

Appendix A
RISKS OF CONDUCTIVE WHISKERS IN
HIGH-RELIABILITY ELECTRONICS AND ASSOCIATED HARDWARE
FROM PURE TIN COATINGS

The drive to eliminate lead from electronics is pushing component manufacturers to consider pure tin coatings as an economical lead-free (Pb-free) plating option. This change in plating material is further motivated by the reported industrial problems due to contamination of Pb-free solders by the Pb contained in protective solder coatings [Seelig and Surasaki, 2002]. During the last several years, many electronic component manufacturers (e.g. Vishay, 2001) have announced plans to increase the use of pure-tin coatings on leads and other external and internal surfaces of active, passive, electromechanical and hybrid devices, as well as on mechanical fasteners and support structures.

Introduction to Tin Whiskering

This transition has resulted in renewed concern regarding the phenomenon of tin whiskering, first reported in the 1940s [Levine, 2002]. An example of a tin whisker in an electronic component is depicted in Figure 1. Occurrences of this phenomenon have been reported in the case of passives (eg. ceramic capacitors and resistors), cavity packages (eg. relays, quartz crystal oscillators or hermetic hybrids), and between the unsoldered leads of a plastic encapsulated component [NASA GSFC Website, 2002]. Plans to eliminate the use of conformal coating (for environmental as well as cost reasons) can be expected to further exacerbate the problem. A lack of industry understanding about tin whisker growth factors and a lack of testing methodology to identify whisker-prone products have made pure tin interconnections and plating risky for high reliability systems, such as those used in avionics, aeronautics, satellites, missiles, and medical systems.

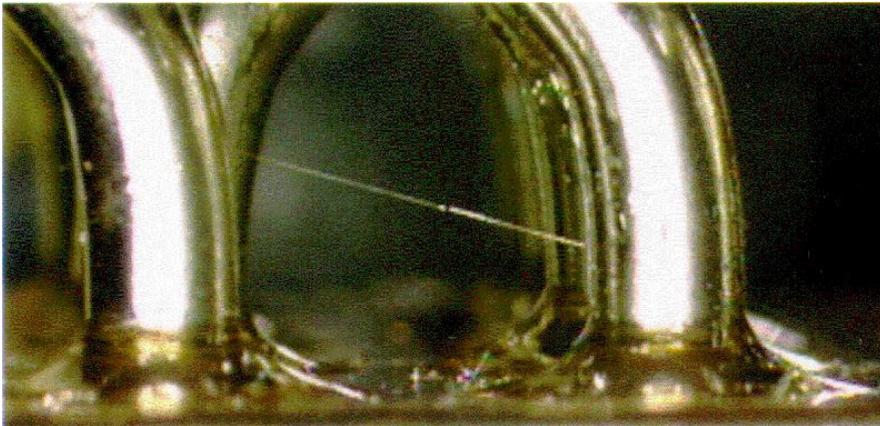


Figure 1 Photo of "pure tin" plated hook terminals of a MIL-R-6106 style relay with LDC 8913 from NASA GSFC stock.

Photo courtesy of Goddard Space Flight Center

The difficulty with addressing the tin whiskering issue stems from the enormous disparities in the literature among its reported drivers (i.e. conditions, geometries,

material characteristics) as well as from the difficulty in identifying the failure-producing whiskers during failure analysis and post-mortems. Tin (and other conductive) whiskers can lead to field failures that are difficult to duplicate or that are intermittent (sometimes referred to as 'could-not-duplicate' or 'no-fault-found' failures) because at high enough electrical potentials the conductive particle can vaporize, thus removing the failure condition. Alternatively, disassembly or handling may dislodge a failure-producing whisker. In some experiments, parts exposed to steady-state or cyclic changes in temperature and/or humidity have shown tin whisker growth, while in other experiments, very similar parts exposed to very similar environments have not [Brusse et. al., 2002]. An even more insidious factor is the large unpredictable variation in the incubation or dormancy period for tin whisker formation. For example, while studies report whisker formation within a period of days to months, the GSFC tin whisker website describes a field failure that occurred more than 20 years after the components were manufactured [NASA GSFC Website, 2002].

What is Tin Whiskering?

Here's what researchers have reported so far. A tin whisker is a single crystal of tin that grows spontaneously from a surface of pure tin. They are typically only a few microns (μm) in diameter but can grow to lengths of more than 10 mm (though lengths on the order of 1 mm are far more common) [NIST Website, 2002]. Tin whisker growth is spontaneous, not relying on external influences of current or electrolytic action, more commonly associated with mechanisms like "dendritic" growth, conductive filament formation and electromigration. While early studies believed that tin recrystallization (which occurs at 50 deg C) played some role in whisker formation, recent studies have reported as much, if not greater, propensity for whisker formation at temperatures as low as room temperature [NASA Web Site, 2002].

Why is Tin Whiskering a Problem?

Tin whiskers can grow between adjacent conductors of differing potential, causing transient or permanent electrical shorts. The demonstrated ability of whiskers to bend due to electrostatic attraction INCREASES the probability of causing a short. In addition, the whiskers can break loose, causing mechanical damage in slip rings, optical components or MEMS [Brusse et. al., 2002]. Also, in low-pressure environments, it is possible for arcing to occur from the tin whisker to an adjacent conductor, causing significant damage. This problem has been demonstrated in terrestrial vacuum tests and is believed to have caused several failures of in-orbit satellites.

The continued push to minimize the size of electronics has resulted in reduction in spacing between electrical interconnects on components and within electronic assemblies. With the reduction in spacing, the probability of a conductive whisker bridging the gap between interconnects and producing a short increases. In addition to miniaturization, the voltage used in many electronics has been reduced. At lower voltages, a conductive whisker is unlikely to be destroyed if it does successfully create a short. As a result, persistent shorting failure may occur. Further, vibration screens

and handling of an electronic assembly may causes surfaces with tin whisker growth to shed. The shed whiskers could then produce shorts within the electronic system. Unfortunately, existing screens may not find whiskers. Whisker growing in fielded product represents a potential failure time bomb. At present, there is no known method that guarantees whisker free surfaces on pure tin finishes.

What are the Factors that Promote Tin Whiskering?

Conventional wisdom attributes tin whiskering to internal stresses in the pure tin layer, with a primary source being the compressive stresses caused by electroplating. However, tin whiskers have also been reported from surfaces where tin has been applied by methods other than electroplating. In the presence of compressive stress, whiskers are extruded over time, as a stress release mechanism. Many factors may contribute to the stress in the plating, including intermetallic formation, thermal expansion mismatches, corrosion of the substrate, and externally applied forces such as bending, lead forming and application of pressure. Defects such as scratches and nicks have been reported to magnify the effects by causing local stress concentrations and possibly providing openings in any protective surface oxide layers. In fact, these external factors may cause whiskering in samples that may otherwise be resistant to the phenomenon. For example, tin whiskers have been observed to form on tin finished surfaces that had been exposed to hot oil dip to fuse the tin (a known mitigating process) [Cunningham and Donahue, 1990]. Adding a trace amount of another element (i.e. Pb or Bi) has been shown to reduce the tendency of plating to grow whiskers. However, whiskers have been observed in 90Sn10Pb [Hom, 2002; Hwang, 2001; Cunningham and Donahue, 1990]. Further, the addition of a trace element to tin plating used for soldering electronic components may result in lower fatigue durability of the solder interconnect [Seelig and Surasaki, 2002]. Environmental factors such as thermal cycling, power cycling, extended storage at various ambient temperatures and humidity have all been observed to affect the whisker formation rates, but there is no consensus yet on the precise nature of these effects, due to conflicting results from different studies. Other factors that have been seen to play a role in whisker growth are grain size, grain orientation, deposit thickness, and underplating [Schetty, 2002]. Of importance is the presence of a gap in the thin oxide on the top surface of the tin coating that permits the extrusion to occur. Whiskering is not limited to tin, but has been seen in other metals including cadmium and zinc. [Downs and Francis, 1994]

Several consortia are currently focusing on tin whiskers. Examples include the formation of committees by NEMI/IPC to develop test methods and modeling approaches for tin whiskers [NEMI Web Site] and the studies being conducted by Soldertec and ITRI in UK. Most of these use comprehensive Design of Experiment (DoE) matrices to empirically explore the effects of critical variables such as plating chemistry, plating process, underplate barrier materials, trace alloy elements, environmental conditions, conformal coating barriers, etc. While many of these studies have provided qualitative insights, no consensus has evolved yet about the key drivers, or about the underlying mechanisms or about the quantitative relationship between the drivers and time to failure.

A more recent and detailed study hypothesizes the following mechanism for whisker growth [Schetty, 2002] in experiments conducted on copper based substrates plated with tin. The initial tin deposit consists of columnar grains of similar orientation (caused by epitaxial effects on the substrate) that are not necessarily under high compressive stress. Copper from the substrate diffuses into the tin, causing the formation of copper-tin intermetallics, which migrate up the grain boundaries between the columnar grains. The higher specific volume of the intermetallic (relative to its components) causes a compressive stress to be set up perpendicular to the growth direction of the grains. The compressive stress extrudes the tin material out of the grains leading to the formation of whiskers.

This mechanism addresses the effects of:

- 1) Grain orientation – columnar grains permit intermetallic formation between them creating cells of compressive stress leading to whiskering. Also, the single-crystal columnar structure permits easy growth of the whiskers.
- 2) Grain size – smaller grains provide more grain boundaries leading to whiskering. This accounts for why bright tin (grain size < 0.5 microns) is more vulnerable to whiskering than matte tin (grain size > 1 micron).
- 3) Plating thickness – thicker platings require longer for the intermetallic to migrate up the grain boundaries and create the full compressive stress cell.
- 4) Underplate – some underplate materials like Ni form intermetallics with Sn more slowly than Cu. Thus the use of a suitable underplate can potentially retard tin whiskering. Again, there are conflicting reports in the literature on the effectiveness of underplate materials under some environmental or test conditions.
- 5) Process parameters: The residual stresses caused by the process contribute to the intermetallic-induced stresses and affects whisker growth rates. Process impurities and alloying elements: Second-phase particles can alter grain structure, reduce grain-boundary diffusion, and impede grain boundary wall motion, thus affecting the rate of whisker formation.

What are the Mitigating Actions Currently Under Investigation?

Based on this understanding of the mechanism, suggestions for mitigating the phenomenon include:

- 1) Using a Sn plating that has more equi-axed grains of different orientations.
- 2) Using matte tin electroplating instead of bright tin. Matte tin has larger grains; the brightness comes from grain refinement.
- 3) Regulating and increasing the thickness of the tin coating.
- 4) Using suitable under-plate materials, such as nickel, may reduce intermetallic formation and mitigate the risk of compressive forces on the tin finish from occurring.
- 5) Controlling the process-induced residual stresses and process defects (like plating defects, scratches, etc)
- 6) Establishing an alternative to Pb, as an effective second phase that retards whisker formation (eg. NIST is examining alternative plating materials)

- 7) Applying a conformal coating to the surfaces of sufficient thickness to contain whiskers.
- 8) Long-term exposure to elevated temperature to increase grain size, reduce residual stresses, and possibly create more uniform underlying intermetallic barrier layers.

What are the Remaining Unknowns to Solve the Tin Whiskering Problem?

Due to the conflicting results available so far, a number of fundamental questions still remain. Some of these are:

1. What are the kinetics of nucleation and growth of the tin whiskers? How much stress is needed to initiate growth?
2. How can the plating process be controlled to produce whisker-resistant microstructures?
3. How do Pb impurity atoms interfere with the growth of whiskers? Do all impurities interfere in the same way? What quantities of different impurities are needed to get the same retardation effect on whisker growth?
4. Does the reflow of tin remove stress or just recrystallize the grains into a larger size in an improved orientation?
5. Why does the intermetallic migrate up the grain boundaries?
6. When can and to what extent does conformal coating mitigate the risks of tin whisker failures– and what are the effects of loss of coating adhesion to the board?
7. What ambient temperature conditions are the worst for whisker growth?
8. Is temperature cycling worse than steady-state temperature aging and if so, why?
9. Is there an effect of humidity (as revealed by the NEMI study) and if so, why?
10. Does inhibiting the formation of a surface oxide layer reduce or retard the tin whiskers?
11. Do the current accelerated tests shift the failure mechanism from that observed in the field?
12. What is the quantitative relationship between the failure drivers and the time to failure? Without such quantitative understanding it will be very difficult to quantify reliability, or to develop acceleration factors for accelerated testing.
13. How can we quantify the risks due to whiskers dislodged during stress screening?

This document is part of a position paper, [**POSITION PAPER ON RISKS TO HIGH-RELIABILITY ELECTRONICS AND ASSOCIATED HARDWARE FROM PURE TIN COATINGS**](#), that has been issued by individuals working in the electronics industry regarding the potential for failure of electronic products due to tin whiskers. In addition to the position paper, a list of tin whisker experiences has been assembled in [**TIN WHISKER EXPERIENCE**](#).

References

J. Brusse, G. Ewell, and J. Siplon, "Tin Whiskers: Attributes and Mitigation," Capacitor and Resistor Technology Symposium (CARTS 02), held at New Orleans, LA, March 25-29, 2002.

J. R. Downs and R. M. Francis, "The Phenomenon of Zinc Whisker Growth and the Rotary Switch," Metal Finishing, pp. 23-25, August 1994.

B. Levine, "Will 'Tin Whiskers' Grow When You Get The Lead Out?" Electronic News, March 25, 2002

M. E. McDowell, "Tin Whiskers: A Case Study (USAF)," Aerospace Applications Conference, pp. 207-215, 1993.

NASA Goddard Space Flight Tin Whisker Homepage, <http://nepp.nasa.gov/whisker/>

NIST Website, www.eeel.nist.gov/omp/interconnect_tinwhisker.html,

Electronics and Electrical Engineering Laboratory, Office of Microelectronics Programs, Tin Whisker Mechanism Study; Contacts: C.E. Johnson, W. J. Boettinger, Kil-won Moon, and M.E. Williams, June 2001.

NEMI Website, <http://www.nemi.org/PbFreePUBLIC/index.html>, Contact: Swaminath Prasad, ChipPAC, May 2002.

R. Schetty, "Tin Whisker Growth and the Metallurgical Properties of Electrodeposited Tin," Proceedings of the IPC/JEDEC International Conference on Pb-free Electronic Assemblies, pp. 137-145, held in San Jose, CA, May 1-2, 2002.

K. Seelig and D. Suraski, "A Study of Lead Contamination in Lead-Free Electronics Assembly and Its Impact on Reliability," Proceedings of the IPC/JEDEC International Conference on Pb-free Electronic Assemblies, pp. 92-94, San Jose, CA, May 1-2, 2002.

K. Cunningham and M. Donahue, "Tin Whiskers: Mechanisms of Growth and Prevention," 4th International SAMPE Electronics Conference, June 1990, pp. 569-575.

Vishay, Lead Elimination in Tantalum Capacitors, Document 40045, Aug, 2001, www.vishay.com

B. Hom," Can Lead-Free Implementation be Cost Effective and Painless?" SAC Lead-Free Technical Session November 16, 2000 San Diego, CA , http://www.sacouncil.org/November2000_presentations/Bance%20Hom%20temp.ppt

J. Hwang, "Environment-Friendly Electronics: Lead-Free Technology", Electrochemical Publications LTD, 2001, pp 698.