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Optimization of Lead-Free Soldering Processes for Volume Manufacturing

Dongkai Shangguan, Ph.D.
Flextronics International
San Jose, CA

Abstract
In this paper, a comprehensive review is provided on the optimization of soldering processes (including reflow, wave soldering, and rework), for different component types, different PCB sizes and finishes, and in different soldering atmospheres (air and nitrogen). The impact of key process parameters on the process yield is discussed in comparison with the Sn-Pb soldering process, and methodologies for optimizing the lead-free soldering processes are outlined. Component compatibility issues are also discussed.

Introduction
As the worldwide electronics industry transitions to lead-free soldering, process optimization for volume manufacturing becomes a very important issue, as it relates directly to yield, quality and reliability, and total cost. The optimization of soldering processes (including reflow, wave soldering, and rework), for different component types, different PCB sizes and finishes, and in different soldering atmospheres (air and nitrogen), needs to be studied to understand the impact of key process parameters on the process yield, in comparison with the Sn-Pb soldering process. Process optimization methodologies and component compatibility are important issues.

Over the past few years, a significant amount of work has been carried out on the materials evaluation and process optimization for lead-free soldering, which has enabled the volume production of various products with lead-free solders, with satisfactory results.

Soldering Materials
In general, different variations of the Sn-Ag-Cu alloy (SAC), with Ag content from 3.0% to 4.0%, are all acceptable compositions for lead-free soldering (including reflow and wave soldering). Recent studies by IPC, solder suppliers and EMS companies have concluded that there is no significant difference in the process performance among these different variations of the alloy composition; Efforts to standardize the alloy composition will be based on the reliability performance, from accelerated reliability tests currently on-going.

The Sn-Cu alloy has generally been found to be inferior to SAC in terms of wettability, dross formation, and reliability under typical loading conditions; however, its much lower cost as compared with SAC makes it an attractive alternative alloy for wave soldering, especially for cost sensitive products. Even though most manufacturers may prefer to use the same alloy for all of the solder interconnects on the entire board (including reflow and wave soldering), there are products in volume production today which use SAC for reflow and Sn-Cu for wave soldering on the same board; as such, methods for inspection, rework, and accelerated testing must be compatible for both alloys. Several variants of the Sn-Cu alloy have also been introduced, including silver (Ag), nickel (Ni), and other elements as alloying additions.

Earlier attempts to simply mix the no-clean flux (developed for Sn-Pb) with the lead-free solder alloy yielded miserable results. The no-clean flux must be re-formulated for the lead-free alloy in order to accommodate its unique characteristics. The chemical reaction between the flux and the solder alloy in the paste affect the rheological characteristics of the solder paste. The difference in the density between the lead-free solder alloy and the Sn-Pb alloy means that the metal loading of the solder paste needs to be different. The higher soldering temperature needed for the lead-free solder requires greater stability of the flux at higher temperatures. The performance of the flux residues after reflow, in terms of ICT probe-ability and electromigration, is also an important consideration. Similarly, no-clean and VOC-free fluxes need to be formulated specifically for lead-free wave soldering. Water-soluble fluxes for lead-free solder paste and wave soldering applications will also be needed for certain applications.

Printing Process Optimization
For SMT and reflow, in terms of printability, tack, slump, and solder balling, there is no clear and consistent difference between Sn-Pb and lead-free solder pastes, because these performances depend on the solder paste formulation, not directly on the solder alloy. Very clear and consistent differences have been observed, however, in wettability between Sn-Pb and lead-free solder pastes; In general, the wettability of lead-free solder paste is not as good as Sn-Pb solder paste. For example, lead-free solder paste exhibits very limited spreading on OSP during reflow, and exposed corners after reflow are quite common, unless overprint or round corner pads are used.

The difference in wettability between OSP and ENIG surface finishes, which is already evident for Sn-Pb solders, becomes even more pronounced for lead-free solders. This has been observed with a variety of solder paste and flux formulations from a number of vendors.

Solderability of PCB Surface Finishes

Lead-free HASL, using lead-free solder alloys (such as Sn-Cu) in place of Sn-Pb, is commercially available. The search for alternatives to HASL (hot air solder leveling) has been on-going for several years, primarily because of the inherent inconsistency in the quality of the HASL finish. For example, the thickness (and therefore solderability) of HASL is difficult to control; In areas with a very thin layer of HASL, consumption of Sn by the formation of Sn-Cu intermetallics will render the areas non-wettable. The HASL finish is typically non-flat (with a dome shape), making it difficult to deposit a consistent amount of solder paste during solder paste printing and difficult to place fine pitch (<25mil) devices.

OSP (organic solderability preservative), a finish which provides a flat pad surface, has also been in use for many years. Both OSP and HASL are relatively low cost alternatives as compared with the other finishes. Board storage and handling, as well as solderability degradation through multiple soldering processes, are some of the drawbacks for OSP. Electroless nickel and immersion gold (ENIG, or Ni/Au) provides good solderability and contact/switch interfaces for most applications, as well as bondability with aluminum wires; however, tight plating process control is necessary in order to prevent the occurrence of catastrophic “black pad” failures. For higher end applications, electrolytic Ni and Au (more expensive than ENIG) provides a more reliable surface finish; Care must be taken to limit the thickness of Au, as too much Au dissolved in the solder joint may cause “Au embrittlement”, while noting that the Sn-Ag-Cu alloy is less sensitive to Au embrittlement than the Sn-Pb alloy. Use of the electrolytic Ni-Au may also be constrained by the layout and available “real estate” of the board. Another consideration for the Ni-Au finish is that the interface between the Sn and the Ni layer is in general more brittle than joints between Sn and Cu (which is formed for Sn-based solders on boards with OSP and immersion silver finishes); This is an particularly important consideration for products (such as handheld devices) for which dynamic mechanical reliability (such as drop) is important.

Immersion silver (I-Ag) is a more recent and less costly alternative. The immersion process is a self-limiting process and can only provide a very thin layer of coating (several hundred atomic layers). The solderability, ICT probe-ability, aluminum wire bondability, and contact/switch pad performance of I-Ag are not as good as Ni/Au, but are adequate for most applications. For I-Ag, the exact chemistry, thickness, surface topography, as well as the distribution of organic constituents within the Ag layer, must be carefully selected and specified. XRF (X-ray fluorescence) is the technique often used to monitor the thickness of the surface finish for process control purposes; careful calibration of the XRF instrument is very critical, especially for I-Ag. Handling and storage also need to be carefully controlled for I-Ag.

In terms of solderability for lead-free soldering, immersion tin (I-Sn) and ENIG surface finishes provide the best wetting results on fresh boards, followed by I-Ag and OSP. However, after storage and heat exposures, the wetting of the I-Sn finish degrades the fastest, with less wetting degradation for the I-Ag and OSP finishes, while the wetting of the ENIG finish remains excellent through various pre-conditionings treatments and heat exposures. Fresh I-Ag boards can withstand up to four lead-free reflow cycles before the final reflow soldering process, and at least two reflow cycles before the wave soldering process, whereas I-Sn finished boards cannot withstand multiple lead-free reflow cycles or a reflow cycle prior to wave soldering process without significant degradation in wetting, unless the I-Sn thickness is significantly increased.

The impact of different surface finishes on the press fit connectors is another factor to be considered when selecting PCB surface finishes for products such as backplanes. The plastic deformation of the Sn plating, the hardness of the surface finishes, along with the dimensional tolerances of the pin and through-holes, the design of the connector pins (and their mechanical compliance), and the mechanical properties of the PCB, all affect the insertion force required (and consequently the retention force) for the press fit connectors.

Reflow

The key parameter for the reflow profile is the peak temperature. Adequate reflow temperature is needed for the solder to melt, flow and wet, interact with the Cu on the pad and the component termination, and form sound intermetallic bond when cooled and solidified. Typically, 30^{o}C superheat (above the melting temperature) is desired. For lead-free soldering, because of concerns about the thermal stability of the components, efforts are needed to minimize the soldering temperature. For SAC alloy with the eutectic temperature at 217^{o}C, the minimum reflow peak temperature should be 235^{o}C for large volume manufacturing, taking into account process robustness, yield, variety of component finishes, oven thermal stability and tolerance, etc. The dwell time (or time above liquidus, TAL) is typically 40-90 seconds. The reflow profile may be straight ramp, or with a pre-heat plateau for the purpose of homogenizing the temperature distribution across the board.

Lead-free reflow may be done in air or N_2. Typically N_2 is not required, and the use of N_2 may even increase certain defects (such as tomb-stoning) especially for small passive components (such as 0201). In certain situations, N_2 may help improve wetting (which in turn may help reduce the amount of voids in the solder joints). For flip chip applications, where flux is used instead of solder paste, N_2 becomes necessary to form reliable solder interconnects. A N_2 atmosphere with O_2 level below 1000 ppm has been found to be effective. N_2 may also be needed if the solder paste deposit volume is very small (such as for 01005) and most of the solder alloy particles are exposed to the atmosphere.

Reflow profile development to minimize the temperature delta across the board, especially for large complex boards, is another important issue. The conveyor speed, board orientation and zone settings are important parameters; For example, slower conveyor speed and having the short side of the board parallel to the conveyor help reduce the temperature delta.

Component fall-off during the second reflow process has been studied as a function of component weight and solder surface tension and contact area. The component weight to contact/pad area ratio has been found to be slightly higher for eutectic Sn-Pb than SAC; however, the difference has been found to be statistically insignificant. Therefore, the same "rule of thumb" (g/in^2) can be used.

Wave Soldering

For wave soldering with lead-free solder, a higher solder pot temperature, typically 255-265^oC, will be required. Flux application (spray, foaming, etc) and amount, and preheat temperature and time, must be optimized for each particular flux. A longer pre-heat may be needed in order to keep the thermal shock (difference between the preheat and peak temperatures) below 100^oC to protect ceramic components (especially ceramic chip capacitors). Dual wave soldering, already popular for Sn-Pb soldering, will still be used for lead-free, and inert (N_2) atmosphere may be used to improve yield, for example, by reducing bridging and improving wetting and hole filling.

The amounts of dross formed with SAC and Sn-Pb solders have been found to be very similar, at the same temperature, for the same duration, and under the same atmosphere, while the Sn-Cu solder forms considerably more dross. Just as with the Sn-Pb solder, N_2 helps reduce dross formation for lead-free solders.

As with reflow, wetting with the lead-free solder is generally not as good as with the Sn-Pb solder for wave soldering, leading to reduced hole filling. However, the overall influences of other process parameters, such as conveyor speed, dwell time and contact length, component orientation and soldering direction (parallel or perpendicular), etc., on the yield and quality for wave soldering, are generally similar for lead-free and Sn-Pb solders. For example, increasing the conveyor speed (i.e. reducing the contact time) helps to reduce solder balls and bridging, but may reduce hole filling at the same time. The use of "thieving pads" can effectively reduce bridging for SMD (surface mount device) components, for both Sn-Pb and lead-free solders.

For lead-free wave soldering, the chemical composition of the molten solder in the pot needs to be closely monitored, especially for Pb and Cu, due to the metal dissolution from the component leads and the PCB surface into the molten solder. For the Sn-Cu solder, the liquidus temperature will change by as much as 6^oC when the Cu composition changes by 0.2%; Such a change may cause significant change in the wave dynamics and the soldering quality (such as bridging). The buildup of Cu in the molten solder can also cause sluggishness of the solder, disturbing the wave dynamics, because the density of the Cu-Sn intermetallics, or IMC, which is 8.3 g/cm^3, is greater than that of the SAC (7.4 g/cm^3) and Sn-Cu solder (7.3 g/cm^3), causing the IMC dispersion in the molten solder, as compared with that of the Sn-Pb solder (8.7), where the IMC tends to float and can therefore be more easily removed.

Rework

Rework for lead-free solders has been found to be more difficult, because the lead-free solder alloys typically do not wet or wick as easily as the Sn-Pb solder due to their difference in wettability; This can be easily seen with QFPs. In spite of these differences, successful rework methods have been developed with lead-free solders (Sn-Ag-Cu, or Sn-Ag), for many different types of components. Most of the rework equipment for Sn-Pb can still be used for the lead-free solder. For area array packages, it is helpful to use a rework system with split vision and temperature profiling features. The soldering parameters must be adjusted to accommodate the higher melting temperature and less wettability of the lead-free solder. The other precautions for Sn-Pb rework (such as board baking) still apply to lead-free rework.

Studies have shown that reliable lead-free solder joints, with proper grain structures and intermetallics formation, can be produced using appropriate rework processes. Care must be taken to minimize any potential negative impact of the rework process on the reliability of the components and the PCB. Surface insulation resistance (SIR) tests must be performed to ensure the compatibility between the reflow/wave solder flux and the rework flux, i.e. to ensure that the rework flux and any products of reaction between the reflow/wave solder flux and the rework flux do not pose any unacceptable risk for electromigration and dendritic growth for no-clean applications.

The issue of "component mixing" or cross-contamination warrants special concern, especially during the industry-wide transition to lead-free. If a Sn-Pb solder board is to be repaired (for example for warranty repair at some future time) with the lead-free solder, from the solder point of view, the reliability of homogeneously mixed lead-free solder and Sn-Pb solder is probably no inferior to the Sn-Pb solder in most cases; However, the temperature impact on the components (especially plastics package parts) would be a concern. Careful consideration must be given to the use of area array packages with lead-free balls to repair a Sn-Pb solder board; In this case, if the temperature is not high enough, reliability concerns may arise.

Quality

It is generally accepted that the IPC 610 standards are still valid for lead-free solder PCB assembly, and work is currently on-going to update the IPC 610 standards for lead-free solders to accommodate the differences. For example, operator and AOI (automatic optical inspection) training is needed for lead-free solder because of the different appearance of the solder joints. The lead-free solder joints are generally more dull and grainy, and less shiny, than the Sn-Pb solder joints. This difference in appearance is determined by the metallurgy of the solder alloys and is generally not a reflection of the workmanship. Whereas the Sn-Pb solder solidifies as a typical eutectic microstructure, the SAC alloy, even though it is a ternary eutectic alloy, solidifies as an off-eutectic microstructure, under typical soldering conditions, due to non-equilibrium solidification. Sn dendrites, which are formed as a result of the non-equilibrium solidification, create the grainy and dull appearance of lead-free solder joints. The issue of "hot tearing", associated with dendritic solidification and shrinkage leading to surface cracks, is another issue under discussion.

Even though the types of defects for lead-free solders are the same as for Sn-Pb, lead-free solder has generally been found to generate more defects of voiding, tomb-stoning, solder beading, bridging, and misalignment, and it takes considerable efforts to achieve the same yield for lead-free solder as for Sn-Pb solder, especially for wave soldering. This is believed to be related to the inferior wettability of the lead-free solder and the consequently reduced wetting force. For example, self-alignment (or self-centering) has been found to be less with the lead-free solder than with the Sn/Pb solder; This is more pronounced with passive components than with area array packages. Therefore, process optimization is critical for volume manufacturing with lead-free solder.

Component Compatibility

Assuming that the components can meet the temperature requirements as discussed above, Sn and Ni/Pd/Au platings are generally considered to be "forward compatible" with the lead-free solder, as well as "backward compatible" with the Sn-Pb solder. The backward compatibility of area array packages (such as CSPs and BGAs with SAC balls) with the Sn-Pb solder, however, is very much questionable. This is primarily due to the fact that the SAC alloy, with a melting temperature of 217^{o}C, will not always completely melt during reflow with the Sn-Pb solder, typically at reflow peak temperatures between 205-225^{o}C (or even as low as 200^{o}C in extreme cases). As such, there will be little or no self-alignment, which is critical especially for finer pitch area array packages, with coplanarity issues further aggravating the situation due to the lack of collapse. Further, very little mixing takes place leading to grossly segregated microstructures. Poor interfacial bonding and increased voids are some of the issues which have been observed, which, in combination with the process issues, render the SAC balled area array packages "incompatible" with the Sn-Pb solder. When the reflow temperature is high enough (>225^{o}C, or preferably >235^{o}C) and self-alignment does occur, mixing takes place between the SAC and Sn-Pb, and the reliability of the interconnect using Sn-Pb solder paste and SAC balls is no inferior to that using Sn-Pb solder paste and Sn-Pb balls, for area array packages. Such a scenario may be technically feasible, but may present nightmares for operations and logistics on the factory floor. As such, area array packages (such as CSPs and BGAs) with SAC balls are considered to be "backward incompatible" with the Sn-Pb solder.

Case Studies

Lead-free soldering processes have recently been developed for various advanced packages, including 0201, 01005, flip chip, CSP, BGA, CCGA, pin-in-paste (PIP), package stacking, etc. 0201 assembly processes have been developed through a systematic study, including pad design, pick-place equipment evaluation, component qualification, and process optimization, and the overall yield is slightly lower for the lead-free solder as compared with the Sn/Pb solder, for reflow in air. The overall process for 01005 is similar to 0201, and it is possible to feed 01005 components on Tape & Reel. Reflow soldering for 01005 may require nitrogen, due to the small size of the solder deposits, to protect the activity of the flux; Further work is underway to optimize the process for reflow in air.

Lead-free solder flip chip assembly on FR-4 has been demonstrated to be feasible both on ENIG and OSP surface finishes with reflow in nitrogen. The self-alignment properties with Sn-Ag-Cu is the same as or similar to Sn-Pb, and the different surface finishes (ENIG and OSP) showed no difference with both showing self-centering with mis-placement up to 50% off pad. Dip fluxing and flux jetting are two feasible fluxing methods for Sn-Ag-Cu flip chips.

Lead-free, Sn/A4.0g/0.5Cu balled, 0.4mm pitch CSP components on Sn/3.9Ag/0.6Cu solder paste, placed up to ~50% off-pad, can self-align to the pad after reflow in air. By considering the PCB pad size/location tolerances and solder paste alignment tolerances, the required alignment accuracy for the pick & place equipment was calculated to be ±50μm @3σ.

Package stacking, or package-on-package (POP), has been developed for Sn-Pb and SAC. In this process, two (or more) CSPs, each may contain one or multiple dice, are stacked together using the pick-place machine, and only a single reflow (along with the rest of the SMDs on the board) is needed for the SMT process. This can be done on either or both sides of the board.

With the lead-free solder, large CCGA devices could self-align to the pad while placed up to 25% off the pad. The main concerns are with the thermal profiling for reflow and rework, and the impact of the temperature on the surrounding components.

For PIP, various PCB variables, stencil apertures, solder paste printing methods and parameters, and component types and insertion methods, have been evaluated for both Sn/Pb and lead-free solders, as an alternative to wave soldering. PCBs with thicknesses of 1.0mm & 1.6mm, with both ENIG and OSP surface finishes, have been tested successfully using metal squeegees.

Summary

Due to the inherently inferior wettability of the lead-free solder as compared with the Sn-Pb solder, lead-free solder has generally been found to generate more defects of voiding, tomb-stoning, solder beading, bridging, and misalignment. It takes considerable efforts to achieve the same yield for lead-free solder as for Sn-Pb solder, especially for wave soldering. Therefore, process optimization is critical for volume manufacturing with lead-free solder. In this paper, a comprehensive review has been provided on the optimization of soldering processes (including reflow, wave soldering, and rework), for different component types, different PCB finishes, and in different soldering atmospheres (air and nitrogen). The impact of key process parameters on the process yield is discussed in comparison with the Sn-Pb soldering process, and component compatibility issues have also been discussed. Case studies have been presented including 0201, 01005, flip chip, CSP, BGA, CCGA, pin-in-paste (PIP), package stacking, etc. Component fall-off during the second reflow has also been discussed.

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