尽管研究在继续，目前最可靠的选择仍然是锡/银/铜合金（尽管铅可能在组装中的任何地方出现）。一旦从电路板面层、元件和紧固件中除去了铅，锡/银/铋合金的低熔点和改进的可熔湿性可能证明更可取。作者还发现，整体合金性质，包括疲劳强度和连接强度，对无铅焊料的可靠性不是有意义的指标。而且，在低温和应变范围内，无铅焊料表现出高达锡铅焊料两倍的疲劳寿命。，最后，仍没有抗疲劳焊料的迹象。

Assessing Solder Joint Reliability in Pb-Free Assemblies

Steve Dowds

Research finds bulk alloy properties are not a meaningful predictor of reliability.

There has been much discussion about the merits of lead-free alloys, with their physical and electrical properties being examined – and sometimes disputed – in great detail. Whatever the end-user's preference, one truth remains: the reliability of a lead-free soldered joint should be at least as good as that achieved with tin-lead solders.

How does a soldered joint fail? To establish how reliable a lead-free solder is likely to be in service, first examine the factors that affect reliability. Consider the mechanism by which a soldered joint fails. The typical failure mode for a sound solder joint is low cycle fatigue (LCF), whereby differential thermal expansion through temperature cycling or power cycling continually stresses the joint until the point of failure. Although LCF failures may have a root cause that stems from a flaw in the material – brittle intermetallics or excessive voiding, for example – keep in mind that even a sound joint has a finite life, and can be expected to fail after a certain number of cycles. Reliability is measured as cycles to failure.

One might reasonably assume the bulk properties of a solder alloy are a good indicator of its behavior and reliability as a soldered joint. If this were the case, lead-free assemblies should exhibit higher reliability for two reasons. First, their (typically) higher melting points suggest that any stress generated during service is less likely to approach the alloy's yield strength, which appears to be confirmed by the better LCF properties of a lead-free alloy in bulk form (Sn-3.5AgCu alloy has been found to be superior by a factor of ten when tested against Sn63Pb at 25°C)[1]. Second, lead-free alloys possess higher strength, particularly creep strength.

But the reality is somewhat different when soldered assemblies are actually tested. Despite the lead-free alloy's superior creep strength, it shows similar reliability to Sn63Pb and Sn62Pb2Ag under fatigue testing. Conversely, whereas the addition of bismuth degrades lead-free performance under isothermal testing of the bulk alloy, the opposite is seen when a board assembled using Sn3.5AgBi alloy is used. Clearly the isothermal bulk alloy tests are a poor guide to assembly reliability.

Design and Process Factors

To see the full picture, a wider selection of factors that affect joint reliability must come under scrutiny. These can be grouped into two main categories: design factors and process factors. The design of the assembly includes considerations such as the size and composition of the components and PCB, and how the board is populated. These details have a bearing on the compliance of the assembly (lower compliance for LCCCs and chip components than for QFPs, for instance) and determine the pattern of stress applied to individual joints.

Process factors – variables such as alloy composition, reflow and cooling profiles, degree of oxidation of component termination and board finish, solder paste characteristics and stencil design – influence joint geometry and integrity, and determine the likelihood of excessive void formation or defects occurring at the solder/substrate interface. The microstructure of the joint may also be modified by the dissolution effect of the solder alloy on board and component finishes.

When assessing and comparing results of reliability tests, the test procedure and conditions must be taken into account to avoid misleading or contradictory reliability claims through inappropriate comparison of data. In particular, the criteria that define failure must be carefully chosen. Typical tests include: electrical monitoring, failure being deemed to occur when a specified resistance is exceeded; measurement of joint strength – chip component joints at, say, 50% of their original strength and QFP leads at 0% could be assessed as failures; and microsectioning joints to monitor crack development.

Having established the factors that affect reliability, reviewing some of the acknowledged test regimes and their results provides a real-life picture of lead-free reliability. First, examine the reliability testing conditions used in the IDEALS (Improved Design Life and Environmentally Aware Manufacturing of Electronic Assemblies by Lead-Free Solder) program, summarized as:

- Thermal shock: -25°/+125°C, 3 min. dwell; -20°/+100°C and -40°/+125°C, 30 min. dwell.
- Power cycling: 20-110°C.
- Vibration: random 50-2000Hz oscillation, 6-43g acceleration, duration 15 min., along x, y and z axes.
- Failure parameters: measure joint strength of 1206 resistors and microsection failed joints.
- The 1206 component outline was chosen because it was inexpensive and available with lead-free terminations. The substrate finish was OSP copper.

The results show that the shear strength of Sn96 alloy under temperature cycling is close to that of Sn62 and Sn63 alloys, being reduced about 50% over 3,000 cycles.[2] Power cycling shows a similar trend, the shear strength of 96SC remaining slightly and consistently below that of Sn62 and reducing by about 45% over 3,000 cycles. When sectioned, the failure mode for the lead-free solder alloy is virtually identical to that for tin-lead, the fracture initiating in the thin layer of solder beneath the component and propagating through the main bulk of the solder fillet (**Figures 1 and 2**).

Next, the NCMS (National Center for Manufacturing Sciences) test regime and results:

Program 1

- Temperature cycling: -55°/+125°C, 20 min. dwells, 11°C/min. (LCCC-44, 1206, QFP-132, PLCC-84, immersion Sn FR-4 PCB).
- Temperature cycling: 0°/+100°C, 5 min. dwell, 10 min. ramp (same components).
- Failure criterion: continuous electrical monitoring – intermittent open circuit (200Ω).

Program 2

- Temperature cycling: -55°/+160°C, 10 min. dwells, 10°C/min. ramp (test components 20-lead LCCC, 1206, 0805, 80-lead UTQFP, on OSP FR-4).
- Temperature cycling : -40°/+125°C, 15 min. dwells, 15 min. ramps (test components fleXBGA, PBGA, on OSP FR-4).
- Temperature cycling : 0°/+100°C, 5 min. dwells, 10 min. ramps (test components fleXBGA, PBGA, on OSP FR-4).
- Failure criterion: continuous electrical monitoring – intermittent open circuit (200Ω).

Looking at the LCCC results for number of cycles to first failure at -55°/+125°C, the Sn43Bi57 alloy offers the best performance (at close to its melting point of 138°C), while other lead-free and SnPb alloys exhibit behavior similar to each other. For the 20-lead LCCCs at -55°/+160°C, the target is to match lead-

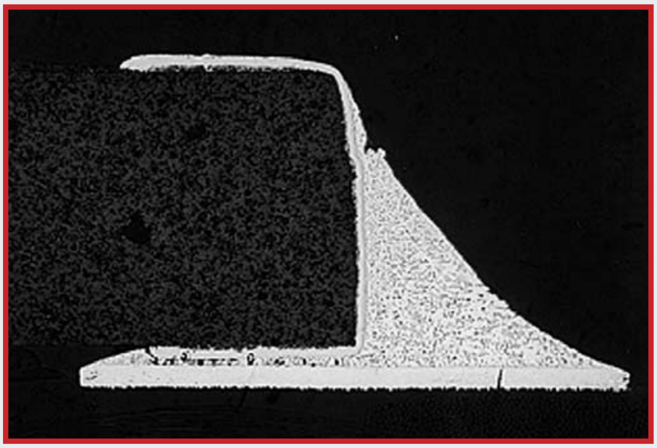

FIGURE 1: Microsectioned SnAgCu solder joint (after 1,000 cycles between -25°/+125°C) showing fracture initiating in solder beneath the component and extending through the solder fillet.

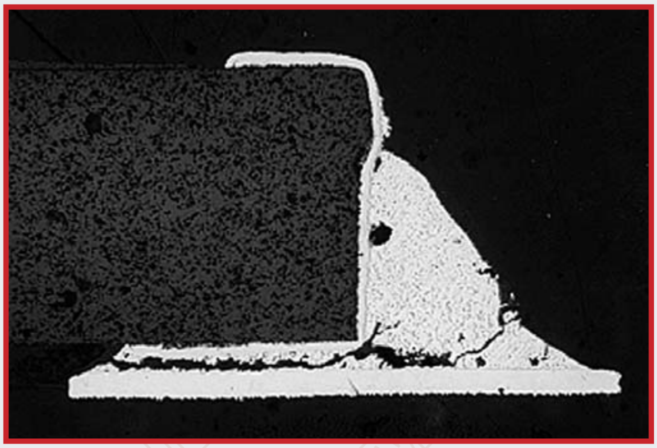

FIGURE 2: SnAgCu solder joint after 2,000 cycles, showing same failure mode as Pb-free joint in Figure 1.

free performance to Sn-Pb performance at -40°/+125°C. The bismuth alloys – SnAg3.4Cu1Bi3.3, SnAg3.3Bi4.8 and SnAg4.6 Cu1.6Sb1.0Bi1.0 – come closest but still fall well short of the target, while the best of the SAC alloys manage less than 50% of the SnPb performance. For fleXBGA at -40°/+125°C, the story is different, with the SAC and SnAgIn alloys narrowly taking the top spots, but without significant advantage over other lead-free alloys and SnPb. Under more moderate conditions of 0°/+100°C, bismuth-containing alloys again come to the fore, with SnAg3.4Cu1.0Bi3.3 and SnAg4.6Cu1.6Sb1.0Bi1.0 outperforming Sn63Pb by almost 300% and the best of the SAC alloys by 25%.

These findings raise the question of the effects of regime severity upon the results. Take two of the alloys; upon normalization the trend is more apparent (**Figure 3**): at 0°C/+100°C, Sn63Pb exhibits a fatigue life only half that of SnAg3.5; at -40°/+125°C this rises to around 85%; and at -55°/+160°C, it leaps to about 220%.

Confusing and contradictory as these results may appear, the following observations may prove helpful in their interpretation:

- Bulk alloy properties, including fatigue and joint strengths, are not a meaningful guide to lead-free reliability performance.
- High-tin, lead-free solders containing silver, copper, antimony and bismuth show broadly similar reliability to Sn63Pb37 and Sn62Pb36Ag2.0 solders.
- Different SnAgCu alloys possess similar reliability characteristics.
- SnPb solders exhibit a higher fatigue life than lead-free solders under more extreme conditions (high temperature and strain ranges).
- Under less extreme conditions (lower temperature and strain ranges), lead-free solders display up to double the fatigue life of SnPb alloys.
- Accelerated testing at high strain ranges extrapolates differently to less extreme conditions for lead-free and tin-lead alloys.

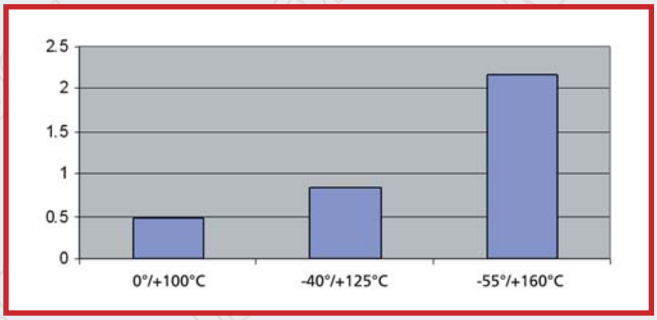

FIGURE 3: Normalized fatigue life for Sn63Pb37 relative to SnAg, different cycling regimes.

- Adding up to 5% bismuth may improve reliability, provided there is no lead contamination that could cause the formation of a low-melting SnPbBi phase.
- As yet, there is no sign of a fatigue-resistant solder, regardless of alloying additions.
- Solders with melting points (mpt) close to peak temperature during cycling seem to perform particularly well; e.g., Sn43Bi (mpt 138°C) at -55°/+125°C and Sn63Pb (mpt 183°C) at 150-160°C peak.

Research continues, but for now the most reliable choice (while lead can potentially occur anywhere in the assembly) remains one of the SAC alloys. Once lead is eliminated from board finishes, components and fittings, the lower melting point and improved wettability of SnAgBi alloys may prove preferable.

References

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