Choosing a Low-Cost Alternative to SAC Alloys for PCB Assembly

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Abstract

Developing low-cost alternatives to near-eutectic SAC alloys for Pb-free assembly is crucial to continue producing affordable electronics products.
Metals prices, especially silver, have been on the rise, and will likely stay at their near historic high levels. Solder alloys with lower silver content have been considered with trade-offs in performance, but are there alternatives?

There are many reasons to consider alternative Pb-free alloys to SAC305. Several new alloys have been recently introduced, while others, which had little popularity in the past, are showing more potential due to changes in the industry. The question is: how much do subtle variations in alloy composition affect the performance and process requirements of PCB assembly? This paper will compare some of these alloys side-by-side and discuss whether existing processes need to be modified for alternative alloys.

Introduction

Numerous groups studied lead-free solders in the late 1990s to early 2000 timeframe in anticipation of the enactment of RoHS legislation in 2006. It was shown that tin-bismuth-based solders may not be desirable due to potential fillet lifting in wave soldering. In addition, the poor mechanical properties of tin-bismuth solders, when alloyed with even small amounts of lead, were a concern as lead might still be in component leads or PWB pad finishes. Tin-zinc solders were also rejected due to the short shelf life of such solder pastes. Hence, tin silver-copper (SAC) seemed to be the solder alloy of choice.

It was natural that those evaluating SAC solders would focus on eutectic or near eutectic solders, as the industry had experienced nearly 100 years of success with eutectic tin-lead solder. The main advantage, among several, being that a eutectic solder has the lowest melting point in its alloy family. This consideration was not a minor one as the melting point of SAC solders is about 34°C higher than tin-lead eutectic solders. It is interesting to remember that the exact composition of eutectic SAC solder is not necessarily agreed upon, but it is near Sn95.5/Ag3.8/ Cu0.7 (SAC387), so this composition was chosen by some of the early pioneers. In about 2001, Motorola started producing mobile phones with SAC387. They started early, to take advantage of SAC's poor spreading in SMT assembly, enabling closer lead spaces without the concern for shorts.

By about 2005, some assemblers were using SAC305. SAC305 is off the eutectic and has a "pasty range." This lack of a sharp melting point minimized tombstoning of passive components and saved a little money by involving less silver. By about 2007, the IPC's Solder Products Value Council declared SAC305 the "preferred" lead-free solder alloy.

From the mid 1990s to about 2005, it could be argued that the defining electronics product was the laptop computer. Although still important, the laptop has almost certainly relinquished this title to the mobile phone. With 5.6 billion mobile phone subscriptions in a world of 7 billion people, it is truly the ubiquitous electronics device. With this increase in mobile products came a new concern: drop shock failures. Investigations into this failure mode indicated that SAC105 was more robust. By the late 2000s, SAC105 was becoming the dominant lead-free solder choice for mobile products.

By 2010, work by Henshall et al [1] and Coyle et al [2] had demonstrated that SAC105 was superior to tin-lead solder in thermal cycling. This work locked in SAC105 as a reliable solder for mobile products.

Around the same time, Lee et al [3] performed work showing that SAC105 with "dopant" levels (<<0.1%) of manganese or cerium was significantly superior to plain SAC105 in both drop shock and thermal cycle performance.

By 2011, in addition to this positive news, the world was now five years into RoHS. Trillions of dollars of electronics products have now been manufactured and sent into the field with no major reliability or manufacturability issues. But by April of 2011, silver was above $40/oz., four times its price on the date of RoHS's enactment (Figure 1). It was time to look at low- or no-silver solder alloys.

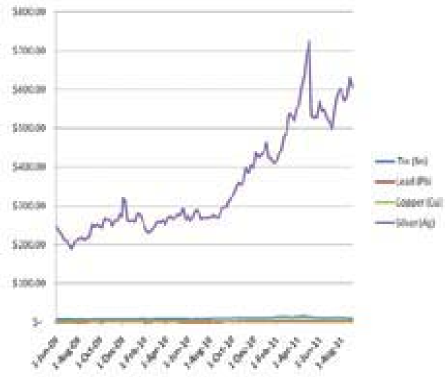


Figure 1. Metal Prices 2009-August 2011.

Considerations for Alloy Selection

After the Pb-free transition, many users adopted SAC alloys, specifically SAC305, or the closer-to-eutectic SAC387. However, as the industry researches and uses Pb-free alloys more pervasively, and as further generations of flux chemistries and alloys are developed, it becomes clear that just one alloy cannot provide the best properties for all processes and applications. Other pressures also force the consideration of alternatives from early de-facto choices.

In the past year, precious metals prices have been on the rise, causing silver, gold, tin, and other metals to skyrocket in price. As a logical result, solder prices have risen considerably, causing some to look for less expensive alternatives. Even though silver comprises a small percentage of alloy composition, its value comprises most of a solder alloy's metal value (Figure 2). Therefore, small changes in composition, or eliminating silver altogether, are tantalizing propositions. Different parts of the industry have adopted different approaches to regulating material costs, while maintaining optimal performance.

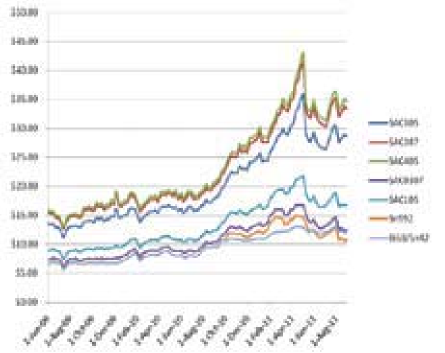


Figure 2. Alloy Costs 2009-August 2011.

With an increasing number of alloys to choose from, it is helpful to group Pb-free alloys into a few distinct families. First are the near-eutectic tin-silver-copper alloys (SAC305, SAC387, and SAC405) which contain 3-4% silver. These alloys were originally chosen for their robustness in thermal cycling, while still balancing performance with good drop shock resistance. Other important qualities are shininess for automatic inspection, compatibility with surface finishes, and reasonable reflow performance.

The second family is low silver alloys such as SAC105 and SAC0307. These alloys have gained in popularity because of better drop shock performance and smaller amounts of silver. The trade-off with less silver is decreased thermal cycling performance. For some applications, compromising on reliability is not feasible because of higher temperature environments or longer product lifetimes. Ideally, for these customers there would be another alloy to enhance reliability without additional silver.

The third family is doped alloys. In order to improve the properties of the second family of alloys, additional metallic constituents are added in small amounts. To compensate for trade-offs in performance, dopants can improve properties like wetting, appearance, and reliability, yet maintain similar reflow characteristics. It seems that each supplier has its own variety in this family, such as SN100C, SACX, SACMn, or Sn992. Each of these alloys has a different mix of dopants, and it is suggested slightly different levels of performance, although it is difficult to characterize how much.

Other alloys worth considering don't fit into these groups. For instance, BiSnAg (Indalloy® 282) has favorable properties for many applications. This alloy's liquidus is 140°C, in comparison to SAC alloy's liquidus, which is approximately 220°C. BiSnAg would be especially suitable for temperature-sensitive applications or for attaching additional components after primary board assembly. Depending on parameters for thermal cycling tests, this alloy can offer acceptable reliability for applications at ambient to low temperatures. However, BiSnAg alloys do not have acceptable drop shock performance for mobile products.

Screening Alternative Alloys in an Existing Pb-Free Process

With so many alloys to choose from, screening several alloys can take a lot of resources. Some testing is time or labor intensive, but there are some comparisons that can be useful for initial testing. Not all alloy changes can be a drop-in replacement for a near-eutectic alloy, but testing a new alloy in the current process can help understand how different these alloys are, and how different a new process would be.

In this example, two different alloys, SAC387 and Sn992, were tested in the same flux vehicle. (Note: This might not be the case for all testing, depending on how different the alloys are.) Both pastes were printed and reflowed on the same type of board using the same two reflow profiles. One profile was the typical process profile used, the other reflow profile was chosen to be harsh, meaning a higher than usual peak temperature as well as a longer time above liquidus, in order to differentiate if there were differences.

The first characteristic to test for was wetting. Alloy choice and its compatibility with the surface finish will greatly influence wetting. In this test, paste was printed onto a copper panel without defined pads. The expectation is that the reflowed solder will stay in the shape of the deposit, and uniformly cover the area.

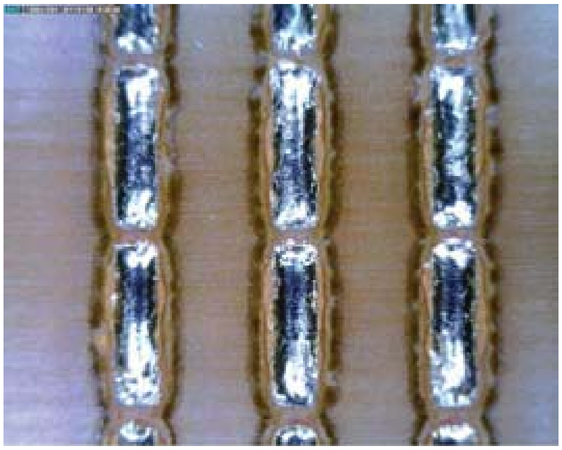


Figure 3a. Wetting pattern for testing for SAC387.

Figure 3b. Wetting pattern for testing for Sn992.

As seen in the Figures 3a and 3b, both SAC387 and Sn992 look comparable and displayed good and even wetting.

Another performance aspect to look at would be defects that are caused by excessive oxidation. These include, but are not limited to, solder balling and graping. These phenomena are not solely influenced by alloy choice, but they can be a good indicator of the match between alloy and flux vehicle, as well as how the alloy works in the current process.

To test this, almost any type of aperture pattern will work. After printing and reflowing a board using the current Pb-free process, it is important to carefully inspect all solder deposits for signs of these phenomena. Solder balling will appear as small metallic satellites. These are oxidized powder particles which did not coalesce into the solder joint. Graping is a defect on the surface of the joint that might look similar to cold solder, but will look like bumpiness on the surface. Ideally all reflowed solder deposits would appear shiny and uniform (see Figures 4a and 4b).

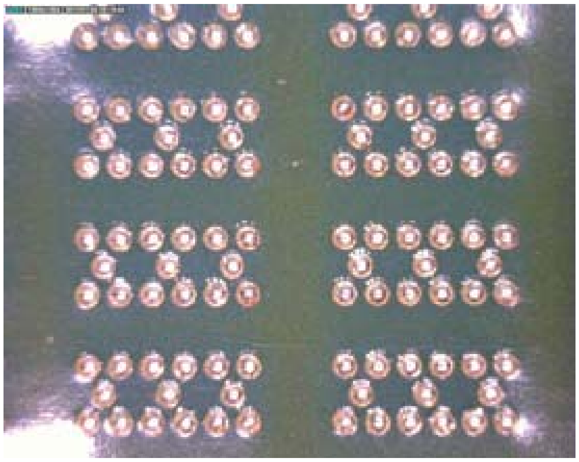


Figure 4a. Small deposits visually inspected for coalescence for SAC387.

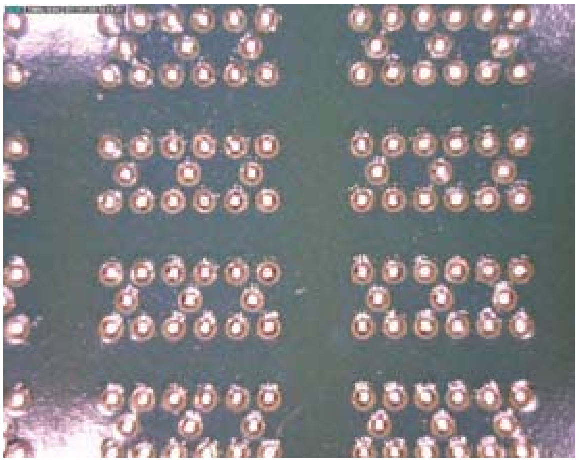


Figure 4b. Small deposits visually inspected for coalescence for Sn992.

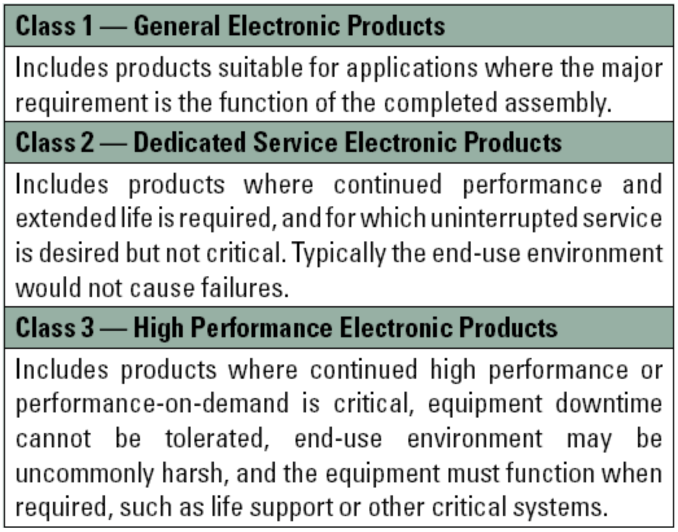
Notes on Reliability

Before RoHS, the main reliability requirements were 1) thermal cycling for typical use type products such as computers, televisions, stereos, and 2) the more severe thermal cycling and special shock and vibration testing for auto and military/aerospace applications. It is interesting to consider that since the enactment of RoHS, a new reliability requirement has emerged: 3) drop shock testing for mobile products, such as mobile phones and portable music devices. So there are now at least three reliability arenas in which solder joints must be evaluated: (The different IPC classes are described in Table 1).

- Reliability requirements for 1) are typically evaluated with thermal cycle testing from 0 to 100°C. These products are usually IPC Class 2 products.
- Reliability requirements for 2) are typically evaluated with thermal cycle testing from -55 to 125°C and perhaps specific MIL- or SAE-specified testing. These products are usually IPC Class 3 products.
- Reliability requirements for 3) are typically evaluated with thermal cycle testing from 0 to 100°C and also drop shock testing such as JEDEC JESD22-B111. These products are usually IPC Class 2 products.

Reliability test results of the lead-free solders are compared against tin-lead eutectic solder as a control. For 1), tin-bismuth solders may be considered as a substitute for the more commonly used SAC305. In addition to having no silver, Sn58/Bi42 has a low melting point of 138°C, which can be attractive for assembling and acceptable if use conditions are in the home or office. However, Sn58/Bi42 does not have good drop shock resistance and must be avoided when drop shock is a concern. For 3), doped SAC105 has been shown to be the current alloy of choice.

The high reliability requirements of 2) have earned an exemption from RoHS for automobile and military/aerospace products. So, tin-lead solder will still normally be used for these products.



Class 1 — General Electronic Products
Includes products suitable for applications where the major requirement is the function of the completed assembly.
Class 2 — Dedicated Service Electronic Products
Includes products where continued performance and extended life is required, and for which uninterrupted service is desired but not critical. Typically the end-use environment would not cause failures.
Class 3 — High Performance Electronic Products
Includes products where continued high performance or performance-on-demand is critical, equipment downtime cannot be tolerated, end-use environment may be uncommonly harsh, and the equipment must function when required, such as life support or other critical systems.

Table 1. Classes of electronics.

Reliability and Microstructure

Aspects of microstructure can indicate the potential reliability of solder joints. A well-formed solder joint will have a uniform texture in SEM images and an intermetallic (IMC) layer formed with copper substrates. This IMC layer is more brittle than the bulk of the solder joint, and often is the origin of joint failure. This layer forms as copper from the substrate migrates into the solder as it is molten, and will continue to mature over time, or is accelerated by aging at temperatures below the liquidus.

As alternative Pb-free solders have been considered, particularly those containing little or no silver, one reason they are less desirable is because they have liquidus temperatures up to 10°C elevated from SAC305. This would indicate that the peak temperature or time above liquidus for these alloys would need to be elevated, causing concern about the temperature tolerance of components on the board. One of the reasons it is assumed that the reflow profile must be modified is to ensure adequate IMC layer growth.

In this investigation, alternative alloys were reflowed, along with SAC305, using the same “typical” Pb-free reflow profile (Figure 5).

In this case, QFN components were used and only solder joints around the outside of the component were investigated. These samples were cross-sectioned and etched to make the IMC layer more visible.

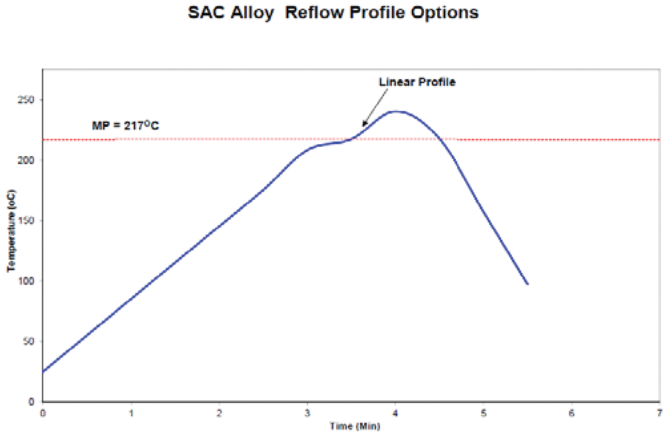


Figure 5. Typical SAC305 linear reflow profile.

Figures 6a, 6b, 6c, and 6d are SEM images comparing the IMC layer of SAC305 to those of SAC105, SAC0307, and Sn992. Despite differences in microstructure inherent to each different alloy, IMC layer formations seem to be of a similar thickness on the order of 1µm.

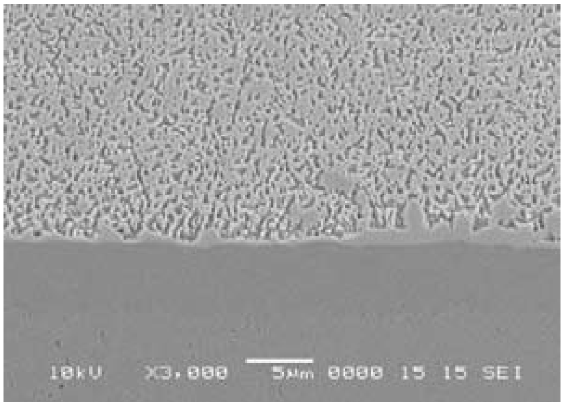


Figure 6a. An etched SAC305 solder joint.

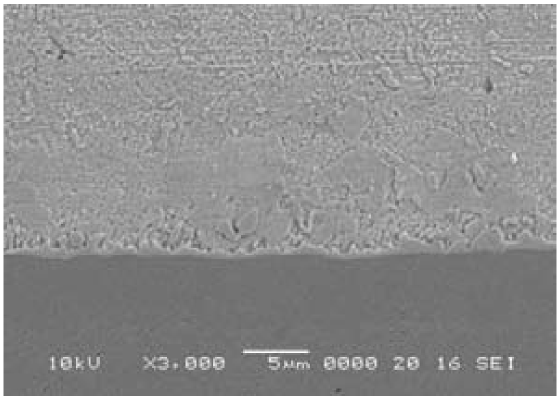


Figure 6b. An etched SAC105 solder joint.

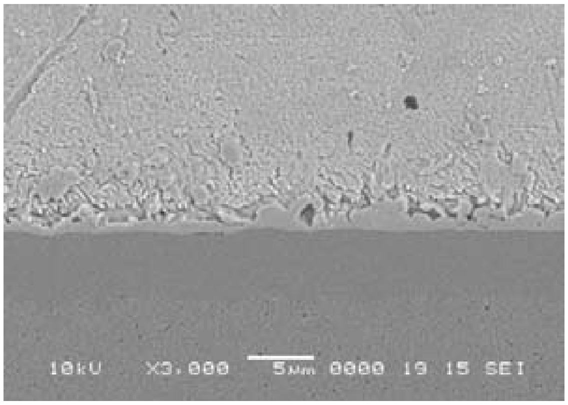


Figure 6c. An etched SAC0307 solder joint.

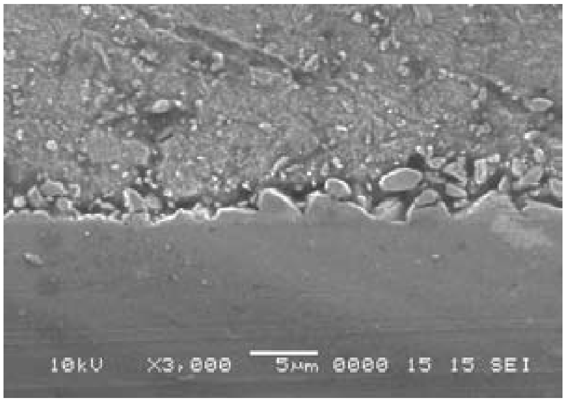


Figure 6d. An etched Sn992 solder joint.

As the reliability of SAC305 and SAC105 have been researched and have shown sufficient properties for many different applications, these results seem to indicate that SAC0307 and Sn992 could perform similarly in typical Pb-free processing conditions. Further research will look into how this IMC layer grows in each alloy after elevated temperature aging. In addition, more measurements should be taken to determine the variance in IMC layer thickness statistically.

Conclusions

In the foreseeable future, it will become necessary for the near-eutectic lead-free alloys to be replaced by lower cost alloys with comparable properties. As many different alloys emerge with favorable properties, there is once again a struggle to find the best option. In order to ensure equivalent comparisons, more work will need to be done to test alloys side by side in the same processes. Further investigations into IMC layer formation with alternative Pb-free alloys are testing. We expect to report the results of this work in the future.

References

F. Song, S.W.R. Lee, *Investigation of IMC Thickness Effect on the Lead-free Solder Ball Attachment Strength: Comparison between Ball Shear test and Cold Bump Pull Test Results,* IEEE ECTC 2006.

B. Salam, N.N. Ekere, D. Rajkumar, *Study of the Interface Microstructure of Sn-Ag-Cu Lead-Free Solders and the Effect of Solder Volume on Intermetallic Layer Formation,* IEEE ECTC 2001.

1. Henshall, Greg; Fehrenbach, Michael, et al, Low Silver BGA Sphere Metallurgy Project, SMTAI, Orlando, FL, October 2011.
2. Coyle, Richard; McCormick, Heather et al, The Effect of Silver Content on the Solder Joint Reliability of a Pb-free PBGA Package, SMTAI, Orlando, FL, October 2011.
3. Liu, Weiping; Lee, Ning-Cheng et al, Achieving High Reliability Low Cost Lead-Free SAC Solder Joints Via Mn or Ce Doping, ECTC 2009.

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