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Implementation of Reliable Lead-free Wave and SMT Processes

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As lead-free gains momentum, many engineers are striving to set-up wave solder and SMT processes that maintain 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 asks two fundamental questions of interest to the process engineer transitioning to lead-free soldering. It gives abridged answers, since each would have required numerous pages to completely answer, but they are the key points to consider.

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 or silver. Due to the lack of silver in these alloys, there costs are substantial 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 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.

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.

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 affected by high tin solder alloys.

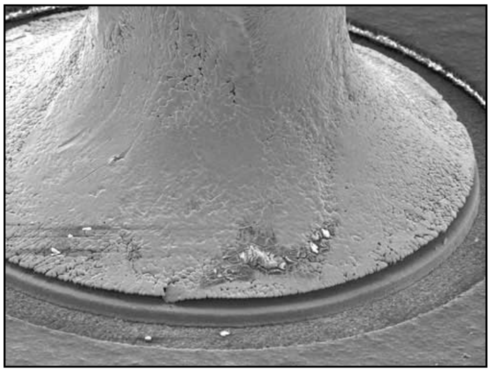
Flux selection will be a critical step to lead-free wave soldering. The flux activity and thermal stability will have to be optimized by the flux manufacturer as to keep defects very low while giving adequate hole-fill. With lead-free solders with higher surface tension and slower wetting properties 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.

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 potential 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 is 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.

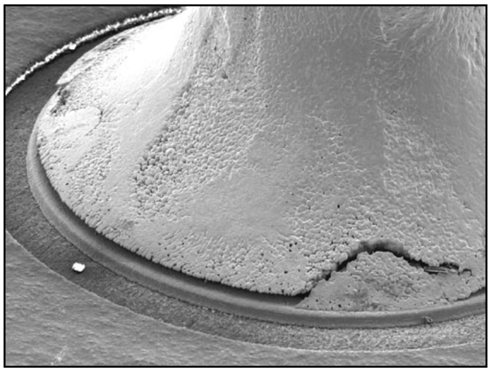
However, new formulations of no-clean liquid fluxes, specifically designed for lead-free also work well. These new no-cleans have enhanced activator packages designed to be thermally stable at higher preheat and pot temperatures. They can sustain slightly longer contact times with the solder and the 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.

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.



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 give the lowest wetting values during wetting balance tests. Bare copper boards with thicknesses in excess of 0.093 inches, is proving 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.

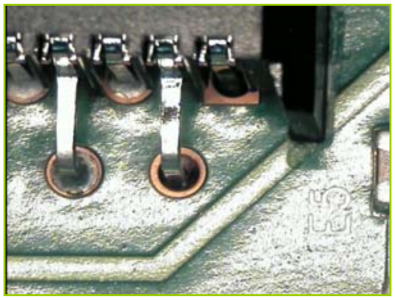
In the soldering of bare copper OSP with lead-free alloys such as SnAgCu or Sn/Cu the following can be tried to improve hole-fill.

- **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 10°C**
- **Use fluxes with higher solids content, higher acid values**

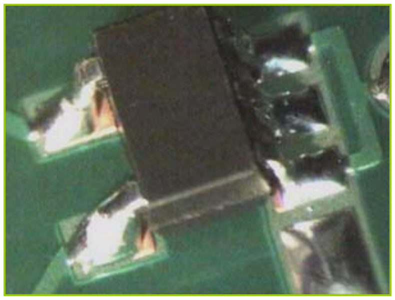
Many of the above points can be applied in situations where hole-fill is not adequate. They apply to lead-free and leaded wave systems.

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.

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 will impact solderability of various finishes and is the single most important parameter to determine.

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 at 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 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.

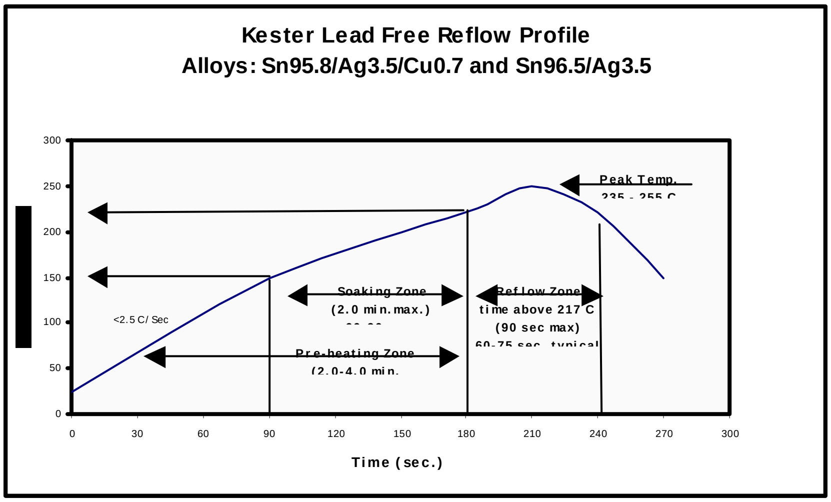
What are the key process requirements to achieve reliable lead-free SMT assembly?

Lead-free SMT can be achieved reliably if several process requirements are implemented carefully. Some of the variables to account for are listed below. The most common alloys used in lead-free SMT are tin-silver-copper alloys, these alloys all have a melting range between 217-220°C. These alloys all melt at higher temperatures than traditional leaded solders such as the 63/37which has a melting point of 183 °C.

Key variables summary

- ☐ **Melting temperature of alloy**
- ☐ **Flux chemistry - activation, temperature effects**
- ☐ **Wetting and surface tension properties of the alloy**
- ☐ **Solder balling and bridging potential increases**
- ☐ **Component / board reliability**
- ☐ **Compatible rework / repair**
- ☐ **Compatible wave, selective soldering process**
- ☐ **Quality inspection criteria**
- ☐ **Cosmetic effects of flux at higher reflow temperatures**
- ☐ **Nitrogen versus air**
- ☐ **Pin testability of flux residues**
- ☐ **Solder voids impact**
- ☐ **Residue cleaning / removal process changes**
- ☐ **Conformal coating and underfill materials**
- ☐ **Oven maintenance, flux decomposition volumes**

Because the melting point of these alloys is higher the thermal profile will also require optimization to avoid excessive temperatures be seen by components and boards. Typically the peak temperature range for tin-silver copper alloys will be between 235and 245°C but if the boards have small thermal masses and the oven has sufficient heating zones temperatures as low as 229° have been used.



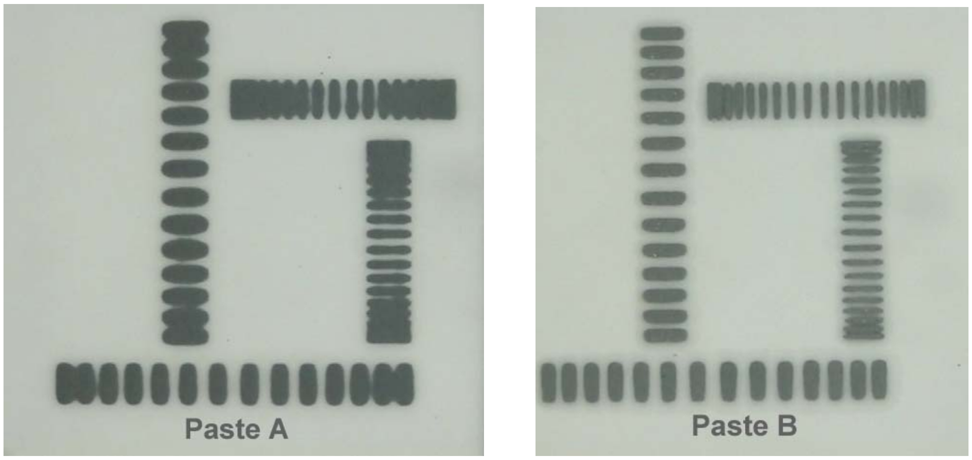
Typical reflow profile used with lead-free SAC and SnAg alloys

The flux chemistry used in lead-free pastes is designed to minimize several of the issues associated with higher reflow temperatures. Higher temperature issues can range from increased paste slump to charring of the residues. Solder paste manufacturers are using chemicals, which offer good hot slump resistance and good activation at higher preheats and at higher peak reflow temperatures.

Some of these newer chemicals are detailed below.

- **New activator packages**
- **New resins**
- **New gelling agents**
- **Better surfactants**
- **Additives to prevent oxidation**
- **Alloy specific fluxes**

Below are photographs of two lead-free solder pastes after hot slump testing at 185° C. Paste A has gelling agents incorporated within its flux system that do not prevent slumping. Paste B contains gelling agents, which prevent slumping at higher preheat temperatures; this paste will reduce the incidence of bridging and solder balls.

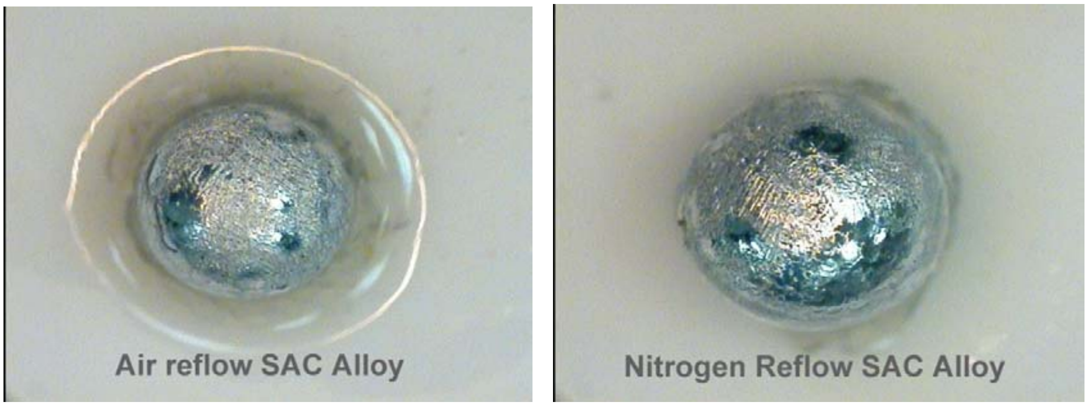


Solder pastes printed on inert ceramic and preheated at 185°C in air

Due to the lower wetting speeds associated with alternative lead-free solders, flux activation will be a critical factor in paste performance. No-clean and water washable solder pastes are being designed to not require nitrogen reflow, and can produce reliable solder connections with good wetting in air. Water washable solder pastes with their higher concentration of activators will solder most metal finishes adequately. No-clean solder pastes will require careful selection of finishes to be soldered but also careful selection of a paste's attributes. Some lead-free no-clean pastes are designed to solder adequately a variety of metal finishes; others have difficulty with second pass bare copper boards due to their lower activity. Some no-clean pastes require lower peak temperatures and others can withstand higher temperatures without charring or polymerization.

Nitrogen will impact solder joint cosmetics as seen in the photographs below. Solder paste reflow in air will offer brighter and more uniform solder joint surfaces. Nitrogen reflow also will enhance wetting with lead-free solders, especially on bare copper OSP surfaces. It must be noted that the vast majority of assemblers seek a solder paste that can be reflowed in air; so many lead-free paste chemistries are being developed with this in mind.

The test below was achieved by printing lead-free solder paste on a white ceramic substrate then reflowing one in air the other in nitrogen. Although the surfaces look dramatically different, this is only a surface reaction.



Impact of nitrogen on Tin-Silver-Copper Solders

Selecting the best lead-free solder paste for the SMT process will be a critical variable and the following can be used as a guide in the selection process.

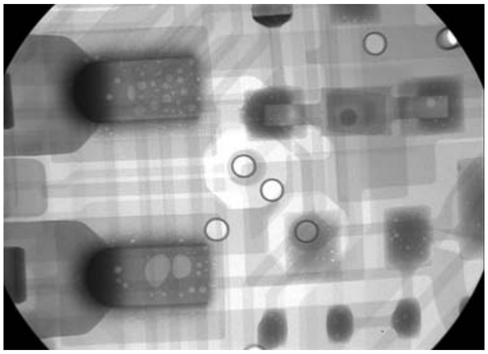
- **Print speed**
- **Abandon time**
- **Stencil life**
- **Tack life**
- **Solder ball test**
- **Slump test**
- **Spread test**
- **Reflow window**
- **Voiding potential**
- **Double reflow window**
- **Clean ability**
- **Pin testability**

Solder paste with excellent print definition

It is not necessary to repeat the above tests in-house, often a good solder paste manufacturer will make the information available to the user.

If the paste is chosen with care and the SMT process optimized, the lead-free transition will be achievable without jeopardizing reliability and product yields. Common defects associated with lead-free are:

- **Off-pad solder balling**
- **Mid-chip solder balling**
- **Tomb-stoning**
- **Bridging (shorts) on fine pitch QFP leads**
- **Open joints**
- **Non-Wetting**
- **De-Wetting**
- **Cold solder joints**
- **Voids**

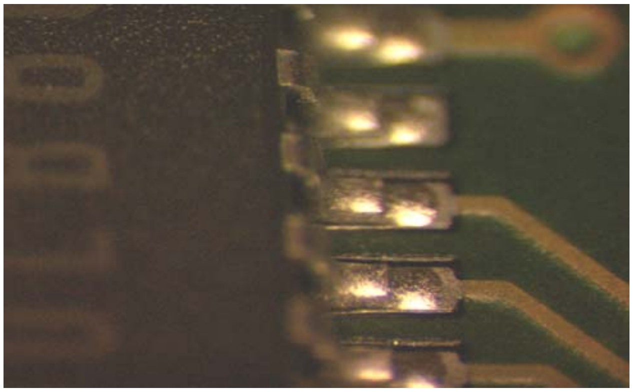


Voids or flux by-products trapped within joints

These defects can be avoided in a properly optimized process with a lead-free solder paste designed to give adequate wetting, low slumping, and low voiding with lead-free alloys.

Lead-free solders due to their reduced wetting, will at times not completely wet the pad. This will be impacted by flux activity and the use of nitrogen in reflow.

However, some assemblers are modifying stencils, as to have less of an aperture reduction. This does require a solder paste with excellent hot slump property to avoid bridging and solder balls. Other assemblers are seeking modifications to pad design.
In many cases, this is not considered an issue.


SAC alloy, ENIG board, with stencil reduction, exposed pad

Developing a lead-free SMT process requires good planning and a close working relationship with all suppliers. Like the lead-free wave-solder process, a team approach and proper training is essential for lead-free integration, especially where dual systems, leaded and unleaded are present.

About the author:

Peter Biocca is Senior Market Development Engineer with Kester in DesPlaines, Illinois. He is a chemist with 22 years experience in soldering technologies. He has presented around the world in matters relating to process optimization and assembly. He has been working with lead-free for over 7 years. He has been involved in numerous consortia within this time and has assisted many companies implement lead-free. He is a Certified SMT Process Engineer and an active member of IPC, SMTA, and ASM.

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