Implementation Of Successful Lead-Free Soldering Processes

by Dr. Denis Barbini,
Vitronics Soltec

Implementing a Lead-free soldering process presents multiple challenges that must be addressed whether you and your company started early or are just tackling the issue today. Selection of materials and developing a robust soldering process are two critical aspects that will influence the quality of the final electronic product. While the implementation of reflow and the wave soldering process are illustrated in this article, selective soldering processes have equally demanding process restrictions that can only be met with flexible and compatible equipment along with careful material selection.

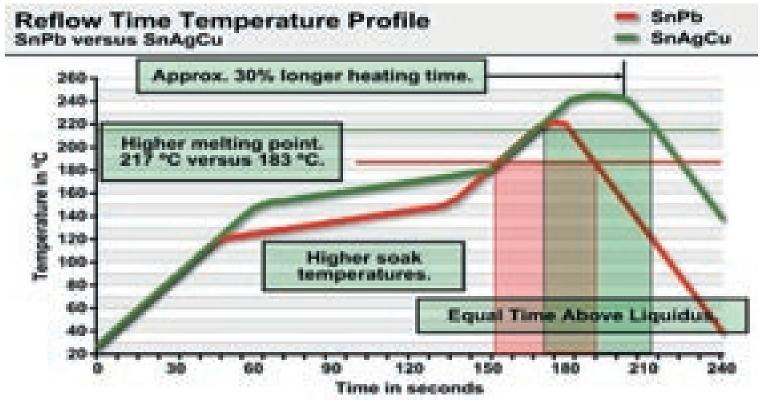


Figure 1 - A Lead-free profile for a BGA and PLCC on a medium-sized board

The implementation of a Lead-free process for any electronic assembly will only be successful when multiple challenges are overcome. These challenges, including supply chain logistics, cost, material selection, and equipment choices/upgrades, require careful planning and organisation. While all aspects are critical, the heart of Lead-free implementation and assembly is found in the soldering process. Understanding the limitations that Lead-free specifications will exert on reflow, wave, and selective soldering processes is critical in developing a robust and reproducible Lead-free process.

Ultimately, the development of a Lead-free soldering process is dictated by two factors.

- The first factor is the characterisation of the impact of the various material specifications. Alloy, flux, board laminate and finish, and component packaging and metallurgy exert individual restrictions on the soldering process 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 as illustrated in Figure 2. More detailed information on the choices and behaviour of the various materials can be found in the "5 Steps to Lead Free" program.

- The second factor is the flexibility and compatibility of the soldering equipment. The various types of soldering equipment, including reflow, wave, and selective, must deliver a precisely controlled process. This process must not only deal with the tight material restrictions but must also meet the throughput requirements. In addition, the equipment must be compatible with the exposure to more extreme operating conditions.

The challenge of optimising a soldering process within the material restrictions by 1 July 2006 has brought much attention to material technology, industry specifications, process development, and process control. This study provides insight to those who are just now tackling the issue of Lead-free implementation.

Regardless of the particular soldering process – reflow, wave, and selective soldering - the technologies developed and employed are designed to deliver soldering processes that are robust, reproducible, and enable the end user to tailor the individual processes to match the material requirements. A closer look at the reflow soldering processes illustrates the critical aspects one must address in developing and implementing a reliable, robust Lead-free process.

Lead-free compatible reflow soldering

Implementation of a Lead-free reflow process requires an understanding of what changes are necessary from the standard eutectic Tin Lead reflow process and how the reflow oven can achieve a compatible process. A typical Lead-free soldering process for a medium-sized board is illustrated in Figure 2. Emphasis is placed upon 4 critical aspects of the reflow process.

1. Preheating: the type of preheating - soak versus straight ramp – exerts an influence on flux behaviour and the optimisation of the relationship between DT and Time Above Liquidous.

2. Peak temperature and TAL: achieving the proper minimum and maximum peak temperature along with an appropriate Time Above Liquidous is necessary in order to maintain component and board integrity and proper joint formation.

3. Cooling rate: with SnAgCu containing alloys, cooling rate exerts influence on the joint microstructure at t_0 as well as bulk solder intermetallics. Faster cooling rates result in a finer, homogeneous microstructure which has been shown to result in stronger joints. Exit temperature is also determined by cooling rate. However, components, solder, and board materials cannot be exposed to excessive cooling rates due to potential damage to these materials.

4. Time: the resulting throughput is determined by the relationship between board size and conveyor speed. Ultimately, throughput is a function of the oven's heated length.

A consequence of the Lead-free transition is an increased awareness in the reflow oven performance. Flexibility, heat transfer capability, accuracy, and precision are critical in tailoring a reflow process that meets all of the specifications necessary to achieve the highest quality possible. From the end user's perspective, a Lead-free compatible oven is defined as the ability of the oven to optimise the preheat, DT, Time Above Liquidous, and cooling rate to fit the process window restrictions while maintaining the cycle time of a Tin Lead process.

Lead-free compatible wave soldering

The implementation of a Lead-free wave soldering process for any electronic assembly will only be successful when multiple challenges are addressed. While the challenges of developing a wave soldering process for the future consist primarily in addressing how the Lead-free transition will alter the conventional Tin Lead process, other technical challenges, as listed in the 2005 NEMI Roadmap for Wave Soldering, will necessitate a comprehensive analysis of where technology gaps exist in wave soldering processes (Table 1).

An additional challenge for the wave soldering process of the future is soldering tighter pitches in plated though hole layouts as the pitch decreases from 60-75 mil down to 16–20 mil. This challenge is made more difficult by the wetting behaviour of Lead-free alloys. The result of this evolution in decreasing pin pitch is determining whether wave soldering technology can deliver defect-free processes or if selective soldering is necessary.

The use of palettes for an ever-greater percentage of boards is also observed. The trend towards shifting more components to surface mount and incorporating more press fit components forces manufacturers to use 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, wall thickness versus palette material selection, usage frequency and maintenance.

In optimising the wave solder flux process for Lead-free, traditional preheat and atmosphere parameters must be revisited. For instance, as one shifts to a Lead-free alloy, it is possible that a conversion from alcohol to VOC-free fluxes takes places. The latter has ramifications on fluxing technology as well as preheating technologies and required temperatures. As a result of 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 an alternative soldering technologies such as selective soldering.

Figure 2 - Typical Lead-free soldering process for a medium-sized board

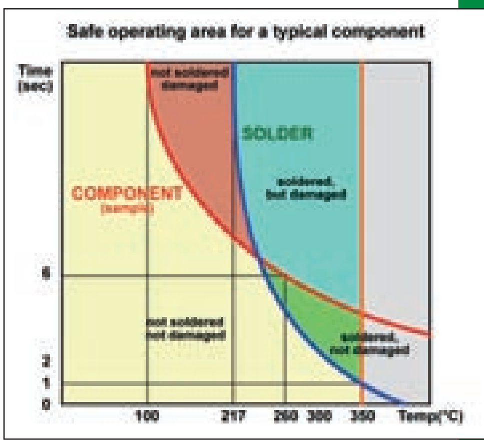


Figure 3 - Lead-free wave soldering profile

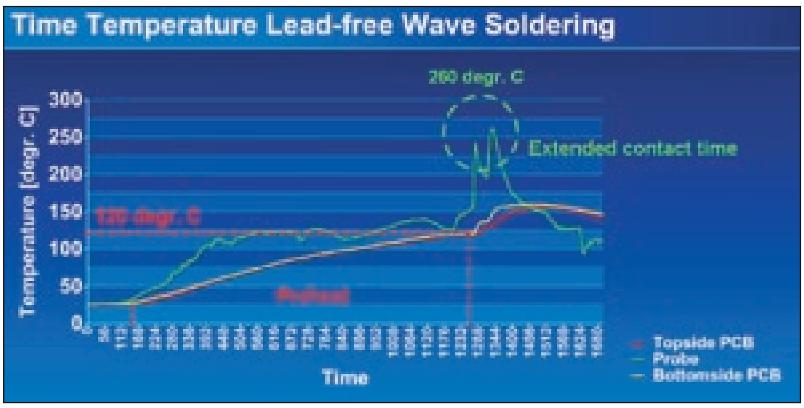
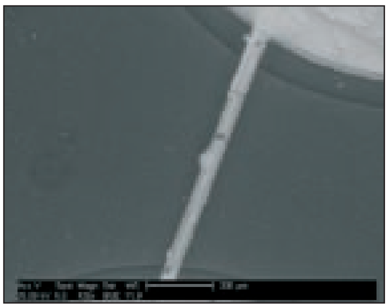


Figure 4 - A 1mm $FeSn_2$ bridge between two through hole leads



Implementing a Lead-free wave soldering process

An in-depth analysis of the Lead-free wave soldering processes, shown in Figure 2, illustrates the critical aspects one must 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 optimisation. The changes in materials and process result in a wave process that also requires increased electrical power demands.

Another critical aspect is the monitoring of the alloy composition over time for elemental contamination as well as Copper percentage increases. This last issue has significant ramifications on material behaviour, process repeatability, equipment compatibility and safety, and ultimately product defect levels.

Parameter	Metric	2003	2005	2007	2009	2015	Comments
Wave Solder Flux	VOC free/Halogen Free (% / %)	18/90	23/92	27/95	30/95	50/95	
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 in PTH layout	mil	75	60	40	20	16	Selective soldering techniques may provide the alternative technology
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 PCB. Reflow connector need higher Temp. capability
Preheat 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	80/20	90/10	

Table 1 - The 2005 NEMI Technology Roadmap for wave soldering

Fluxing and preheating

The profile is broken into the various processes including fluxing, preheating, and soldering. Characterising the issues with the individual processes is critical to developing an overall repeatable and robust Lead-free wave soldering process. In order to achieve this goal for the fluxing process, flux selection and flux delivery will significantly influence the ultimate quality. Addressing the transition to VOC-free fluxes from alcohol based fluxes, and understanding the differences in the behaviour of the flux material are required. The differences in physical properties of isopropyl alcohol and water, as listed in Table 2, significantly alter the required fluxing and preheating processes.

The surface tension of water is 350% greater and the boiling point is 22% greater than that of isopropyl alcohol. This behavioural change impacts the wetting of flux 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 the 120°C recorded on the topside laminate. Depending on the complexity of the board, bottomside temperatures are between 5°C and 30°C higher than on 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 whereby the ability of the preheaters to achieve the required temperatures may require a decrease in conveyor speed. These attributes illustrate the challenges of employing a VOC-free flux in a Lead-free process. The addition of a palette adds considerable complexity to the optimisation of 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 quality and yield of the interconnects. The challenges associated with achieving a robust and repeatable soldering process are listed below:

- Alloy type and composition
- Operating temperature
- Dwell time – operating temperature relationship
- Monitoring the alloy composition
- Inspection criteria
- Dross formation and cost
- Atmosphere and cost
- Solderpot compatibility with Lead-free alloys
- Power consumption

Each parameter listed above impacts the process settings, the quality of the soldered assembly, and the cost associated with manufacturing the product.

The appropriate operating temperature – dwell time relationship is dependent on product type and board technology utilised. A product characterised as single sided can generally be processed at relatively low temperatures for Lead-free - 250°C-260°C with dwell times of 2–5 seconds - while double-sided boards requiring visible topside wetting are generally processed at 260°C - 265°C with dwell times of 3–8 seconds. Some complex boards are soldered at operating alloy temperatures of 270°C, which require slower conveyor speeds. While this generally addresses the issue of operating alloy temperature, it is critical that the time–temperature relationship be optimised for each specific assembly, characterised by a unique thermal mass and component sensitivity.

Monitoring the alloy composition for elemental levels as well as contamination is critical to maintaining a stable soldering process. Analysis of the SnAgCu phase diagram illustrates that any deviation from the original alloy composition will result in a change in the melting behaviour of the alloy.

Within the general operating conditions of wave soldering today, it is possible for Copper levels to increase beyond 1.0 – 1.3%. This increase in Copper content impacts the melting range as well as potentially forming Cu_6Sn_5 needles. 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 either board finish or component finish. Currently, many Lead-free wave processes are soldering boards containing a number of Lead-finished components. Over time, the Lead dissolves into the solder pot and can reach the 0.1% to 0.5% range, although higher percentages are possible depending on the conditions and materials. This contamination will alter the original alloy by lowering the melting point, extend the melting range, and result in different alloys/phases present in the solder pot. The addition of Lead to SnCu will result in the formation of SnPb. Likewise, the addition of Lead to SnAgCu will result in the formation of SnPbAg and then SnPb depending on concentration of Lead. Lead contamination leads to a change in the soldering process and raises possible joint quality/reliability issues as is observed in surface mount joints. Also, note that this Lead level may not be acceptable according to the RoHS directive and that removing Lead contamination is not possible without changing over the entire balance of the solderpot. 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 solderpot, and legislative violations.

Another element to monitor is Iron. The only source of Iron is the actual solderpot and its internal parts. Many Lead-free alloys containing high Tin levels (95%+) are corrosive in nature and will aggressively react with Iron to form $FeSn_2$ intermetallics. This intermetallic takes the form of needles and is characterised by a melting point of approximately 510°C. As a result of the high melting point and increased density compared to SnAgCu, once the needles form, they will continue to grow over time at the bottom of the solderpot until reaching a critical mass when they can get into the wave itself.

Iron, as a contaminant, is clearly a safety hazard, impacts the equipment, alters the process, and affects board level reliability. An example where the Iron contamination impacted the product reliability is shown in Figure 6. In this case, Iron from the solderpot dissolved and reached a critical mass where it was able to impact joint formation. The result is an $FeSn_2$ intermetallic bridge between joints. In summary, Iron contamination must be monitored just as closely as Lead contamination by understanding the materials used in the solder pot and how to protect it. Iron contamination, once started, is difficult if not impossible to remove. As in the case of Lead contamination, cleaning requires complete removal of the contaminated alloy.

Developing a robust process

A consequence of the Lead-free transition is an increased awareness in the controls required to develop a repeatable and robust process. In this study, the entire process was divided into separate processes in order to address specific issues that are unique to fluxing, preheating, and soldering. By addressing these challenges before implementing a Lead-free wave soldering process, the end user will mitigate the potential process, cost, reliability, and equipment issues.

Table 2 - Physical properties of selected solvents used in wave soldering fluxes

Solvent	Boiling Point	Freezing Point	Surface Tension at 25°C	Specific Heat
	(°C)	(°C)	(dynes/cm)	(°C)
Water	100	0	73	1
Isopropyl Alcohol	82.3	-87.8	20.8	0.65