What I Don't Know That I Don't Know:
Things to Worry About with the Pb-Free Transition

The issues and concerns with transitioning to lead-free can be summed up in one question:

Will my Pb-free product keep my customer just as happy as SnPb?

The answer is somewhat simple. For your customer to be happy, your product has to work. And for your Pb-free product to work, it has to have no defects (quality) and last just as long (reliability). Designing, controlling, and ensuring sufficient quality and reliability is fundamentally based on understanding what has changed with Pb-free and how these changes influence quality and reliability.

FIRST PASS

So, what in Pb-free is there to worry about it? At first pass, quite a bit. It can include:

- Component Plating
  - Tin Whiskers
  - Creeping Corrosion (Palladium Plating)
- Connector Plating
  - Fretting Corrosion
  - Stress Relaxation
- Board Plating
  - Long-Term Storage
  - Champagne Voiding
  - Black Pad
- Solder
  - Tin Pest
  - Kirkendall Voiding
  - Electromigration
  - Mixed Solder
  - Long Term Reliability
  - Board Flexing
  - Mechanical Shock
  - Insufficient Hole Fill
  - Fillet Cracking
  - Pad Liftoff
- Reflow Profile
  - Popcorning
  - Melting (SMT Connectors)
  - Loss of functionality
- Capacitors
  - Ceramic (flex cracking and thermal shock)
  - Tantalum/Polymer (popcorning)
  - Aluminum (electrolyte boiling)
- Printed Circuit Boards
  - Cracking/Delamination
  - Degradation of plated through holes (PTHs)
  - Dendritic Growth
  - Conductive Anodic Filaments (CAF)

Don't panic! A closer look at this list reveals that not all problems are created equal.

TIN WHISKERS

Tin whiskers are needle-like growths that emanate from tin-based platings on components and connectors. If these conductive whiskers grow long enough, they can bridge adjacent connections and cause electrical shorts.

This failure mechanism seems to be causing the greatest degree of discomfort in the Pb-free transition. NASA and the US Air Force have banned tin plating because of whiskering concerns. Industrial consortiums like iNEMI and ELFNET have spent years attempting to predict tin whisker's behavior.

What is a Director of Reliability to do?

The first step is to focus. Excluding life-threatening or mission-critical applications, components of concern should be limited to those that have one of the following characteristics:

- Lead-to-lead pitch less than 1 mm
- Metal can housing (e.g., through-hole crystals/oscillators)
- Compressive contact points (e.g., see Figure 1)
- Welds

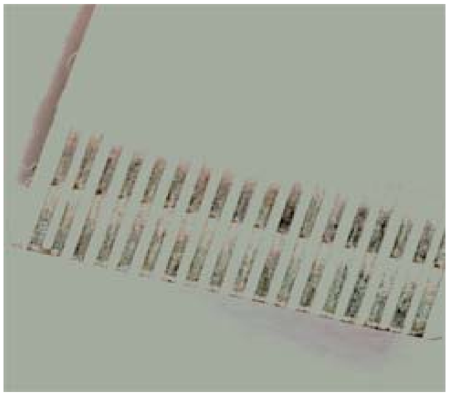


Figure 1: Do not use tin plating on flex circuitry

Once the critical components are identified, ask the supplier if you can get the plating changed to palladium (or gold, in the case of flex circuitry). After initially being resistant, the component industry has responded to increasing concerns by offering OEMs a choice, even if your production volumes are relatively low. Some component manufacturers have even changed their entire fine-pitch line to palladium plating. And asking for palladium tends to be cheaper, quicker, and more definitive than any other mitigation technique available.

If there are no alternatives to tin plating, the next step is based on your level of risk. If your reliability requirements are low or your design life is short, require test results based on JEDEC standard JESD22A121. Come up with your own failure definition as an industry standard is currently absent. Some specifications state absolute requirements, such as a maximum whisker length, while others provide relative requirements (1/3 or 1/2 the minimum spacing).

If your reliability level is medium or your design life is closer to 10 years, require the manufacturers of your at-risk components to perform mitigation. The most widely accepted techniques are a nickel underplate (minimum thickness of 1.2 microns) between the copper leadframe and the tin plating, or annealing the component at 150ºC for 1 hour within 24 hours of plating. Some component manufacturers will claim to have proprietary whisker-free tin plating process, but be skeptical and ask for data. Their process may work, but if they don’t know why, it will be difficult to maintain consistent tin whisker behavior for every batch.

If you need high reliability for a long time (20 years or more), you may have to consider elimination. This currently includes solder dipping or conformal coating. Both come with their own risks.

Long-Term Storage of Pb-Free Solderability Plating

Pb-free board platings, which includes electroless nickel/immersion gold (ENIG), immersion tin (ImSn), immersion silver (ImAg), and organic solderability preservative (OSP), have been on the market for years, so most failure mechanisms or quality issues are pretty well known at this point. Examples include Black Pad with ENIG and Champagne Voiding with ImAg. If you have always used HASL plated boards, the biggest change will be storage times. Except for ENIG, which many companies tend to avoid because of cost, all alternative Pb-free platings should be limited to 12 months of storage. This is because over time ImSn will form intermetallics (temperature), OSP-coated copper will oxidize (humidity), and ImAg will tarnish (gaseous sulfides).

Kirkendall Voiding

One other issue with board plating that also involves solder is Kirkendall voiding. Kirkendall voiding occurs when voids form at the interface between two dissimilar materials due to differential diffusion (see Figure 2). If these voids coalesce, solder joint failure is more likely, especially under mechanical shock/drop conditions.

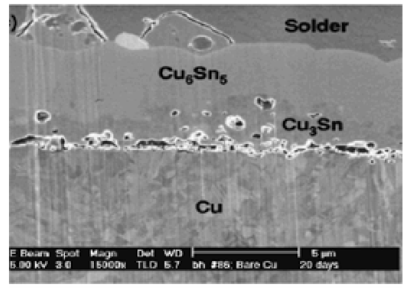


Figure 2: Image of Kirkendall voiding (Zeng, 2005)

So, is Kirkendall voiding a problem? The answer is currently up in the air. Even though the root-causes have not been definitively identified, Kirkendall voiding is a repeatable mechanism observed by multiple organizations. And since the behavior is latent and undetectable, real problems could occur years after the product is in the field, creating a warranty nightmare.

On the other hand, a team from TI/UCLA recently induced this failure mechanism in SnPb even though Kirkendall voiding has never been known to cause field failures during the 30 years of SnPb and SMT. Which begs the questions: Are these test conditions relevant? Has Kirkendall voiding been overlooked as a failure mechanism in SnPb? Or has something changed in copper plating over the past few years?

Mixed Solder

Mixed solder refers to when you are not ready to make the transition to Pb-free, but your ball grid array (BGA) components already have. How to reflow SnAgCu (SAC) solder balls using SnPb solder paste? The answer is very carefully and slightly hotter. The SAC solder ball must collapse, which means a minimum peak temperature of 217C. Most component manufacturers and OEMs recommended at least 225C - 230C, which is not substantially hotter than existing SnPb profiles (215 - 220C). A slight twist is that the finer the pitch, the harder this is to accomplish. If your BGAs are 1 mm pitch, mixed solder should be fine. If your components are 0.5 mm pitch, you may wish to switch to Pb-free sooner than later.

Long Term Reliability of Pb-Free Solder

The figurative pot of gold at the end of the rainbow has been predicting the long-term reliability of Pb-free solder. That is, what happens to Pb-free solder after thousands of hours of temperature cycling, power cycling, or vibration?

For temperature cycling, the complete answer is too complex for this short article. But the general trend can be seen in Figure 3. For high risk components (large, ceramic, leadless) subjected to accelerated testing (-40 to 125C, -40 to 85C, 0 to 100C), there is the potential for SnPb to outperform SAC. Extended dwell times at hot temperature increases this risk. However, under more realistic field conditions, such as room temperature to 85C, it can be seen that SAC is far superior to SnPb, even with extended dwell times.

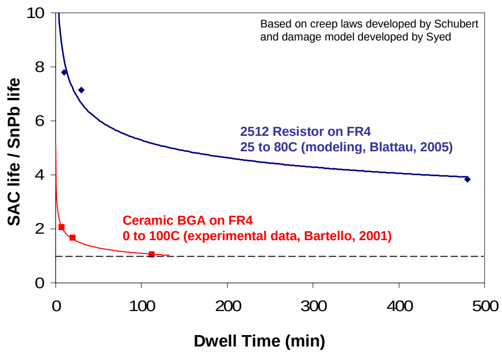
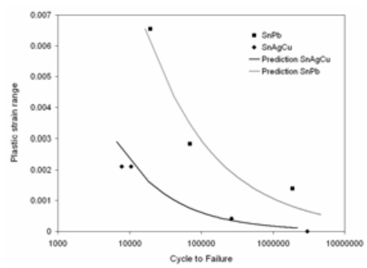


Figure 3: Influence of dwell time on reliability of SAC solder

For vibration environments, SnPb outperforms SAC at higher plastic strain ranges where low-cycle fatigue occurs. Under the lower plastic strain ranges expected in the field, the time to failure becomes roughly equivalent.



$$N_f(50\%) = \frac{1}{2}\left(\frac{2\varepsilon_f^{'}}{\Delta\gamma_p}\right)^{-\frac{1}{c}}$$

Material	ε_f	c
SnPb	0.325	−0.442
SnAgCu	0.325	−0.57

Figure 4: Vibration behavior of SAC slder

Board Flexing / Mechanical Shock

The bigger concern with SAC solder is its ability to resist board flexure during manufacturing and mechanical shock during shipping and operation. A number of studies have shown that SAC alloys can fail at loads up to 50% lower than SnPb when subjected to shock, drop, or static board bending. This loss in performance seems to come from a combination of brittle intermetallics and a greater transfer of stress because SAC is a stiffer material than SnPb.

In response, companies are focusing on maintaining better control over the manufacturing environment, specifically by reducing the maximum allowable strain values from 1000 to 750 or 500 microstrain. In addition, since SnNi is not as shock resistant as SnCu, companies that expect shock and drop in their operating environments are moving away from ENIG as part of their Pb-free transition.

Wave Soldering

Issues related to wave soldering have only recently started to be addressed. The biggest concerns are insufficient hole fill and fillet cracking shown in Figure 5.

Insufficient hole-fill can turn a double-sided solder joint into a single-sided solder joint. Fillet cracking can turn a single-sided solder joint into an early failure. Luckily, both flaws are preventable (higher solder pot temperatures can prevent insufficient hole fill and slower cooling and some design changes can mitigate fillet cracking) and detectable. Just be sure to be look for them.

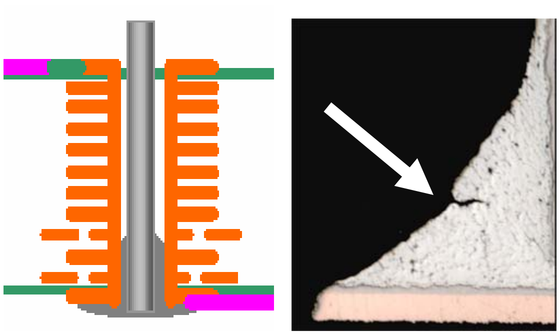


Figure 5: Examples of insufficient hole fill and fillet cracking

Ceramic Capacitors (Thermal Shock)

Initial concerns with ceramic capacitors and SAC solder focused on the potential for increased flex cracking. Recent research by Kemet and DfR have proved this not to be case. The issue that remains is thermal shock. Because of higher temperatures for SAC solder, the maximum wave solderable chip capacitor should be reduced from 1210 to 1206 or 0805.

Printed Circuit Boards

Maintaining the quality and reliability of printed circuit boards (PCBs) as they are subjected to higher reflow and wave temperatures is probably the number one quality concern of OEMs. As a general guideline, the larger the PCB and the higher its density, the greater the potential for quality issues during Pb-free reflow.

OEMs with small boards with no BGAs may have to do little other than perform some construction analysis on their PCBs. OEMs with larger boards, e.g. 12 x 18, and with BGAs and CSPs, may have to consider changes in board material and qualification testing.

For those OEMs with PCB designs at higher risk, the first step is to re-categorize your laminates to include both glass transition temperature (Tg) and time to delamination (t260 or t288). Tg should be at least 150C and t260 should be at least 15 minutes. Once your materials are chosen, qualification testing should be performed using test coupons. These coupons should assess the reliability of the PTH and the robustness of the design to conductive anodic filament (CAF) formation after multiple Pb-free reflows.

Once the laminate is qualified, construction analysis of the initial build is still necessary. Areas of potential cracking includes under BGA pads and between plated through holes with a pitch 1 mm or less.

In conclusion, there are potential quality and reliability issues during the transition to Pb-free, but they can be overcome with the appropriate knowledge and preparation.

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