Lead free Defects and Process Yields – Real Case Studies on How Assemblers are preventing them and Maintaining Yields

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Abstract

The industry is in full transition towards lead-free assembly. Due to the different physical, mechanical and chemical properties of lead-free solder alloys, transitioning lead-free soldering without creating defects or reducing yields has been a challenge to some.

This paper summarizes the findings coming from customer experiences and details ways these defects may be caused and how to prevent additional costs due to added repairs or reduction in production yields. The alloys of focus are the popular tin-silver-copper (SAC305); this solder has experienced the most use in the industry at this time.

The present experiences with lead-free solders seem to indicate that a properly selected alloy, flux chemistry, equipment selection and process optimization can give reliable assemblies with lead-free SAC. This paper will focus on the SMT process although similar analysis has been done at the customer level with wave, selective and hand-assembly.

Lead-free Defects in Reflow Soldering

Lead-free SMT can be challenging however this challenge can be minimized if the basic changes associated with this transition are clearly understood. Both paste selection and the reflow process will need to cater to carefully to avoid defects.

Tin-Silver-Copper alloys are the primary choice for lead-free SMT assembly. Although there are other options available such as alloys containing bismuth or indium and other elements, tin-silver-copper solders, also known as SAC alloys are by far the most popular. They are used by approximately 65% of users and their use is on the increase, the main solder of choice is the 96.5 Tin 3.0 Silver and 0.5 Copper, known as SAC305, it was endorsed by the IPC Solder Value Council last year as the preferred choice.

The lead-free SMT process differs from a 63/37 process in numerous ways. A good understanding of these differences when using SAC alloys, will enable process engineers to bring about the necessary changes to the SMT process and reduce soldering defects, increase lead-free assembly reliability and maintain production yields.

Often when a manufacturer transitions to lead-free soldering an increase in defects is noticed, in other cases a reduction in production yields. These negatives are often the result of a not properly implemented process. Soldering defects are good process indicators, and addressing them at the on-start will reduce the overall costs of production.

The main differences between a leaded and lead-free SMT process are summarized below:

- Solder physical properties, melting point, surface tension, oxidation potential, metallurgy and metal leaching potential
- Higher peak temperatures
- Higher preheat temperatures
- Lead-free finishes for boards and components (preferred)
- Solder cosmetics and surface effects
- Solderability differences such as wetting speed and solder spread
- Less self-centering effects or self-alignment of components
- Higher surface tension leading to increased voids

The liquidus temperature of SAC alloys is 217-220 °C; this is about 34°C above the melting point of eutectic 63/37. This higher melting range requires peak temperatures to achieve wetting and wicking to be in the range of 235-245°C. Lower peak temperatures can be used with SAC solders such as 229°C. This lower peak temperature often can only be used for boards with lower overall thermal masses or assemblies, which do not have a large thermal mass differential across the board. This lower peak temperature may also require extended times above liquidus (TAL). If the solderability of components or boards are poor, this lower temperature has been found to give poor wicking of solder and a reduced spread.

Higher reflow profile temperatures will require the use of new solder paste flux chemistries. Solder paste flux accounts for nearly 50% of the solder paste volume. Its ingredients characterize the paste's rheological properties, its ability to print, avoidance of cold and hot slump, tack life, stencil life and abandon time. The flux system is also the main contributor in void occurrence.

As the preheat is engaged during reflow, the flux system will prevent hot slump, reduce the oxidation potential of the metals to be joined, deoxidize the solder powder and remove oxides of the metals to be joined. The flux system insures an oxide free and therefore solderable surface as to give the lowest surface energies to enable spread and wicking of solder.

After reflow is complete the flux system must be easily removed in water if it is a water washable paste or remain benign if it is a no-clean type paste. With some no-clean solder pastes the residue must not undergo complete polymerization as to remain pin-probeable.

The basic ingredients in a solder paste flux can be summarized as indicated below:

- Resins solid and liquid types
- Activators, organic acid and/or hydrohalides
- Solvents and co-solvents
- Gelling agents
- Surfactants
- Chelating agents

Solder paste manufacturers have had to revisit most of these ingredients to account for the higher temperatures experienced in the reflow operation. Most of these ingredients are organic compounds and thermal stability to 245°C plus is essential to avoid issues of decomposition, oxidation, charring and polymerization of paste flux during reflow.

Lead-free solder pastes designed for lead-free alloys and also alloy specific will function best and help prevent solder defects.

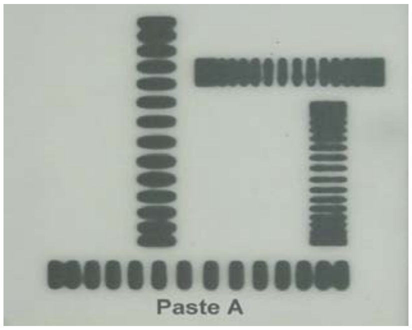
Typical defects associated with lead-free reflow soldering are:

- Bridging
- Solder balls
- Mid-chip balling
- Poor wetting
- Voids
- Tomb-stoning
- De-wetting
- Leaching of metallization

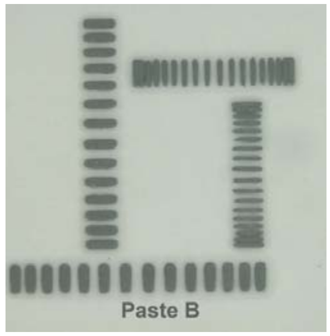
Bridging, Solder balls and Mid-chip Balling

The first three defects bridging, solder balls and mid-chip balling can arise from the solder paste selection process. Since preheats are higher with lead-free, the hot slump character of the paste is critical; solder pastes with good hot slump at higher temperatures such as 185°C are needed. Traditional 63/37 pastes have already melted and flowed at these temperatures; the gelling materials have broken down.

The example below, demonstrates this quite well, two no-clean lead-free SAC, Type III powder solder pastes are shown. The difference in chemistry is evident in their slump performance.



No-clean LF Paste A @180ºC



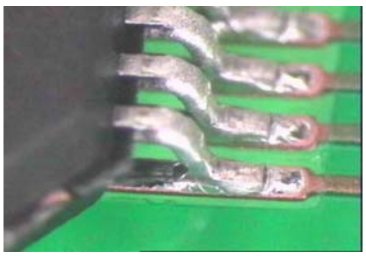
No-clean LF Paste B @180ºC

Both pastes were run through a reflow oven at 180°C. Paste B has better hot slump properties than Paste A and caused less bridges, solder balls or mid-chip balling. For fine pitch components it is critical to select a lead-free paste with a heat stable gelling agent, as indicated in Paste B.

Poor wetting of terminations and pads

Non-wetting or insufficient wetting is also encountered. It must be understood that different metallization will exhibit differing spread and wicking characteristics and also flux activity will play an important role. Lead-free SAC alloys during solderability testing using wetting balance tests demonstrated the best wetting when water washable flux systems were used. No-clean flux systems containing less activator and/or free of halides demonstrated lower wetting speeds and lower maximum force readings.

Bare copper OSP boards, which have seen more than one thermal cycle, are prone to incomplete pad wetting. While pure tin, silver immersion finishes exhibit better solder spread. Ni/Au if the nickel is not affected with impurities or oxides will normally solder well. Below are two examples, one with SAC alloy on copper and the other on silver immersion; both QFP's were reflowed in air, using a SAC no-clean paste ROLO type flux. This type of paste is free of halides.



SAC on bare copper OSP

SAC on Silver Immersion

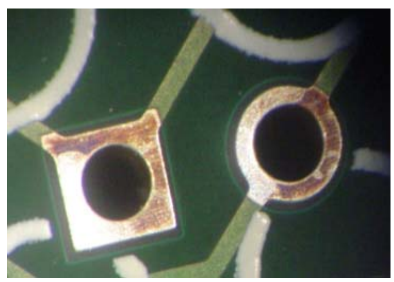
Poor solderability, insufficient wetting, poor wicking of solder, and large contact angles can also result from an inadequate thermal profile. It is very important to achieve good thermal equilibrium across the whole board, this becomes more important with lead-free since the peak temperature window is narrower.

In many cases assemblers have had to revisit storage and handling of components and boards.

Since SAC solders have lower wetting speeds than 63/37 solder, any deterioration of the solderability will result in reduced wicking of the solder. In several situations assemblers using leaded solders have had to revert to gloves and proper storage practices to reduce wetting defects when converting to lead-free.

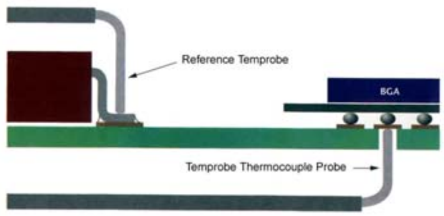
The photo on the right shows the degradation of the silver finish due to storage with higher humidity and oxidizing elements present in the storage room.

Sealing of component and board bags becomes important with lead-free soldering. Component and board rotation is also critical to avoid poor wettability. Storage in a sulfur-free environment is also important.



Silver Immersion Board Oxidation

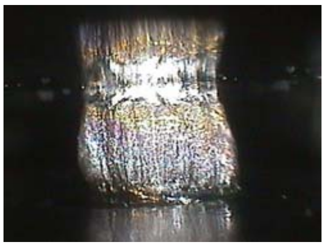
If BGA's are present on the lead-free assembly, these components act as heat sinks, the solder paste may not completely reflow under the BGA, while other smaller components may show good soldering. It becomes very important to establish good thermal profiling points across the board, including under BGA's. To properly insure wetting has occurred completely, optical inspection or X-ray inspection may be necessary.



A test board is essential for the first lead-free assembly to insure thermal requirements are met across the board. The diagram to the left shows the proper way to measure the heat applied to the balls in the grid array.

Proper way to thermally profile a BGA

BGA poor wetting



Excessive Temperature

Good wetting

The photo on the left shows balls, which have not undergone reflow due to insufficient heat. By measuring the temperature accurately at the ball site, this can be avoided. The temperature at the ball site had not seen 217°C the melting point of SAC balls.

The photo in the center shows what happens when excessive temperature is seen by the BGA, in this case the temperature was measured at about 265°C at the ball site.

The photo on the right, shows the proper collapse of lead-free balls with the thermal profile properly set. The standoff distance may be higher with lead-free SAC due to its higher surface tension.

There are other reasons why lead-free reflow demonstrates poor wetting and the main causes are summarized below:

- Solder paste activity level is too low
- Excessive preheat temperatures
- Too long a preheat
- Difficult to solder finishes
- Insufficient time above liquidus temperature
- Excessive oxidation of parts to be joined

Lead-free solder pastes require activation to be sustained beyond traditional tin-lead systems up to 217°C and beyond for SAC alloys. Like traditional 63/37 no-clean pastes, such as ROLO types, the prevention of oxidation to parts and boards is critical. Flux classifications such as ROM1 may contain halides and are therefore better able to cope with oxides or difficult to solder parts.

Tin-Silver-Copper solders wet most metal surfaces more slowly and adequate times above the melting point of the solder is needed to achieve good wicking and solder spread. Normally the range is 60-90 seconds with peak temperatures from 235-245°C.

If soldering is jeopardized by oxidation of parts to be soldered, this can be verified using solderability test methods such as the wetting balance test.

Voids in lead-free joints and BGA's

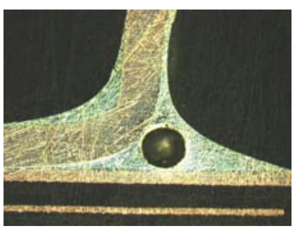
Much has been written about void prevention when soldering with lead-free solder pastes containing tin-silver-copper. Excessive solder voids can create a reliability issue especially in applications where the lead-free assembly will be exposed to thermal cycling conditions or in applications where the assembly will be exposed to vibration, or flexing during box builds. Also voids can reduce thermal performance and reduce electrical integrity.

It must also be stated that smaller voids can in cases increase reliability by changing the crack pattern. Studies have shown that there is no reduction in reliability when voids are present to up to 25% by volume in the joint. Voids can act as stress relievers, due in part to the compressive nature of air pockets.

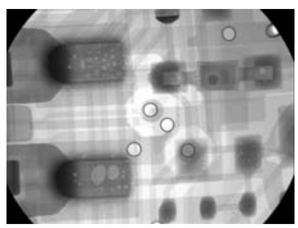
This is documented in the technical paper, Voiding: Occurrence and Reliability Issues with Lead-free, by Martin Wickham of the National Physical Laboratory.

Some causes of voids in joints are summarized below:

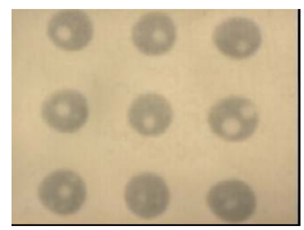
- Solder paste chemistry
- Solder surface tension effects
- Thermal profile
- Oxidation of the outer surface of solder joints
- Termination geometries, joint shape
- Metallization of finishes for boards and components
- Component board out-gassing during reflow



Voids, no-clean paste



Voids, no-clean paste



Voiding in BGA

Lead-free alloys such as SAC alloys have slight higher surface tensions when compared to 63/37. It is important to select a solder paste which has a flux chemistry designed for the higher preheats and peak temperatures. Choosing a solder paste, which does not contain resins and activators, which decompose at these higher temperatures, is the primary factor in void reduction.

Optimizing the reflow profile as to remove any volatiles by extending the preheat times and increasing the time above liquidus will also help in reducing void entrapment. Insuring components and boards are free of moisture and plating contaminants will also help to reduce voids

In some cases joint geometries are contributors. Components such as leadless chip carries or large flat surfaces, perpendicular to the board will prevent out-gassing during the soldering process; this results in void increases. Solder flux by-products both liquid and gases, will have to slowly make their way upwards. Component geometries, which prevent the proper upward flow, will usually result in an increase in voids.

Tombstoning defects with lead-free

Lead-free may increase the uplifting of smaller components. This is due in part to the reduced wetting behavior of lead-free alloys. Component placement is more important with lead-free alloys since less centering will occur during reflow. This can increase the incidence of tombstones.

SAC305 tends to reduce tombstones, this alloy has a concentration of 96.5 Tin, 3.0 Silver and 0.5 Copper and has melting range of 217-220°C. Because of the small pasty range the component prone to tombstone is tacked by the initial melting phase of the alloy.

A solder paste, which exhibits excessive out-gassing during the initial stages of the melting of the solder powder, will also increase tombstone defects. The paste manufacturer must carefully choose resins and solvents, which do not decompose or vaporize at the melting point of the alloy.

De-wetting with lead-free

De-wetting is often due to a lack of flux activity. This behavior rarely occurs with water-washable type pastes since these pastes are highly activated. Lower activity solder pastes in the category of ROLO, halide free no-cleans pastes tend to create this on more difficult finishes such bare copper OSP or on Ni-Au where the nickel base metal, may have experienced oxidation or plating contamination.

Below are test coupons on which SAC no-clean paste was applied to two surfaces.
The test coupons were then reflowed in air using the manufacturer's recommended thermal profile. The one on the right shows de-wetting while the one on the right exhibits good wetting. The pooling of the solder was due to the base metal being difficult to solder to. The molten solder initial spread across the surface but not a good enough intermetallic bond was formed, resulting in surface tension pulling the solder away.

Dewetting, SAC **Good wetting, SAC**

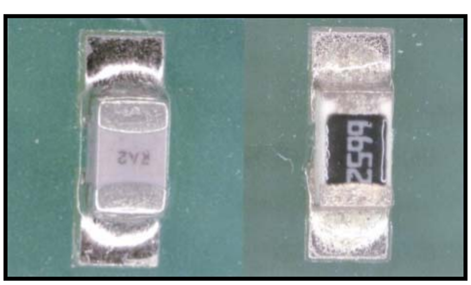
Ways to reduce or prevent de-wetting with lead-free SMT are:

- Select a paste with excellent activity up to the melting point of the alloy, up to 217°C for SAC alloys
- Use a more active flux system
- Insure metals to be joined are oxide-free as possible
- Insure base metals are solderable with the selected flux type
- Reduce the preheat time or temperatures as to preserve flux activity
- Increase time above liquidus (217 °C), if flux activity is good

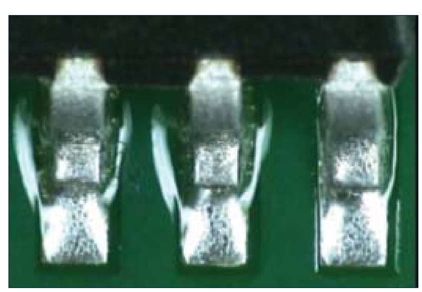
Excessive dullness and surface effects with lead-free

SAC alloys offer solder joints which are less reflective than 63/37; the contact angles tend to also be higher and spread is less. These are not considered defects but only cosmetic. If air reflow is used, SAC joints will be less bright and show surface effects such as crazing which are due to the intermetallics within the solder and oxidation effects.

If nitrogen reflow is used the joints will be more reflective and spread will be enhanced. Below are two photos. The one on the left is 63/37, while the other shows joints done with SAC305 alloy.



63/37 Solder in air **SAC Solder in air**



SAC in Air Reflow

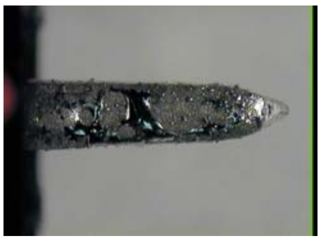
Lower peak temperatures and lower times above liquidus will reduce both intermetallic growth but also increase the overall brightness of the solder joints.

Leaching of Component Metallization

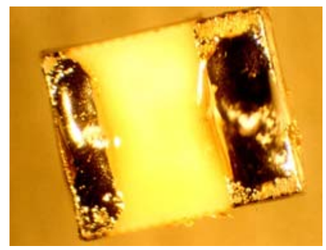
Leaching of component terminations has occurred with high tin solders and this in some cases has resulted in assembly failure due to a lowering of pull and shear forces required to break the bond.

Leaching of most metals does occur more readily with lead-free. Lowering the time above liquidus and the peak temperature, or both can reduce this occurrence. If the metallization is too thin this will increase the risk of these types of failures. Measuring the thickness of metal finishes can be done quantitatively with XRF (X-Ray Fluorescence).

Below are two cases of metallization dissolution, one is a SMD component showing leaching away of the nickel plating and the other is from a waved component, showing dissolution of the plating leading to de-wetting.



Pin plating dissolution



Nickel Dissolution on SMD

In future development work, there may a requirement to revisit metallization thicknesses for lead-free applications to completely eliminate this problem. This issue has appeared in SMT but also wave soldering and hand-soldering.

Conclusion:

Lead-free reflow soldering can be achieved reliably if the solder paste is selected carefully, the solderabilty of the parts to be joined preserved, the reflow process optimized to suit the board assembly and the flux chemistry which is used.

Soldering defects can be eliminated if the whole operation is well understood and then defined for each assembly. Using optical inspection but also X-ray and endoscopic analyses where applicable can also reduce latent defects.

Many defects seen with lead-free are due to a process requiring optimization. Some could be due to metallization issues such as leaching effects and may require component modifications. However the process can be altered to accommodate this limitation in some cases.

Proper training will be required when transitioning to lead-free assembly. Operators will need to be given quality acceptance criteria for solder joints that will look quite different from traditional leaded systems.

Acknowledgements:

OK International, Photos of BGA Optical Inspection and Cosmetic Joint Comparisons.

Bob Willis U.K., Photos BGA with SAC alloy.

Gintic Manufacturing Consortium, Singapore. Lead-free Report.

Kester Des Plaines, Illinois, Applications Laboratory, Photos Paste Slump, Spread Tests.

Voiding: Occurrence and Reliability Issues with Lead-free, Martin Wickham, NPL, U.K.

Lead-free Electronics, 2004 Edition, Sanka Ganesan; Michael Pecht, Calce Press.

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