The Continuing Dangers of Tin Whiskers and Attempts to Control Them with Conformal Coating

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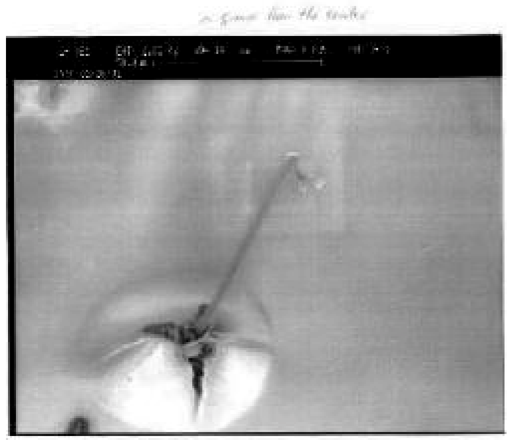


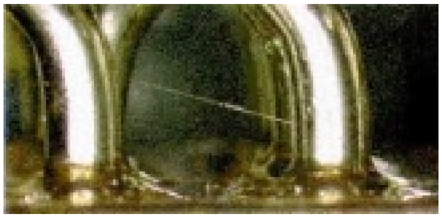
Figure 1. SEM photo of a tin whisker breaking out from beneath conformal coating (x625)

Abstract:
A 1998 commercial satellite failure caused by tin whisker induced shorts prompted NASA Goddard Space Flight Center (GSFC) to issue a NASA Advisory (NA-044 and NA-044A) [1,2] to remind the NASA community of the tin whisker phenomenon and the inherent risks associated with the use of pure tin plated components. Indeed the NASA Advisory served as a "reminder" since the spontaneous growth of tin whiskers from some tin plated surfaces has been known and studied for over 50 years with dozens of technical publications and several GIDEP Alerts produced during that time. During the 1990s the US Military modified most (but not all) of their electronic component specifications to prohibit the use of pure tin finishes in order to minimize the risks of whiskering. However, as regulations and a world economy push today's electronics industry to use environmentally friendly (Pb-free) alternatives, the prevalence of pure tin plated components is bound to increase potentially increasing NASA's risk of exposure to risks associated with tin whiskers significantly.

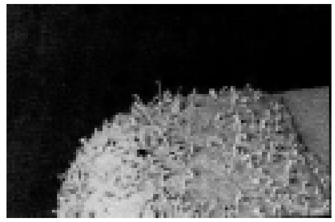
In an effort to evaluate risk mitigation techniques, NASA GSFC initiated experiments to study the effects of Uralane 5750 (a commonly used conformal coat) on tin whisker growth. After more than two years of experimentation, we have found that conformal coat does not prevent tin whisker formation although it does appear to substantially reduce the rate of growth. We have observed that a tin whisker has grown through an area of conformal coat that is approximately 1/4 mil thick (see figure 1). Numerous tin nodules growing beneath a nominal 2 mil thick coating are also being monitored to determine if and when they will be able to penetrate this barrier. We have also observed that tin whiskers can bend in response to forces of electrostatic attraction; thus increasing the probability of tin whisker shorts either from two whiskers colliding or from one whisker bending to contact another conductor. Especially for long duration missions, use of conformal coat as a sole means of risk mitigation may not be completely effective. Research is ongoing.

BACKGROUND:

The growth of tin whiskers on pure tin plated electronic components and associated hardware has been documented for decades. Notable examples of pure tin plated components that have exhibited tin whisker formations include electromagnetic relays, transistors, hybrid microcircuit packages, terminal lugs and very recently ceramic chip capacitors. A few such examples are shown below in figure 2:



Electromagnetic relay terminals
Photo courtesy of NASA GSFC



Ceramic chip capacitor termination
Photo courtesy of Ericsson

Hybrid microcircuit lid
Photo courtesy of JPL

Figure 2. Examples of Tin Whiskers Growing on Pure Tin Plated Electronic Components

An article was published in the December 1998 edition of the EEE Links Newsletter that provides a basic overview of the tin whisker phenomenon and some of the inherent risks.(3) Included in that article are explanations of the possible effects of tin whiskers in more conventional earth-based environments. Also, interim results and a detailed explanation of GSFC experiments were reported in a September 2000 paper entitled "Effect of Conformal Coat on Tin Whisker Growth".(4) The authors of this current article guide interested readers to these two publications for a simple primer on tin whiskers and details of the GSFC experimental process as those details will not be repeated here. In addition, the NASA Goddard Tin Whisker Homepage provides an extensive list of reference materials on the topic as well as access to our published paper:

http://nepp.nasa.gov/whisker

A 1998 on-orbit commercial satellite failure was reportedly caused by tin whiskers emanating from the surface of a pure tin plated relay.(5) Over time the whiskers grew to such a length that they were capable of short circuiting the spacecraft bus. Laboratory tests dating back to the early 1990s demonstrated the potential for a tin whisker short to form a plasma in reduced barometric pressure environments (vacuum). (6,7) If sufficient energy and a low impedance path are available from the power source, this plasma can sustain an arc that is capable of carrying HUNDREDS of AMPERES! Such a short circuit is reported to have occurred on the commercial satellite opening protective fuse elements thus rendering the spacecraft non-operational. Since 1998 it has been reported that two additional commercial satellites employing a similar bus design have failed from this same mechanism. (8)

Despite the extensive research performed to date by industry and academia, an accepted comprehensive description of the growth mechanism(s), effective risk mitigation practices and industry accepted tin whisker test methods still elude researchers. It is however, commonly believed that the whiskers form in order to relieve residual stresses in the plating that result from internal and/or external stresses. As such, "bright" tin finishes which have a high residual stress after plating are more prone to whiskering. Numerous other factors also affect whiskering propensity such as substrate material, plating chemistry and process, plating thickness and grain size. The studies to date have not conclusively demonstrated the relative importance of these factors nor combinations of these factors and as such a "proven" whisker-free pure tin plating process that is adaptable to all types of components is not yet available.

Some studies suggest that alloying as little as 0.9% lead (Pb) with the tin dramatically reduces the size and growth rate of whiskers to a low enough level that is safe for current microelectronic geometries. As such, NASA Advisory NA-044 reports that the most effective risk mitigation technique against tin whisker induced short circuits is to prohibit the use of electronic components and associated hardware that employ pure tin plating as a final surface finish (common practice is to require a minimum of 3% Pb). The current worldwide initiative to reduce the use of potentially hazardous materials such as Pb is driving the electronics industry to consider pure tin plating as an alternative to tin-lead plating. With respect to factors such as solderability, ease of manufacture and compatibility with existing assembly methods pure tin plating is a viable alternative. However, the current lack of an industry accepted understanding of tin whisker growth factors and/or test methods to identify whisker-prone products makes a blanket acceptance of pure tin plating a risky proposition for high reliability systems.

Knowing that simple prohibition of pure tin plating will become more and more difficult, NASA GSFC decided to conduct experiments to study the effectiveness of other tin whisker risk mitigation techniques. Several mitigation approaches have been suggested in the past including annealing or reflowing the plated surface with high temperature to relax internal stresses, covering solderable surfaces with a Pb-containing solder or coating the surface with a protective barrier of conformal coat. All of these practices have benefits and limitations. The conformal coat approach seemed to be the most practical and least invasive technique for high reliability systems. GSFC review of the available literature found limited information related to the benefits of conformal coating as a risk mitigation technique. Therefore, in December 1998 NASA GSFC began experiments to evaluate the effectiveness of using conformal coat to mitigate the risk of tin whisker growth.

Experimental Approach:

The objective of the GSFC experiments was to determine if conformal coat could be used as an effective risk mitigator, when whisker-prone (or unknown whisker propensity) components are used in electronic systems. Uralane 5750 was selected as the conformal coat material for these experiments because of its common use in NASA flight hardware. Experiments were devised to evaluate the effectiveness of Uralane 5750 at:

- **Delaying the onset** of tin whisker formation (incubation period)
- **Affecting the growth rate** of tin whiskers
- **Affecting the growth density** of tin whiskers
- **Preventing tin whiskers from growing through the coating**

As such, for the purpose of these experiments, test specimens with extremely high propensity to form tin whiskers were intentionally produced, so that the effects of the coating on whiskering could be observed and documented. A literature search found that brass substrates with "bright" tin electroplate of approximately 200 microinches were highly prone to whisker formation. The specimens for our experiments were procured from a commercial plating shop.

- <u>Substrate Material:</u> Brass Type 260 (test coupons were 4" x 1" x 0.032")
- <u>Underplate:</u> 50% of samples have a copper strike and copper plate to 0.0001" min
50% of samples have NO underplate (i.e., tin plate direct on brass)
- <u>Plating Process:</u> "Bright" tin bath
- <u>Tin Plate Thickness:</u> 200 ± 50 microinches

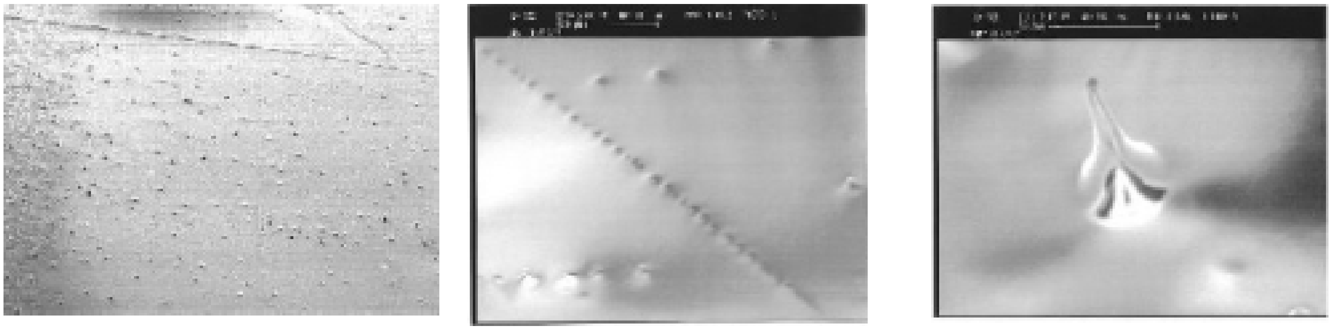
To further promote whisker formation, portions of the test specimens were intentionally scratched using a knife blade. Such surface defects are reported to create localized stresses in the plating that may promote whisker formation. Samples were then coated over half their surface using Uralane 5750 to a nominal thickness of 2 mils; the other half was left uncoated as a control. Seven (7) samples were stored under ambient laboratory conditions (approximately 22°C and 30% to 70% relative humidity) while eight (8) samples were stored at 50°C which our literature review found to be commonly reported as the optimal temperature for whisker formation.

Experimental Results/Observations After 2 ½ Years:

For the last 2 ½ years the test specimens have been examined periodically, using both optical techniques and scanning electron microscopy (SEM).

Incubation Period and Whisker Density:
Our experiments to date have shown that Uralane 5750 conformal coat applied over top of whisker-prone test specimens does NOT PREVENT the formation of tin whiskers. Tin nodules initiated within one month of plating on both the conformal coated and non-coated specimens. Interestingly, after 4 months, the density of the nodules was 4 to 5 times higher on the coated side compared to the non-coated side. However, one year after the initiation of the experiment the density of whisker formations was found to be approximately equal on both coated and non-coated specimens. It was hypothesized that the rapid formation of tin oxide on the non-coated side increases the incubation period for whisker formation. This hypothesis has not been tested.

Figure 3 shows the formation of tin nodules beneath the conformal coat on several specimens. Such growths under the conformal coating are common on all of the specimens regardless of storage conditions (room temperature vs. 50°C). In these SEM images the tin whiskers resemble a spike being pushed into a rubber membrane, deforming the surface into a sharp-tipped cone. It is interesting to observe that many of the whiskers in Figure 3 formed along a surface scratch or defect in the substrate that was NOT intentionally introduced. These minor defects were most likely present on the substrate prior to plating or were introduced through the handling of the specimens just prior to initiation of the experiments. This observation raises the concern that basic handling during manufacturing or user assembly may impart stresses to the plating surface which become nucleation sites for whisker growths.



10X magnification *43X magnification* *670X magnification*

Figure 3. SEM photos of tin domes forming beneath conformal coating

Whisker Growth Rate:

The application of conformal coat appears to retard the rate of whisker growth compared to an uncoated surface. The longest whisker observed on these specimens on the non-coated side is on the order of 2 mm, whereas those whiskers growing beneath the conformal coat are on the order of 0.05 mm (at present). Still unknown is whether the rate of growth will increase once the whisker has broken through the coating material. The average growth rate of the needle-like whiskers on the non-conformally coated areas is about 0.13 mm/year. The fastest growth rate from these specimens is approximately 0.80 mm/year.

Whisker Penetration of Conformal Coating:

Figure 1 shows the most extreme observation we have recorded to date where a tin whisker has actually grown through the conformal coating approximately 2 years after application of the conformal coat. Attempts to measure the actual thickness of the coating at this location have been difficult because this area of the test specimen has a relatively thin layer of conformal coat. Estimates of the coating thickness in this location are on the order of 1/4 mil. After emerging from the coating, the tin whisker can become a risk for inducing short circuits. As noted previously, there are numerous other whisker growths beneath the thicker areas of conformal coating (~ 2 mil thick) that we anticipate will eventually penetrate the conformal coating. With some NASA missions extending over 10 years, and a few to 20 years, it is possible (but not confirmed experimentally) that coatings even as thick as 10 mils may not prevent whiskers from protruding.

Future inspections will continue to look for more whiskers penetrating the coating and if possible, experiments may be conducted to examine the effect of the conformal coating at quenching an arc formed by a whisker induced short circuit under reduced barometric pressure conditions (vacuum).

Demonstration of Whisker Deflection due to Electrostatic Attraction:

Theoretical calculations predict that a whisker that emerges from a coated surface and then comes in contact with a 2nd coated surface will buckle before being able to penetrate that surface.[1] However, short circuits caused by tin whiskers growing outward through a conformal coating are **still a real risk**. Suppose two whiskers emerge from beneath separate conformally coated surfaces at different electrical potentials. **The electrostatic force generated by the potential difference between the whiskers will attract them towards each other thus significantly increasing the likelihood of the whiskers shorting together.** Figure 4 shows tin whisker growing from a mounting tab of a pure tin plated relay. In this GSFC experiment, the mounting tab (and thus the tin whisker) was electrically grounded. A test probe (used to simulate a 2nd whisker) was brought into close proximity (~ 1 mm) of the whisker, but situated such that physical shorting was not possible. The test probe was then placed at 50 V relative to the whisker. As can be seen from this enhanced photo, the tin whisker bends as a result of electrostatic force generated by the potential difference between the whisker and the test probe. After removal of the test potential, the whisker bends back to its original position. This experiment was repeated hundreds of times without causing the whisker to break. Further experiments to study this behavior are planned.

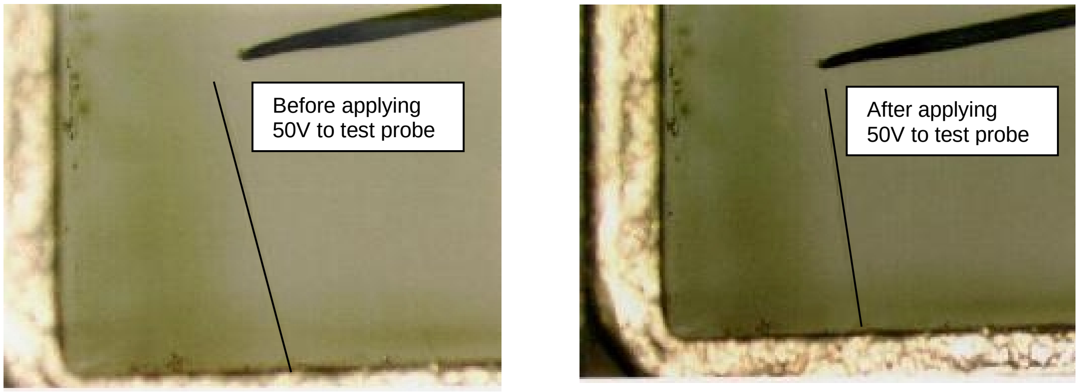


Figure 4. Optical photo of tin whisker movement due to electrostatic attraction
(Note: Photo has been graphically enhanced to aid in observation of the thin whisker)

Effects of Storage Temperature:
Contrary to other studies on tin whisker formation, GSFC observed higher density of whisker growth on samples stored under room ambient conditions (approx. 22°C, 30%-70% RH) than on samples stored at 50°C. This is not at all unusual in the study of whiskers - experimenters often find conflicting results, suggesting there is some underlying factor or factors that are not recognized and are not being controlled. This situation makes it particularly difficult for us to have confidence in claims by commercial interests that they have developed whisker-free coatings, especially given the great variability in incubation time that is also reported in this literature. Table 1 provides a comparison of the whisker density and typical length after 2 years versus storage conditions and substrate preparation. These comparisons were made for whisker formations from non-conformal coated sides only.

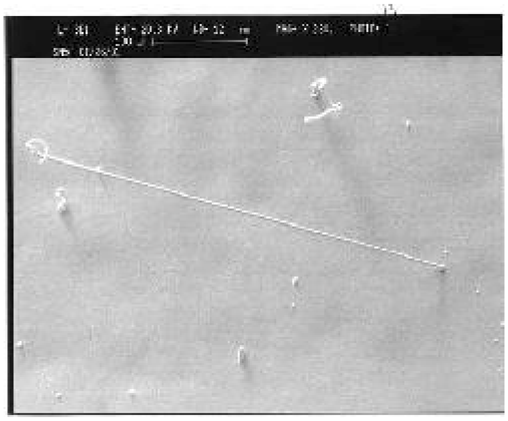
Table 1. Whisker density and length comparison between the specimen stored at 25 °C and 50 °C after 2 years.
(Non-Coated Specimens)

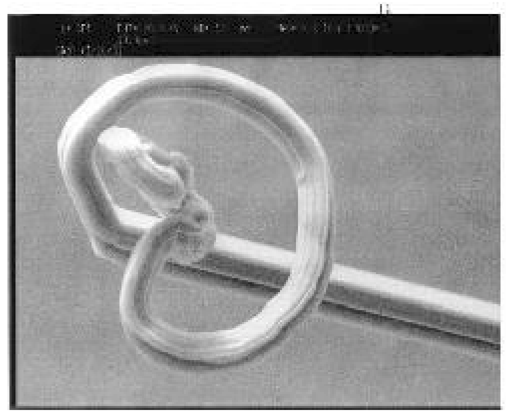
Stored at 50 °C					
Specimen without Cu flash			Specimen with Cu flash		
S/N	Average density (whiskers/mm^2)	Typical whisker length for needle-like whiskers (um)	S/N	Average density (whiskers/mm^2)	Typical whisker length for needle-like whiskers (um)
1T	18	20	1C	6	20
2T	18	20	2C	6	20
3T	18	20	3C	17	200
4T	18	20	4C	7	280

Stored at room ambient conditions					
Specimen without Cu flash			Specimen with Cu flash		
S/N	Average density (whiskers/mm^2)	Typical whisker length for needle-like whiskers (um)	S/N	Average density (whiskers/mm^2)	Typical whisker length for needle-like whiskers (um)
5T	50	900	5C	26	250
6T	50	900	6C	32	138
			7C	32	132

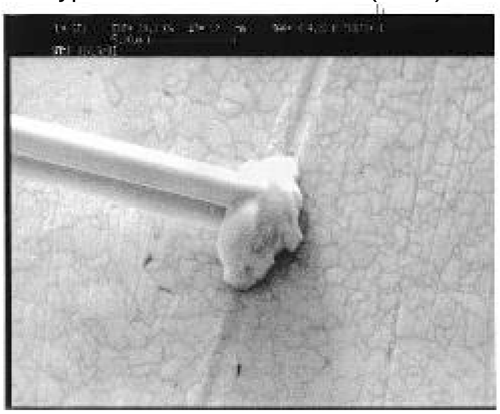
As shown in Table 1, the density of the whiskers on samples stored at room temperature is two to three times higher than for those stored at 50°C. This observation is independent of the presence of a copper flash intermediate layer between the brass substrate and the tin plating. In general, the whiskers are also much longer on specimens stored at room temperature. This finding contradicts observations reported by other experimenters. The longest whisker we have observed to date is about 2 mm long after just over 2 years

Some photographs documenting growth behaviors of tin whiskers on non-conformally coated specimens are shown in Figure 5.





A. Typical needle-like whisker (x230)   B. Tip of a whisker shown in A. (x3200)



C. Base of whisker shown in A (x4220)   D. Kinked area of a whisker (x6500)

E. Typical straight whisker (x450)   F. Thinning of a whisker (x2200)

Figure 5. Various tin whisker formations observed in GSFC experiments

Conclusions

Catastrophic failures of electronic systems caused by tin whisker induced short circuits have been reported in commercial satellite applications. Despite decades of research into the tin whisker phenomenon, a comprehensive understanding of the mechanisms that affect their growth is not available. Currently, there are no industry accepted test methods for determining a particular component's (or plating process's) propensity to form tin whiskers. Some experimenters report the incubation time before initiation of whisker growth can be months, if not years. These observations are particularly concerning for long duration missions.

Historically, various forms of pure tin plating (especially, "bright" tin plating) have been found to be prone to tin whisker formation. Currently, the most effective risk mitigation technique against tin whiskers is to avoid the use of components that are most prone to whiskering of the form that is large enough to pose a reliability hazard. In the event such usage cannot be avoided or confirmed, users are advised to carefully review the use of pure tin plated components against application conditions, circuit geometries and mission objectives.

NASA GSFC is evaluating the effects of Uralane 5750 on tin whisker formation. Experimental observations and data are summarized below:

1. Uralane 5750 does not prevent whisker formation
2. Uralane 5750 shortens the incubation period of whisker formation
3. Although, whiskers initiate more rapidly under Uralane 5750, the coating also retards the growth rate of whiskers
4. Whiskers are capable of growing out from beneath a 1/4 mil thick Uralane 5750 coating
5. Tin whiskers can bend under forces of electrostatic attraction, thus increasing the probability of shorting

NASA GSFC is continuing this evaluation and plans to perform periodic inspections of the test specimens to further document the effectiveness of the conformal coat against tin whisker induced problems. In addition, GSFC is planning to evaluate some of the following issues:

- Tin whisker growth from pure tin plated capacitor terminations
- Tin whisker growth from pure tin plated leads of Plastic Encapsulated Microcircuits (PEMs)
- Tin whisker growth from pure tin plated shell of connectors
- Tin whisker growth from Tin/Lead finished components
- Evaluation of conditions that may accelerate tin whisker growth in conjunction with an industry task group trying to develop test methods to quantify whisker propensity of various plating chemistries.

This work is being done under the guidance of Dr. Henning Leidecker and Mike Sampson at NASA GSFC.

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