Transitioning to Pb-Free Assemblies

By Carol Handwerker

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Convergence on a single lead-free alloy means studying compatibility (backward and forward), and materials and process development.

Five years ago the international microelectronics industry was considering and testing several lead-free alloys that could potentially replace SnPb eutectic for solder reflow and wave solder applications. Today, a narrow range of compositions in the SnAgCu system is the most widely recommended as a general purpose, standard alloy for surface-mount, wave and hand soldering in a variety of product types. There is no drop-in replacement for SnPb, but when considering melting point, toxicology, cost, availability and chemical resistance the SnAgCu system has emerged as the most acceptable compromise, both for solderability and reliability. SnAgBi alloys are sometimes used as low-temperature alloys, especially for surface-mount consumer products.[1] They are more common in the Far East, and rare in the U.S. Although bismuth-containing alloys tend to have good reliability in surface-mount joints, the reliability can deteriorate significantly if there is any lead in the resulting joint and high-tin bismuth solders can show fillet lifting in through-hole joints.

Other alloys considered had drawbacks as well. For example, supplies of bismuth and indium are limited, making them costly; indium in particular may be subject to cracking in the solder joints.[2] Zinc-containing alloys are difficult to use for most applications because it oxidizes too rapidly in processing.

Extensive testing has proven SnAgCu to be at least as reliable as SnPb eutectic. Several industry groups have recommended the SnAgCu alloys, including iNEMI (inemi.org), IPC's Solder Products Value Council, High-Density Packaging User Group, E3 (the top three European semiconductor manufacturers: Infineon, Philips, STMicroelectronics), the IDEALS program in Europe (Improved Design Life and Environmentally Aware Manufacture of Electronics Assemblies by Lead-free Soldering), Soldertec at ITRI (Europe), the Printed Circuit Interconnection Federation (a U.K. trade organization) and the Japan Electronics and Information Technology Industries Association.[1-4]

SnAgCu solders are tin-rich alloys with 3.0 to 4.0% silver and 0.5 to 0.6% copper. Compositions of specific alloys are expressed in weight %. For example, Sn3.0Ag0.5Cu is 3.0% silver, 0.5% copper, with the remainder being tin; in this case, 96.5% is tin. The leading alloy compositions are Sn3.0Ag0.5Cu (JEITA), Sn3.8Ag0.7Cu, (E3/Soldertec) and Sn3.9Ag0.6Cu (iNEMI). With J-STD-006 specifying that an alloying element less than 5 wt% can vary in composition by ±0.2 wt%, Sn3.9Ag0.6Cu is indistinguishable from Sn3.8Ag0.7Cu.

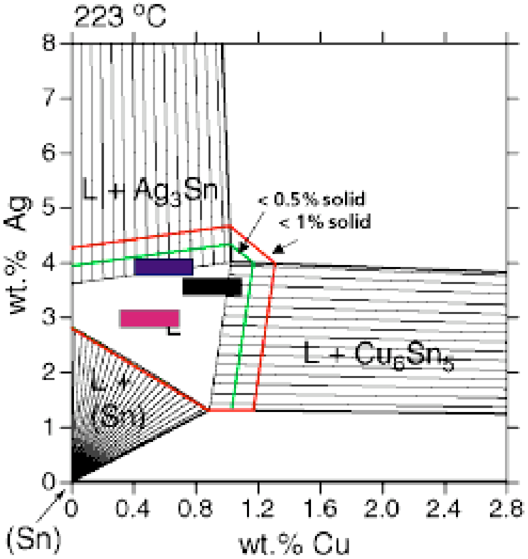

Figure 1: SnAgCu phase diagram shown at 223°C. The rectangles correspond to the iNEMI (blue) and JEITA (purple) alloy ranges. The region bounded by the green line contains less than 0.5% solid; the region bounded by the red line corresponds to less than 1% solid.

From an assembly point of view, alloys within the full composition range from Sn3.0Ag0.5Cu and Sn3.9Ag0.6Cu are similar: the solder consists of greater than 99% liquid above 220°C, as described by Rae and Handwerker,[3] and illustrated in the isothermal section of the SnAgCu phase diagram (**Figure 1**). A phase diagram is a three-dimensional graph of the equilibrium melting, solidification and precipitation behavior of alloys as functions of their composition and temperature. **Figure 1** is a planar cut through the phase diagram at 223°C showing regions of composition where alloys are completely liquid, a mixture of liquid and solid (Sn, Cu_6Sn_5 or Ag_3Sn), or solid. (See References for background on the process technology and reliability data for SnAgCu.)

Since the EU's RoHS Directive contains certain product exemptions to the requirement for lead-free solder alloys in electronics, these products will, for some time, continue to be built with SnPb solder and assembly processes. As the industry moves toward lead-free assembly, expectations are that in the near future some components will no longer be available with SnPb surface finishes. Questions are emerging regarding manufacturing and reliability when SnPb and SnAgCu materials and processes are mixed. These questions arose because of the 34°C difference between the eutectic temperature in the SnAgCu system of 217°C and the eutectic temperature of SnPb of 183°C. For example, if a BGA component for an exempted application can be obtained only with SnAgCu solder balls and is processed with a SnPb solder paste and reflow profile, what effect will this have on the structure, performance and reliability of the final joints?

This column discusses the assembly behavior when alloys and processes are mixed and the effects on the structure and properties of the as-solidified solder joints. The conditions under which SnPb pastes, solder baths and processes form reliable joints with lead-free surface finishes and solder balls on components and lead-free surface finishes on boards is referred to as "backward compatibility." Likewise, during the transition to completely lead-free assemblies, the conditions for "forward compatibility" are found when SnAgCu pastes, solder baths and processes form reliable joints when used with SnPb surface finishes on components and boards.

Surface-Mount Technology

Backward compatibility. For area array components, the greatest problems are expected when SnPb pastes are combined with SnAgCu solder balls and assembled at temperatures too low for the combined solder to melt. The ternary eutectic temperature for SnAgCu is 217°C, but the joint does not have to reach this temperature for the overall solder to melt when SnPb eutectic and SnAgCu alloys are mixed. If we estimate that an Sn3.9Ag0.6Cu solder ball constitutes 75% of the final solder in the joint, the average composition of the solder in the ball and paste is Sn9Pb2.9Ag0.5Cu. For the alloy in the joint to completely melt, the joint temperature must be greater than 207°C and held long enough for mixing to occur. With a starting solder ball composition of Sn3.0Ag0.5Cu, the joint temperature must be greater than 210°C. With some board designs and reflow conditions, some solder joints may not reach even 207°C, leading to regions of unmelted SnAgCu solder balls in the joint. This was confirmed in a recent paper by Hua, et al,[4] in which VFBGA* and SCSP** packages assembled using a ramp profile with a low peak reflow temperature (208°C) and a short time above SnPb liquidus (30-60 sec.) resulted in unacceptable solder joints. The SnPb solder paste melted, but large portions of the original SnAgCu solder ball were intact.

* VFBGA (very fine pitch ball grid array) package is composed of a very thin core substrate wire-bonded to the silicon die.

** SCSP (stacked chip-scale package) is a molded BGA package capable of accommodating two or more die.

Reliability issues appear only when portions of the solder ball are not melted. Hua et al found that, at slightly longer times above liquidus (60-90 sec.), the joints had largely melted during reflow and such joints exhibited uneven composition and microstructure distributions (**Figure 2**). These distributions illustrate the processes involved in melting and homogenization: melting of SnPb, dissolution of SnAgCu, wetting of the SnPbAgCu along the interfaces between the tin dendrites, and ultimately melting of the whole joint. Most importantly, such inhomogeneities did not result in reduced reliability compared with SnPb controls or mixed joints reflowed at 222°C. The longest times above liquidus in these experiments (90-120 sec.) were sufficient to produce uniform joint compositions and microstructures, and again had reliability comparable to SnPb controls or mixed joints reflowed at 222°C. It is unlikely that similar issues will arise for leaded components or passives because the SnPb solder paste volume is significantly greater than the volume of the solder contributed by the lead-free surface finishes on component and board.

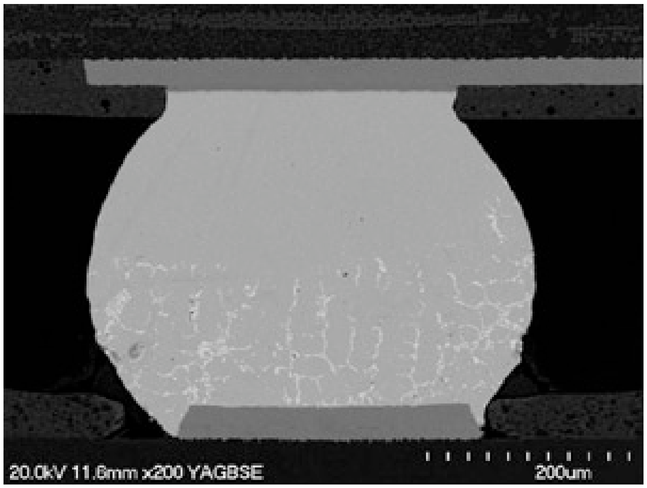

Figure 2: Incomplete mixing seen in BGA after reflow at 208°C, 60-90 sec. above 183°C, ramp profile (no pre-soaking) as reported by F. Hua et al. (Micrograph courtesty of Hua, et al, Intel Corp.)

Forward compatibility. The iNEMI Lead-Free Assembly Project found no problems with manufacturing or reliability when components with SnPb surface finishes or solder balls were processed with SnAgCu solder paste under SnAgCu reflow conditions.[5] Accelerated thermal cycling results indicated that all assemblies with SnPb surface finishes and SnAgCu solder paste, including those with area array components, have reliabilities greater than or equal to SnPb assemblies.

Wave Soldering

Backward compatibility. For wave soldering, no issues arise with backward compatibility. The industry has been successfully assembling boards with lead-free surface finishes (NiAu, OSP, tin) using SnPb eutectic wave solder alloys for decades.

Forward compatibility. Assembling SnPb hot-air-solder-leveled (HASL) boards with SnAgCu alloys has been found to produce widespread fillet lifting in through-hole joints, as reported by NCMS, Biocca and others.[6,7] Fillet lifting is the separation on the topside fillet between the solder and the land at the end of wave soldering (**Figure 3**). Alloys of SnAgCu without lead show good resistance to fillet lifting; however, additions of lead cause an increase in the pasty range of SnAgCu alloys, a necessary condition for the fillet lifting. It is not certain whether fillet lifting adversely affects joint reliability since topside fillet formation is not always a requirement for joints to be acceptable.

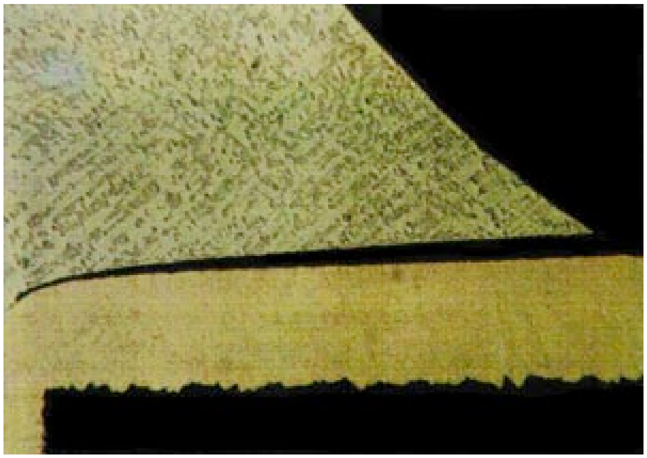

Figure 3: Typical joint showing fillet lifting in a through-hole joint. The separation of the solder from the land occurs during solidification at the end of wave soldering.

Other Materials and Processing Issues

Undoubtedly, additional issues and questions will arise as new materials and processes are introduced into the mix. As with SnPb technologies in the past, materials and processes may have to be refined to make them work in a particular application. As new tests are developed for SnAgCu assemblies, issues may arise that have little to do with the SnAgCu alloy itself. For example, the Universal Instruments Consortium observed that, upon isothermal annealing at 150°C, some SnAgCu (SAC) solder joints showed increased void formation at the interface between the Cu-Sn intermetallic layer and the copper plating. Although they initially referred to this phenomenon as "SAC fragility,"[8] closer study of the data suggests this is probably a board plating issue: only one out of six board lots showed this voiding, and this same voiding occurred during annealing of SnPb solder joints on the same board lot, but not on the other board lots.

In a recent paper, Vianco and colleagues showed that similar voiding may occur with long time, elevated temperature annealing (>170°C, 300 days) of Sn3.9 Ag0.6Cu solder on oxygen-free high-conductivity (OFHC) copper.[9] Those results indicate that we need to study the compatibility of SnAgCu alloys with materials and processes in more detail.

Understanding and resolving these types of materials- and processing-related phenomena will permit the industry to manufacture lead-free assemblies with greater reproducibility and, hence, with greater confidence. Furthermore, identifying the sources of problems as they arise will require careful analysis of the full set of variables, not just changes to the alloy composition.

For SMT, the most serious issue is backward compatibility related to insufficient reflow temperatures or time above liquidus for SnAgCu balls combined with SnPb paste. For wave soldering, fillet lifting may result from assembling SnPb HASL boards with SnAgCu alloys. Materials and processes may have to be analyzed and modified quickly to eliminate barriers to rapid conversion to lead-free solders and to ensure good solder joints with mixed alloys.

References

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Author's note: This activity is part of the NIST Electronics Packaging and Interconnection Program that also includes modeling and measurements of tin-whisker formation, metrology for on-chip interconnections and public-domain modeling tools for solder joint design.

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