Lead-free Wave Soldering

Some Insight on How to Develop a Process that Works

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As lead-free gains momentum, many engineers are striving to set-up a wave solder process that maintains production yields but also offer reliable assemblies. Much has been written on these topics in the past 5 years. Less confusion does exist today about alloy choices available to replace leaded solders, however many are struggling with their successful implementation.

Once the lead-free alloy is selected, a solid understanding of its chemical and physical properties is required to enable reliable soldering. But this is only part of the story since a strong relationship must be developed with component, board, chemistry and equipment suppliers. These relationships are essential and each supplier must understand the needs of the assembler to adequately recommend the material, equipment and chemistry changes to achieve the end result-reliable lead-free electronics.

This article examines the key elements in establishing a reliable wave operation and tries to answer the following question in some depth.

What are the key process requirements to achieve reliable lead-free wave soldering?

Lead-free wave soldering can be achieved reliably and is being done in a large scale in Asia now for some time. Lead-free wave can be more demanding to implement as a lead-free process, when compared to SMT and hand soldering operations. A solid understanding of the various principles of wave soldering will go a long way in reducing its implementation time but also insure reliable through-hole joints with a limited loss of production output.

With traditional leaded wave soldering the use of 63/37 solder with its relatively low surface tension, tinned or tin-lead coated components and the use of well developed fluxes, wave soldering had become quite unchallenging. This is no longer the case; with lead-free solders the need to revisit the basic principles of soldering is required.

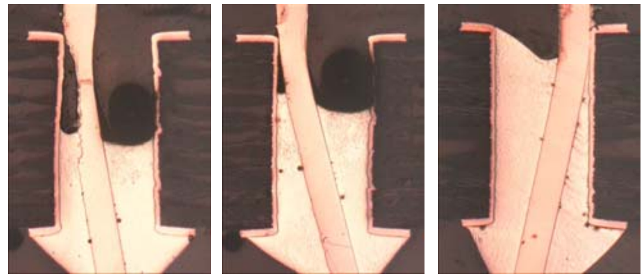
The wave soldering equipment will have to be lead-free compatible. Due to the higher tin content of lead-free alloys such as tin-silver-copper, the leaching of iron can be an issue, which may require the solder pot, impeller and ducts to be replaced with materials, which prevent dissolution. This can be a capital expenditure ranging from a cost of $15,000 to $25,000 or more depending on pot size and features.

In transitioning to lead-free wave soldering, alloy selection will be the primary choice that will impact solder joint quality, reliability and production yields. Most assemblers are choosing tin-silver-copper alloys (SAC) for leaded solder replacement. On a global basis Sn96.5 Ag3.0 Cu0.5 has been the favored solder recipe. This alloy also known as SAC305 has melting range of 217-220 °C; the traditional alloy 63/37 has a melting point of 183°C. These alloys have higher melting temperatures but also have higher surface tensions.

Some manufacturers are choosing Sn/Cu alloys such as 99.3 tin/ 0.7 lead, some with small additions of nickel, silver, bismuth, germanium, and other elements. Due to the lack of silver in these alloys, their cost is substantially less than SAC alloys.

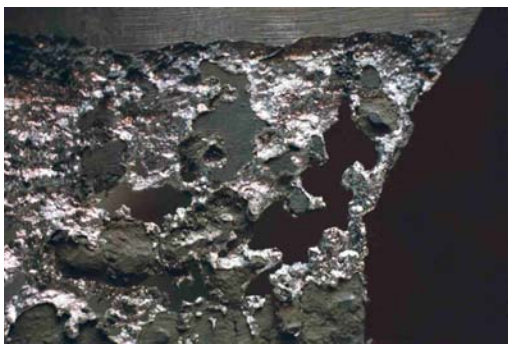
The Sn/Cu alloys melt at 227°C but wetting balance tests done with a variety of surfaces such as Ag/Imm, Gold/Nickel, and bare copper OSP indicate that Sn/Cu based alloys give reduced wetting forces. In production this will translate into longer contact times at the wave solder to achieve hole-fill. The melting temperature being higher will also require slightly hotter pot temperatures. SAC alloys can be run at 255-260°C; Sn/Cu will require 260-270°C. In some cases some assemblers are using as high as 275°C for Tin-Copper based solders. These higher temperatures may put a strain on both board and bottom-side component reliability.

Solder pot temperature will play a role in hole-fill as temperature is increased. The photos to the right, indicate the degree of hole-fill as solder temperature increases from 240, 250 to 260°C using SAC solder.



Materials compatible with higher tin solders are nitrided steel, titanium, cast iron or ceramic coatings. It is recommended to call the manufacturer of the solder wave machine for lead-free compatible parts and equipment; availability of replacement parts may be an issue; this may be the case with older units. Cast iron is often used in smaller dipping pots and this will not be largely affected by high tin solder alloys.

The pictures below show typical erosion of iron from a stainless steel solder pot assembly. The iron dissolves into the lead-free solder and forms crystals of Iron-Tin, this increases viscosity and may interfere with solder flow.



Iron erosion of stainless steel pot material

Wave pot assembly erosion

Flux selection will be a critical step to lead-free wave soldering. The flux activity and thermal stability will have to be optimized by the flux manufacturer as to keep defects very low while giving adequate hole-fill. With lead-free solders with higher surface tension and slower wetting properties when compared to 63/37, flux will play an important role. Most fluxes designed originally for 63/37 systems will not give adequate hole-fill with lead-free without increasing the flux volumes applied or using longer contact times. Fluxes designed for leaded (63/37) systems may work, but conveyor speeds may have to be reduced substantially, impacting production output.

Typical wave fluxes for lead-free wave soldering will have the following characteristics:

- Thermal stability at higher pot temperatures
- Stable activity at higher preheats up to 130°C.
- Sustained activity to enable longer solder contact times
- Resins that do not discolor at higher temperatures
- Ingredients that remain water washable, if applicable, after higher temperature exposure
- Higher acid value numbers and solids percentage for thicker board assembly

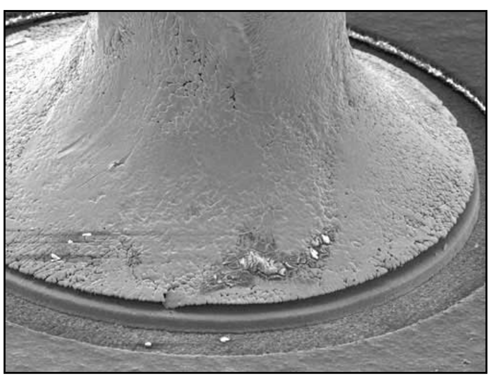
It has been demonstrated that liquid fluxes with higher activity and higher solids content perform better with lead-free solders. Water washable fluxes, with flux residues developed to be cleaned in water after soldering, contain higher levels of activators and more aggressive ingredients. They have been proven to give the best hole-fill with lead-free including more difficult surfaces such as bare copper OSP. The activators are potentially corrosive but they remove all oxides adequately even with the longer contact times and hotter soldering temperatures used with lead-free. Because activators in these fluxes are usually in excess there are enough active ingredients to keep the surface oxides to a minimum, reducing the surface tension of lead-free to its lowest value, insuring good wetting and hole-fill.

However, new formulations of no-clean liquid fluxes, specifically designed for lead-free also work well. These new no-cleans have enhanced activator packages designed to be thermally stable at higher preheat and pot temperatures. They can sustain slightly longer contact times with the solder and the activity is still present as boards emerge from the wave, reducing bridging but also promoting better hole-fill. This characteristic of the flux is also called sustained activity.

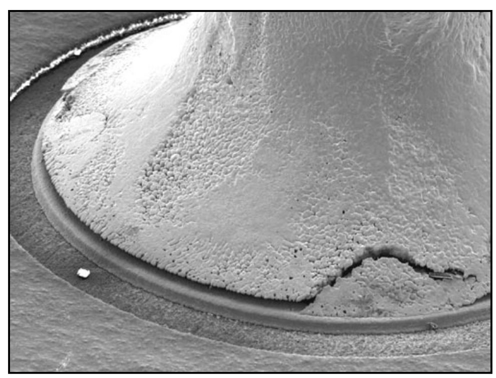
The trend in wave soldering around the world is the use of VOC-free fluxes in conjunction with lead-free solders. This offers a completely “green” wave solder operation. VOC-free fluxes do perform well with lead-free and higher solids in the range of 4% or higher are best. Of course, spray flux applicators and convection heaters are ideal for these water-based fluxes. With these materials proper preheat conditions Is essential to remove moisture prior to wave entry. It is important to ask yourself the question: Is my preheat going to be sufficient?

Board and component finish selection is another selection parameter, which can impact reliability and production output. Component finishes containing lead or bismuth can cause fillet lifting. Most component leads are available in pure tin format with a nickel barrier over copper. This is done to prevent tin whisker growth. Tin is a very easy metal finish to solder to, and has a reasonable shelf life if stored under controlled conditions.

Also the European RoHS Directive specifies a 0.1% lead maximum limit in the solder joint. Lead-bearing terminations will increase the lead(Pb) loading in the solder pot, resulting in RoHS non-compliance issues. Once the lead exceeds the limit of 0.1% the only way to reduce it is to dilute the solder with fresh solder, this is costly, time consuming and hazardous.



Fillet lifting, photo from Bob Willis



Fillet lifting with cracking, photo from Bob Willis

Boards finishes of matte tin will give the best soldering results. However gold over nickel finishes and immersion silver will also solder well. Bare copper OSP with the use of no-clean fluxes gives the lowest wetting values during wetting balance tests. Bare copper boards with thicknesses in excess of 0.093 inches, is prove difficult to solder with lead-free solders. Although more difficult, the soldering of thicker boards is not impossible, but may require modifying wave process parameters or the flux chemistry to obtain the desired hole-fill.

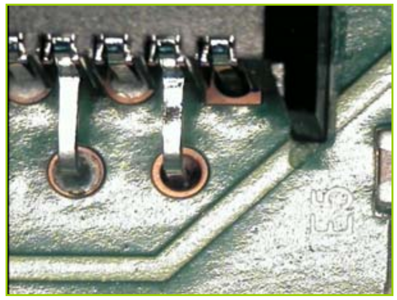
In the soldering of bare copper OSP with lead-free alloys such as SnAgCu or Sn/Cu the following can be tried to improve hole-fill.

- **Reduce conveyor speed, to increase solder contact time**
- **Increase flux volume applied, reduce air knife pressure**
- **Use more active flux systems such as water washables or higher solids no-clean fluxes**
- **Increase solder pump rpm’s to push molten solder higher into the barrel**
- **Increase solder pot temperature by 5-10°C**
- **Use fluxes with higher solids content, higher acid value number (mg KOH/Gram of flux)**

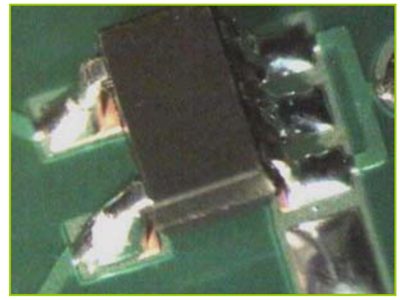
Many of the above points can be applied in situations where hole-fill is not adequate. They apply to lead-free and leaded wave systems also.

The main concern with lead-free wave soldering is the potential increase in soldering defects. The following defects can see increases in a poorly optimized lead-free wave process.

- **Non-wetting**
- **Insufficient solder**
- **De-wetting**
- **Icicling**
- **Cold solder joints**
- **Grainy joints**
- **Blow holes**
- **Solder balls**
- **Fillet lifting**



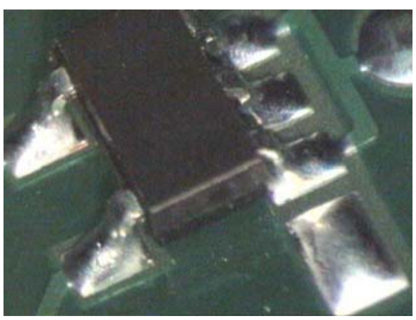
Insufficient hole-fill



Exposed copper on bottom-side SMD

The most common defects that occur are insufficient solder, skips, a lack of hole-fill and grainy joints. These defects are due to a variety of issues but with lead-free alloys and their reduced wetting potential, coupled with higher pot temperatures, the flux selection will make the most difference in reducing their occurrence. If the problem persists, slowing down the conveyor speed to increase solder contact will increase hole-fill.

The use of nitrogen at the solder pot area will reduce oxide creation but also increase solder wetting. Nitrogen reduces oxide formation on board and components and with the reduced wetting behavior of lead-free solders this can be an advantage. This is even more so if no-clean fluxes are used.



Nitrogen used at solder pot

The photo on the left shows the impact of nitrogen on the same component seen above using nitrogen blanketing at the wave solder. While the above photo shows exposed copper around the soldered leads during bottom-side assembly, exposed copper is not observed when nitrogen is used.

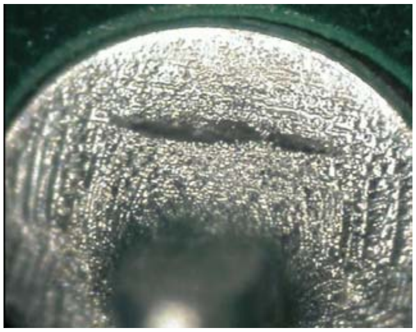
Nitrogen would be beneficial especially to bare copper assemblies, which will have seen multiple heating cycles prior to wave soldering. Nitrogen will also reduce bridging and icicling. Thicker boards will also benefit with better hole-fill.

Below are photos showing good soldering of bottom-side SMD’s and another photo showing the effects of icicling using lead-free solders. Icicling has a higher tendency to occur since the surface energy of lead-free solders such as SAC and SnCu based alloys is higher. To avoid this insure the flux has good sustained activity and therefore flux is still present at the exiting point of the board as to offer a good peel back of the solder. This defect is more common with low residue no-clean fluxes.

Well soldered SMD bottom-side

Icicling of SMD using No-clean ROLO Flux

The IPC-610D Section 5, shows a variety of photographs of good lead-free joints and also several soldering anomalies. One worth a mention is the Hot Tear/ Shrink Hole. This shrinkage effect will be noticed on wave-soldered joints but also on some hand-soldered joints. These surface shrinkage effects are not considered a defect.



The photo on the left shows the heat tearing effect of tin-silver-copper solder after the wave operation. This tearing effect will not occur on all joints but does occur with all tin-rich solders. It is caused by the rapid cooling of the solder phases incorporating the solder joint. It is not seen in 63/37 joints.

Further work is ongoing to determine the impact of these tears after extensive thermal cycling conditions. At this time they are not considered to be a problem for reliability. The wave solder project presently in the build-stages through iNEMI will further examine this effect and a report is due this year.

Optimizing the Wave Solder for Lead-free

Taking all these points in consideration, how does an engineer optimize his wave solder machine? What are the steps to take to achieve reliable lead-free through-hole joints?

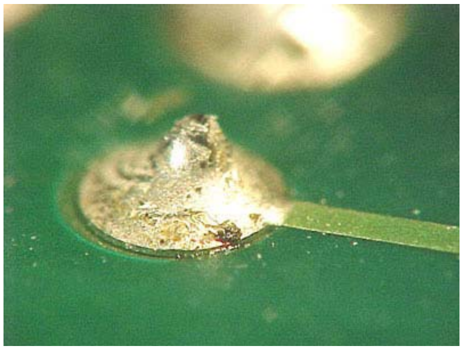
The process can be summarized as follows:

- ❑ **Make the equipment lead-free compatible, talk to the supplier**
- ❑ **Identify lead-free components and boards, work closely with parts suppliers**
- ❑ **Select a lead-free solder, SAC305 or Sn/Cu or other compatible choices**
- ❑ **Choose the flux chemistry, VOC-free flux preferred, designed for lead-free**
- ❑ **Run a design of experiment**
- ❑ **Determine best set of parameters to achieve maximum wetting and hole-fill**
- ❑ **Set up a lead-free wave, define the process, and statistical limits**
- ❑ **Insure lead-free materials are segregated from leaded materials**
- ❑ **Set up compatible hand-soldering and rework processes**
- ❑ **Train all wave personnel on the new process, and quality acceptance criteria**

Of these points, the determination of lead-free components and their subsequent identification on the assembly line will require the greatest amount of time. Most components are available with lead-free finishes as are circuit cards, in some cases they are not. Working with component suppliers to obtain parts that are lead-free compatible can take months.

Alloy selection and temperature will impact solderability of various finishes and is the single most important parameter to determine. Temperature excesses should be avoided for reasons described previously but also to avoid excess intermetallic growth and dissolution of termination base metals.

Lower solder pot temperature



Higher temperature pot 275°C

If the equipment is lead-free ready, the next selection should be flux type, working closely with chemistry suppliers; obtaining solderability data on the flux and how it performs with your specific alloy choice on different finishes. Lead-free solder spread on various metal finishes will give the engineer an indication of what can be expected in process in reference to the soldering of different board finishes.

During the initial design of experiment, the following process parameters should be determined:

- **Solder alloy**
- **Solder temperature**
- **Flux type**
- **Flux volume; the use of air knife or not**
- **Preheat requirements**
- **Nitrogen inerting of the pot or not**
- **Conveyor speed and contact time**
- **Minimum hole-fill requirement**
- **Residue compatibility with ICT, if no-clean**
- **Cleaning process parameters, if water washable**

In some cases flux residues tend to polymerize into a harder crystalline material, which can impact probe-testing but also the clean-ability of the residues. This will be very much chemistry dependent, however higher solder temperatures and longer contact times play a role. At times if a cleaning agent is used in water wash systems it may require changing to alternatives designed for lead-free cleaning. Many solder companies have already assessed the cleaning effectiveness of their new fluxes with manufacturers of cleaning agents, asking for their recommendation is the first step.

During the initial installation of a lead-free wave operation, leaded and lead-free waves may be in operation.

It is important to avoid cross-contamination, lead-free solder are similar in color to leaded 63/37. Ideally lead-free solder bars should be supplied with a unique shape, unique markings and uniquely labeled box to avoid costly errors.

The consensus at the present time is to keep Pb levels at 0.3% maximum in the solder pot, to avoid reliability issues.

It is also worth noting that the maximum lead level to qualify as a lead-free joint is 0.1% lead. This does not allow for much contamination of lead in the wave solder pot.

Lead-free Wave Bar Packaging

Segregating dross or oxides from solder pots should also be encouraged. In some cases some companies use red or black buckets for leaded oxides and green or white buckets for lead-free. The value of lead-free oxides is substantially more then for 63/37, keeping them separate will insure maximum return when sold for recycling. It is also advisable to label wave solder machines with “lead-free” inscriptions as avoid confusion. Soldered board identification will also be required to determine which are lead-free and which are not. This is important in for rework and field servicing operations.

With proper care and a methodical approach lead-free wave soldering can be accomplished reliably. Resources are available through various published papers and websites on how to achieve this with confidence.

Acknowledgements:

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