CHOOSING A LOW-COST ALTERNATIVE TO SAC ALLOYS FOR PCB ASSEMBLY: PRELIMINARY WORK

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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 have been on the rise, and other factors, such as concerns about "conflict tin", indicate that this trend could likely continue. Solder alloys with lower silver content have been considered, with trade-offs in performance, but are there alternatives? This paper discusses some new alloy options, comparing performance to current low-cost options, and considers approaches to enhance the performance of low-cost solder alloys.

INTRODUCTION

Numerous groups studied lead-free solders in the late 1990 to early 2000 timeframe in anticipation of the enactment of RoHS 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.

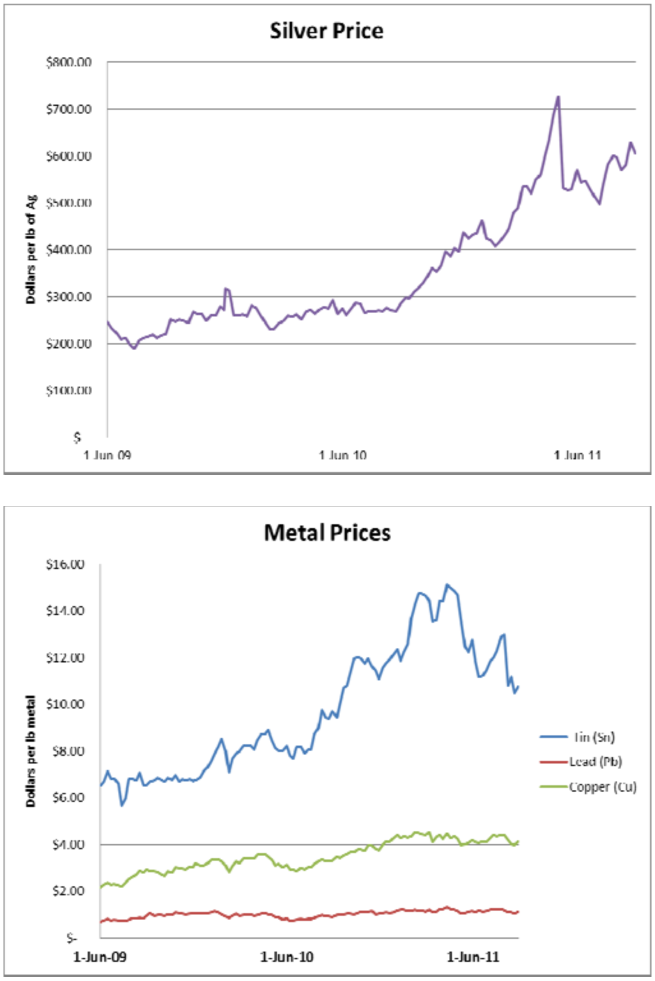
It was natural that those evaluating SAC solders would focus on eutectic or near eutectic solders, as the industry had experienced nearly 100 years of success with eutectic tin-lead solder. The main advantage, among several, being that a eutectic solder has the lowest melting point in its alloy family. This consideration was not a minor one as the melting point of SAC solders is about 34^{o}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 $Sn_{95.5}Ag_{3.8}Cu_{0.7}$ (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 poorer 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 electronic product was the laptop computer. Although still important, the laptop has almost certainly yielded 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 electronic 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[i] and Coyle et al[ii] 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[iii] 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 electronic 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. See Figure 1. It was time to look at low- or no-silver solder alloys.



Figures 1a and 1b. 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. See 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 increasing numbers of alloys to choose from, it is helpful to group Pb-free alloys into a few distinct families. First are near-eutectic tin-silver-copper alloys (SAC305, SAC387, and SAC405) which contain 3-4% percent Ag. 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 or SAC0307. These alloys have gained 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 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.

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 that solder joints must be evaluated in (The different IPC classes are described in Table 1 below):

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

These products would usually be IPC Class 2 products.

Reliability test results of the lead-free solders would be 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, $Sn_{58}Bi_{42}$ has a low melting point of 138^{o}C, which can be attractive for assembling and acceptable if use conditions are in the home or office. However, $Sn_{58}Bi_{42}$ 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.

Table 1: Classes of Electronics

"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."

SCREENING ALTERNATIVE ALLOYS IN AN EXISTING P-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 quick comparisons that can be useful for initial testing. Not all alloys are drop-in replacements for a near-eutectic solder 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 the first test, two different alloys, SAC387 and Sn992, were tested using the same flux vehicle. (Note: This might not be possible for all alloy pairs, depending on how different the alloys are.) Sn992 is a tin-based alloy with 0.5% copper, 0.3% bismuth and cobalt as a dopant. Both pastes were printed and reflowed on the same type of board using the same two unique reflow profiles each. 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 tested for was wetting. Alloy choice and its compatibility with the surface finish greatly influences wetting. In this test, paste was printed onto a copper panel, without defined pads. The expectation was that the reflowed solder would retain the shape of the deposit, and uniformly cover the area.

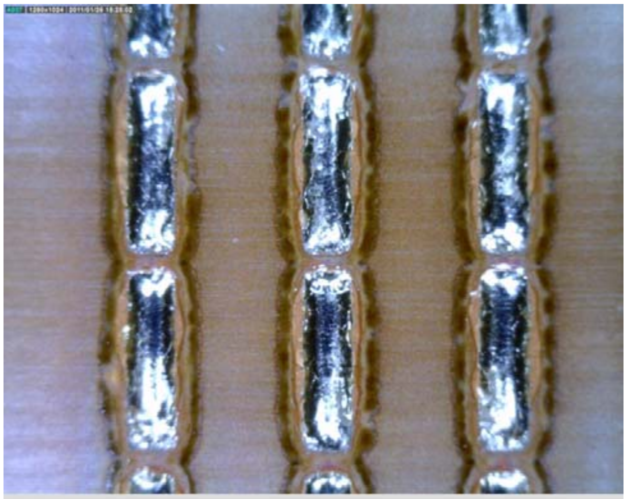


Figure 3a. Wetting pattern for testing for SAC387

Figure 3b. Wetting pattern for testing for Sn992

As seen in the Figures 3a and 3b, both SAC387 and Sn992 looked comparable with each displaying good and even wetting.

Another aspect of performance evaluates potential 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 that manifests itself on the surface of the solder joint. It often looks similar to cold solder, with bumpiness (grapes) on the surface. Ideally all reflowed solder deposits would appear shiny and uniform.

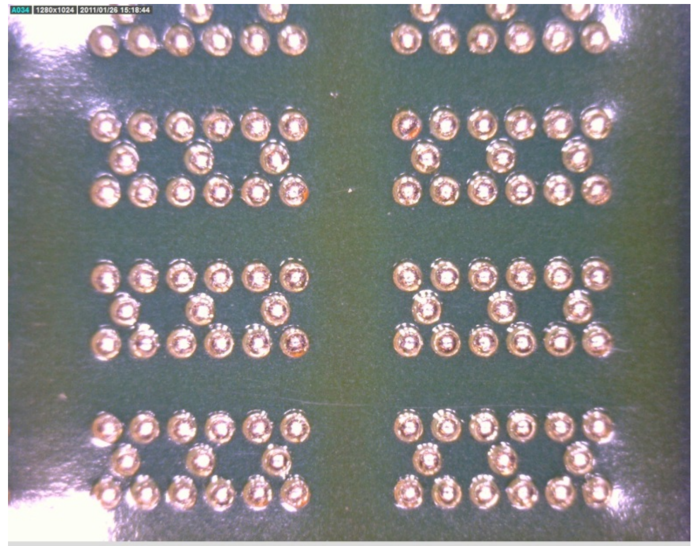


Figure 4a. Small deposits visually inspected for coalescenceSAC387

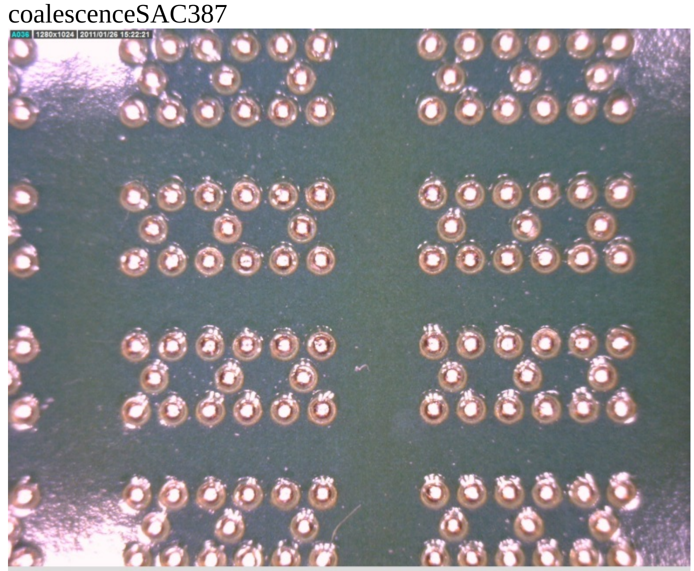


Figure 4b. Small deposits visually inspected for coalescence Sn992

This testing set is, by no means, complete, but it will identify crucial issues quickly. Additional tests would include thermal cycling and drop shock, as mentioned before. Both of these tests are time and labor intensive, thus being more reasonable for focused testing on a few short-listed alloy candidates.

CONCLUSIONS

In the foreseeable future it will become necessary for the near-eutectic 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 insure equivalent comparisons, more work will need to be done to test alloys side by side in the same processes. We expect to report the results of this work in the future.

REFERENCES

[i] Henshall, Greg, Fehrenbach, Michael, etal, *Low Silver BGA Sphere Metallurgy Project*, SMTAI, Orlando, FL, October 2010.

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[iii] Liu, Weiping, Lee, Ning-Cheng etal, *Achieving High Reliability Low Cost Lead-Free Sac Solder Joints Via Mn Or Ce Doping*, ECTC 2009.