# Electroplated Tin and Tin Whiskers in Lead Free Electronics

Fred W. Verdi
11/5/04

American Competitiveness Institute
One International Plaza, Suite 600
Philadelphia, PA  19113

Introduction:

The electronics industry is under extreme pressure from the environmental community to remove elemental Lead (Pb) in the form of the commonly used tin-lead solders from electronic components and assemblies. Pure tin is being electroplated onto component terminals as an inexpensive, solderable, drop-in replacement for the tin-lead alloy electroplated component terminal finishes that have been successfully used for some 60 years. This replacement of tin-lead alloy with pure tin makes the formation of whiskers by tin (Sn) and tin alloys in electronic assemblies a major concern for failure (1). When these electrically conductive, single crystal tin whiskers grow significantly, (e.g.>50 μm and sometimes several mm), electrical shorting between fine pitch circuits becomes possible, leading to catastrophic electrical short circuit failures in high reliability systems such as heart pacemakers, spacecraft, or military weapons and radars. Worse yet, the thin filamentary tin whisker can fuse, creating a plasma that can conduct hundreds of amperes, destroying electronic equipment such as power supplies in high-current applications.

Tin whisker growth is not a new problem. The Bell System has documented the growth of tin, cadmium, and zinc whiskers and subsequent short circuit failures, on electroplated hardware in telephone switching equipment as early as 1946 (1). After extensive study, Bell Laboratories recommended alloying the tin with lead, and the result has been essentially whisker free electronic assemblies, using tin-lead alloy plating on component leads and circuit boards and using tin-lead solder attachment in assembly, for the last 60 years.

Because of the recent global environmental emphasis in eliminating lead (Pb) from electronics, a firm metallurgical understanding of tin (Sn) whisker growth and methodologies to predict or mitigate growth are needed. Such mitigation techniques are not conclusively known, making the situation of electrical failure risk due to tin whiskers, particularly in high reliability systems unacceptable. A spontaneously growing, electrically conductive, tin whisker in an expensive and/or life supporting military or high reliability medical assembly can cause catastrophic failure.

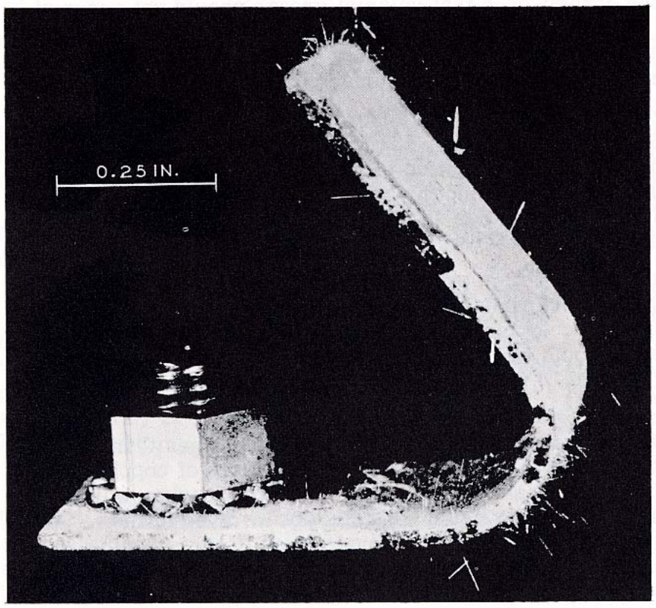

Figure 1. Early photograph of spontaneously growing, tenth-inch long single crystal tin whiskers from Bell Laboratories investigation of electrical short circuit failures from tin plated details in telephone switching equipment in the 1940's.

From the 1940s until the last decade of the twentieth century, tin-lead electroplate and tin-lead solder was routinely used for electronic assembly, with virtually no chance of tin whisker failures. The history since then begins to show the growing menace and attempts at mitigation.

In 1993, M.E. McDowell of the United States Air Force (2) outlined the method used by the USAF in dispositioning Sn plated parts in inventory. No position was taken relative to the prohibition of Sn usage (as previously recommended by Dunn of the European Space Agency (3)). This would prove to be an unfortunate situation, as later events were to show, relative to reliability failures on USAF equipments. Between 1990 and 2004, Brusse from NASA compiled a list of high reliability system failures caused by metal whisker growth. Tin, Zinc, and Cadmium are all prone to whisker growth. This list of failures in the time period from 1990 to 2004 counts scores of well-documented whisker failures in electronic assemblies, from heart pacemakers to NASA and commercial satellites, and many millions of dollars in monetary losses. A typical tin whisker shorting issue is depicted in Figure 2 (After Brusse/NASA ref. 4).

Figure 2 Tin whiskers causing electrical shorts between connector pins after 10 years in service.

This increased incidence of whisker failures has not gone unnoticed by the scientific community. In the first two years of the 21st century, there were more presentations/papers on Sn whisker matters than in the prior 15 years. The advent of lead free electronics manufacturing (in response to environmental legislation) undoubtedly accounts for much of this renewed interest. Many commercial and military organizations have begun consortia and programs to define mitigation techniques that might be able to stem the tide of whisker failures. As of this writing, no conclusive set of mitigation techniques is widely accepted, and so the only accepted mitigation for tin whiskers is to electroplate component terminals with a solderable metal other than pure tin. Immersion Silver, Electroless Gold, Nickel-Palladium, all can be substituted for tin, but at significantly higher cost than electroplated tin.

Metallurgical Theory:

White Sn (β Tin), the phase of tin constituting the tin whisker, has a body centered tetragonal crystal structure. The c/a ratio is less than one, meaning that the unit cell for tetragonal tin is longer on one side than the other (rectangular in cross section). This configuration of a material (i.e. not cubic) is usually an indication of anisotropic properties. For tin, the coefficient of temperature expansion (CTE) and the self diffusion coefficient are higher in the "a" direction (longer side) than in the "c" direction (shorter side). Other metals that have such an anisotropic crystal structure (c/a ratio less than one), such as Zinc and Cadmium with their hexagonal close packed structure, also form whiskers readily. In fact, the first well documented occurrence of whiskers was on cadmium plated military hardware in 1948. Another common failure is for the zinc-chromate coated steel supporting structures for raised floor clean rooms to grow spontaneous zinc whiskers over time, resulting in conductive particle contamination of the laminar air flow in the clean room.

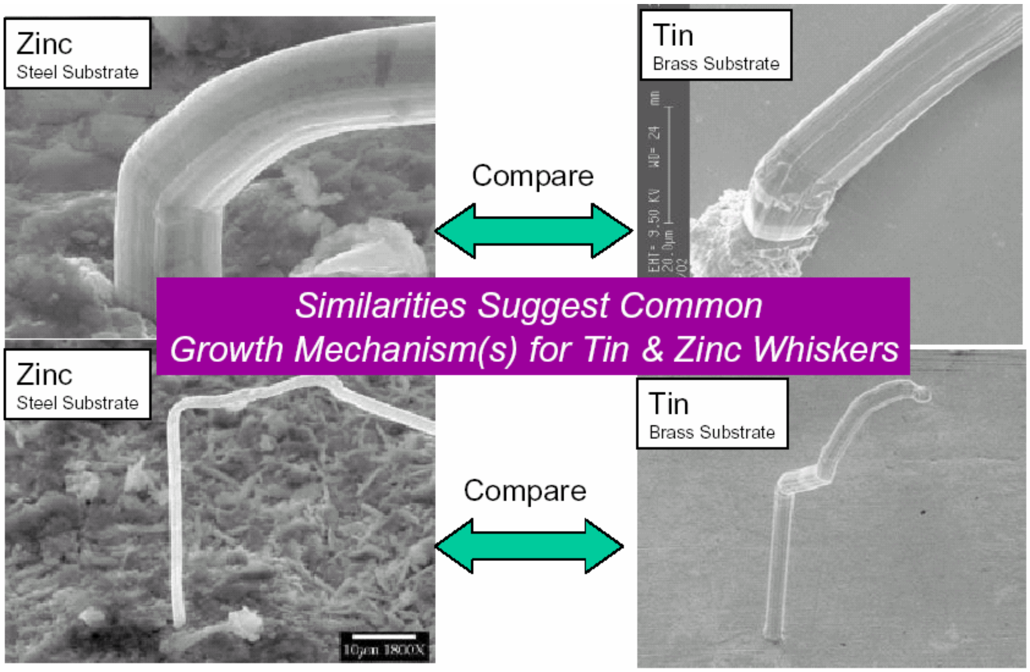

Figure 3. Similarity between the tin and zinc spontaneous whisker growths. Both are conductive single crystals (From J.A. Brusse, NASA ref. 4)

Sn is known to have several active slip systems and direction along with an active twinning system, Table 1. Multiple growth directions for Sn whiskers have been found during investigations of whisker growth

| **Allotropic Phase** | **Slip Planes and Directions** | **Twin Plane** | **Whisker Growth Directions** |
|---|---|---|---|
| **β – Tin (Body Centered Tetragonal)** | (110)[001], (010)[100], {101}1/2[111], {101}[101], {121}1/2[111],{121}[101] | 331 | 110, 001, 103, 321 |

Table 1: Slip Planes, Slip Directions Twin Planes and Whisker Growth Directions for Sn (5).

Investigations of high strain deformation of Sn in a "Deformation Processed Metal-Metal Matrix Composite" (DMMC) shows Sn takes on a <001> texture. It's assumed that this texture is brought about by the Sn deforming in a plane strain condition (6). Several authors investigating Sn whiskers have seen a similar texture in the Sn single crystals. Many researchers have cited the <001> direction as a predominant growth direction for tin whiskers.

Since the melting point of Sn is very low (504.9K), at normal room temperature Son is above T/Tm = 0.5. At high homologous temperatures dislocation motion becomes a predominant deformation mechanism.

Mechanical Stress Model:

It is well documented that internal compressive stress is a driving force for the growth of tin whiskers. This stress can come from the naturally occurring compressive stress that occurs when tin is electrodeposited from a plating bath. The more organic brightening addtions in the plating bath, the higher the internal stress in the tin deposit will be. The highest stressed deposits are obtained from baths that yield "bright" or specular (mirror-like) deposits, often used for decorative electroplates. Somewhat less prone to whiskers is the "matte' or dull finished tin, which is usually lower stressed, but still will grow (usually fewer and/or shorter) whiskers.

Other sources of internal stress in tin electroplate are intermetallic compounds formed from the base metal onto which the tin is electroplated. For example, the tin is often plated onto a copper component terminal lead or printed circuit trace. An intermetallic compound, $Sn_6Cu_5$, or in some cases, $Sn_3Cu$ are readily formed, and cause internal compressive stress in the tin layer as the intermetallic compound grows. This internal stress can accelerate whisker growth. A mitigation for this effect is to electro- or electrolessly plate a nickel diffusion barrier between the tin and copper layers.

Hot dipped or reflowed tin tends to grow fewer and shorter whiskers as well, once again so long as precautions are taken to avoid stress-causing intermetallics.

Elimination of compressive stress (including imposition of tensile stress) into the electroplated Sn finish layer will suppress whisker growth to a great extent (6). Although this elimination of compressive stress in the Sn plate has been successful in minimizing whisker growth, verification of the stress level in a plated deposit requires X-Ray diffraction on the deposit, an analysis that needs to be executed in a laboratory. It would be much preferable to discover an alloying addition which (in the same manner as Pb) can be detected in the deposit by XRF (X-Ray Fluorescence). XRF, which can be done in a routine component incoming inspection, has been adopted as the method most commonly used by the major defense OEMs to accept or reject components based on their inclusion of at least 3% of Pb in the Sn plating on the component contact areas. Of course, availability of such components for the defense and critical high reliability applications has become very limited as the suppliers target the huge lead free commercial market with pure tin electroplated component finishes.

A much more conservative approach to mitigation of the tin whisker issue would be to select the proper tin alloy, verifiable by XRF, that eliminates the possibility of whisker growth in an analogous fashion to the way that (at least >1%) Pb in the Sn plating finish does today. This would allow virtual elimination of whisker growth from Lead-Free components. Obviously, there are alloying additions to tin that *do not* suppress whisker growth (such as Cu, Bi, or Ag). The crystallographic mechanism by which the chosen lead substitute is effective in suppressing whisker growth will be the same mechanism that works for the tin-lead system.

The successful mitigation program will concentrate on the electroplating process to finish lead free components with the correct whisker-immune electroplated Sn alloy. This tin alloy can then be verified by use of XRF (X-Ray Fluorescence), just as the current SnPb alloy compositions are being verified by most large defense OEMs. Verification can be accomplished by electroplating tin or selected tin alloys onto a surface that initiates immediate whisker growth such as controlled externally applied compressive stress, and observe the resulting whisker propensity.

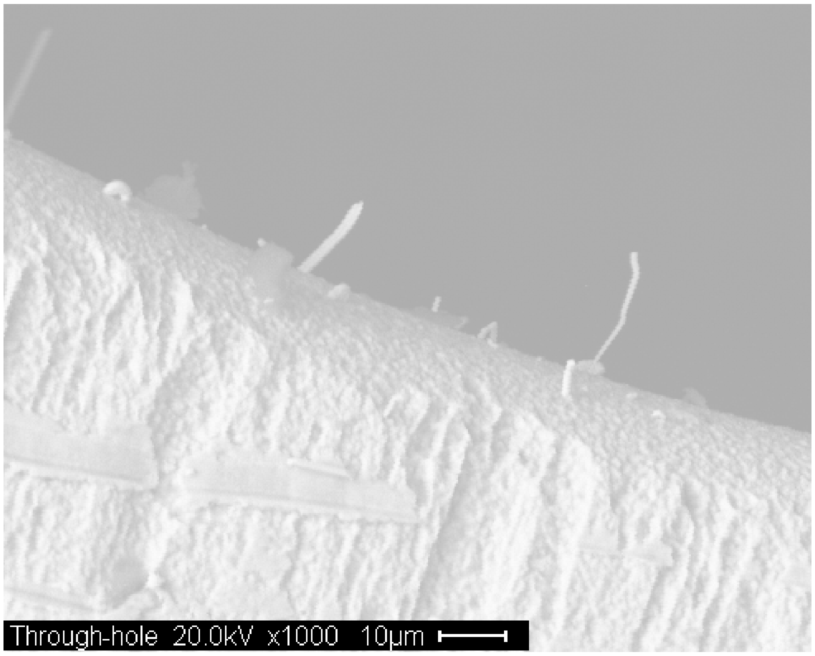

Figure 4. Scanning Electron Micrograph of tin whiskers grown on tin coating inside of plated through holes in an immersion tin plated printed wiring board after only 5 days of storage. Such accelerated growth could enhance the study of the tin whisker phenomenon to help identify and eliminate its root cause.

## Accelerated Whisker Testing

Experiments have shown that immersion Sn plating will cause whisker formation from the immersion plated tin on interior surfaces of Copper (Cu) plated through holes in PCBs (Printed Circuit Boards) in several days rather than months or years. Apparently this accelerated growth results from the mechanically applied compressive stresses developed by cooling the printed circuit substrate from the plating bath temperature to room temperature (thousands of psi), and the high Z axis CTE of the FR-4 substrate, putting a high “squeeze” or compressive stress on the plated film that coats the inside walls of the plated thru holes in the circuit boards. This phenomenon could be used to more quickly verify the mitigating effects of the electroplated alloying of the tin.

Until such a root-cause study is executed, tin whisker mitigation will continue to be a risky business. At this writing the only scientifically supported and confirmed mitigation technique remains to alloy the tin with at least 1% Lead, just as it was in the 1950s.

References:

1) G. T. Galyon, “Annotated Tin Whisker Bibliography,” IBM Server Group Chair, NEMI Tin Whisker Modeling Project, July, 2003.

2) M.E.McDowell, “Tin Whiskers: A Case Study”, *Aerospace App. Conf.*, pp. 207-215, 193.

3) "A Laboratory Study of Tin Whisker Growth", B.D. Dunn, *European Space Agency (ESA)* STR-223, pp. 1 - 50, September 1987

4) J.A. Brusse, “A Discussion of the Significance of Metal Whisker Formation to the High Reliability Community,” November 2003, J.A. Brusse.1@gsfc.nasa.gov

5) Metals Handbook 9th Edition, ASM, Metals Park, OH.

6) Chen Xu, Chonglun Fan, Yun Zhang, and Joseph A. Abys, “Whisker Prevention” Proceedings of the Techn ical Conference APEX, Jan. 19, 2002.

7) Yuki Fukuda, Tong Fang, Michael Pecht, and Michael Ostermand, “Effect of Heat Treatment on Tin Whisker Growth” CALCE Electronic Products and Systems Center, University of Maryland, College Park MD.