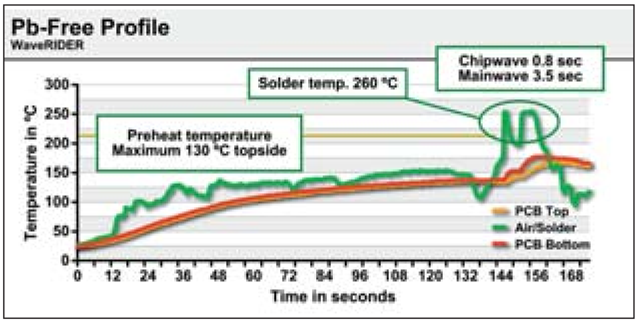

FIGURE 1. The lead-free wave soldering profile developed by the iNEMI Lead-Free Wave Soldering Project.

Depending on the complexity of the board, bottomside temperatures range from 5°C to 30°C more than the topside. Compatibility of the flux and components for this preheating requirement must be evaluated. Simultaneously, the amount of energy required to evaporate all of the water-based flux significantly increases and, as a result, the product may require a decrease in conveyor speed to achieve the target topside temperature. These attributes illustrate the challenges of employing a VOC-free flux in a lead-free process. Use of a palette adds considerable complexity to optimizing the fluxing and preheating processes.

Wave Dynamics

The actual solder interconnect is formed during the contact of the board with liquid solder in the form of single or multiple waves. The wave process itself is critical for the ultimate interconnect quality and yield. Several challenges are associated with achieving a robust and repeatable soldering process:

- Alloy type and composition.
- Operating temperature.
- Dwell time/operating temperature relationship.
- Monitoring the alloy composition.
- Inspection criteria.
- Dross formation and cost.
- Atmosphere and cost.
- Solder pot compatibility with lead-free alloys.
- Power consumption.

Each of these parameters will impact process settings, quality of the soldered assembly and the cost of manufacturing the product.

In defining the operating temperature, dwell time depends on product type and board technology. A product that is characterized as single-sided can generally be processed at relatively low temperatures for lead-free (250 to 260°C), with dwell times of two to five seconds, while double-sided boards requiring visible topside wetting are generally processed at 260 to 265°C with dwell times of three to eight seconds. Some complex boards are being soldered at operating alloy temperatures of 270°C, which require slower conveyor speeds. While this generally addresses the operating alloy temperature, it is critical that each assembly, characterized by its unique thermal mass and component sensitivity, is optimized for a specific time/temperature relationship.

Monitoring the alloy composition for elemental levels as well as contamination is critical to maintaining a stable soldering process. Within the general operating conditions of wave soldering today, it is possible for copper levels to increase to levels in excess of 1.3%. This increase in copper content impacts the melting range as well as potentially forming Cu_6Sn_5 needles. As a result, these changes will impact the process stability and ultimately affect joint formation.

In addition to monitoring the elemental levels, controlling contaminants such as lead or even iron is critical to process control and board quality. Sources for lead contamination are the board finish or component finish. Currently, many lead-free wave processes are being used to solder boards containing a number of lead-finished components. Over time, the lead dissolves into the solder pot, and can increase the percentage of lead as much as 0.5%. Higher percentages are possible, depending on the conditions and materials. This contamination will alter the original alloy by lowering the melting point and extending the melting range, and will result in different alloys/phases present in the solder pot. The addition of lead into SnCu will result in the formation of SnPb. Likewise, the addition of lead into SnAgCu will result in the formation of SnPbAg and then SnPb, depending on concentration of lead.

Lead contamination may change the soldering process and introduce possible joint quality and reliability issues, as have been observed in surface mount joints. Also, this amount of lead may not be acceptable under the RoHS Directive. Removing lead contamination is not possible without changing over the entire balance of the solder pot. In summary, lead contamination has the potential to result in process variability due to alloy changes, possible quality concerns, significantly increased cost in cleaning the solder pot, and environmental violations.

Another element to monitor is iron. The only source of iron is the actual solder pot and its internal parts. Many lead-free alloys containing high tin levels (95% or more) are corrosive in nature and will aggressively react with iron to form $FeSn_2$ intermetallics. This intermetallic takes the form of needles and is characterized by a melting point of approximately 510°C. As a result of the high melting point and increased density compared to SnAgCu, once needles form in the solder pot, the intermetallic will grow over time at the bottom of the solder pot, reaching a critical mass when it can get into the flow into the wave itself.

Iron, as a contaminant, is clearly a safety hazard, impacts the equipment, alters the process and affects board-level reliability. The impact of iron contamination on product reliability is shown in **FIGURE 2**. In this case, iron from the solder pot dissolved and reached a critical mass where it was able to impact joint formation. The result is an $FeSn_2$ intermetallic bridge between joints. Iron contamination must be monitored as closely as lead contamination by understanding the materials used in the solder pot and its protection. Iron contamination, once started, is difficult or impossible to remove. As in the case of lead contamination, cleaning requires complete removal of the contaminated alloy.

Transition to lead-free electronics requires an increased awareness of the controls required to develop a repeatable and robust wave solder process. Phase I of the iNEMI Lead-Free Wave Soldering Project divided wave soldering into separate processes to address issues that are unique to fluxing, preheating and soldering. By addressing these challenges before implementing a lead-free wave soldering process, users will mitigate potential process, cost, reliability and equipment issues.

The information compiled during Phase I regarding the impact of process parameters have on various defects will be used to develop a robust process for the Phase II study. Phase II focuses on the performance of lead-free joints formed by an optimized process for a variety of components as well as board design variations. A test vehicle has been internally and specifically designed for this purpose. Results will be released in a timely fashion. **PCD&M**

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