Effects of Conformal Coat on Tin Whisker Growth

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Abstract

A whisker from a tin plated part was blamed for the loss of a commercial spacecraft in 1998. Although pure tin finishes are prohibited by NASA, tin plated parts, such as hybrids, relays and commercial off the shelf (COTS) parts, are something discovered to have been installed in NASA spacecraft. Invariably, the assumption is that a conformal coat will prevent the growth of, or short circuits caused by, tin whiskers. This study measures the effect a Uralane coating has on the initiation and growth of tin whiskers, on the ability of this coating to prevent a tin whisker from emerging from the coating, and on the ability to prevent shorting.

A sample of fourteen brass substrates (1"x 4"x 1/16") were plated by two separate processes: half of the specimens were "bright" tin plated directly over the brass substrate and half received a copper flash over the brass substrate prior to "bright" tin plating. Each specimen was coated on one half of the substrate with three bi-directional sprays of Uralane 5750 to a nominal thickness of 25 to 75 μm (1 to 3 mils). Several specimens of both types, Cu and non-Cu flashed, were placed in an oven maintained at 50 °C as others' work suggests that this is the optimal temperature for whisker formation. The remaining specimens were maintained at room ambient conditions.

The surfaces of each specimen have been regularly inspected using both optical (15 to 400x power) and Scanning Electronic Microscopy (SEM). Many types of growths, including needle-like whiskers, first appeared approximately three months after plating on the non-conformally coated sides of all specimens. At four months, 4 to 5 times more growth sites were observed on the coated side; however, the density of growth sites on the non-conformally coated side has since increased rapidly, and now, at one year, is about the same for both sides.

The density of growth sites is estimated at 90/mm^2 with 30% of the sites growing whiskers (needle-like forms) with the potential to cause short circuit bridging. The average growth rate of the needle-like whiskers on the non-conformally coated areas is about 130 μm per year with some outliers reaching 800 μm after one year.

It is more difficult to make growth measurements under the conformal coat. As yet no whiskers have been observed to penetrate through the coating surface; however, a number of tin nodules appear on the verge of breaking through the thinner regions of the coating surface. These domes are developing sharper and sharper tips, as if a growing whisker is about to push its way through a tough skin.

Our observations are that the specimens with copper flash show a much lower density of nucleation sites and significantly slower whisker growth compared to the specimens that have only bright tin plating over brass. The specimens kept at room temperature have a higher whisker density than those stored at 50 °C. This is an unexpected result and does not agree with the published findings of others. All of the whiskers originate from small surface defects (thin, tiny scratches) that appear over the entire surface of each specimen.

Key words: tin whiskers, Uralane conformal coating, plasma arc, electroplating, pure tin,

Introduction

This report provides status for an ongoing experiment to study the effects of Uralane conformal coating on tin whisker growth. It was initiated by National Aeronautics and Space Administration (NASA) Goddard Space Flight Center in December 1998 when one NASA program learned that they had installed the same type of relays that were used in a commercial satellite that later failed to function due to a short circuit caused by a suspected tin whisker. Whisker-induced short circuits under normal atmospheric conditions are frequently insignificant or unnoticeable to most ground-based electronics since the current necessary to fuse a typical tin whisker under these conditions is a few milliamperes, or less. Vacuum experimentation has shown that tin whisker-induced short circuits are capable of forming a plasma of tin ions and electrons capable of sustaining hundreds of Amperes [1], [2]. It has been suggested that such an event occurred on a commercial satellite causing protective fuses on the spacecraft bus to open, leaving the spacecraft inoperable. For this reason, tin whiskers in space flight are a significant concern.

The phenomenon of tin whisker formation from pure tin plated surfaces is well known and documented. However, little research has been published to document the effects of using protective barriers such a conformal coat to prevent or inhibit whisker formation. Although NASA guidelines prohibit the use of pure tin plating on space flight components, it still happens that devices with pure electroplated tin surfaces are sometimes installed. Adding 1 to 3% lead (Pb) to electroplated tin is accepted as substantially eliminating tin whisker formation. However, use of any lead brings risk to health and environment. In these situations, consideration needs to be given to understanding the potential benefits of using a protective coating over the tin surface.

Most published literature on tin whiskers agrees that brass with a bright tin finish is a combination that promotes whisker formation [5], [6]. While there is a widespread assumption that a conformal coat would be protective, a literature search for documentation of this protection was unsuccessful [6]. Therefore, we designed an experiment to study the effects of a conformal coat on an electroplated tin surface. We chose Uralane as the coating. The purpose of the experiment is to determine:

Does conformal coating prevent, or inhibit tin whisker growth? Does conformal coating prevent penetration of whiskers growing from other surfaces? Does conformal coating protect against arcing from a whisker to an adjacent surface?

Throughout the experiment we were also able to determine the incubation period for whisker formation, the rate of whisker growth, and the density of the tin whiskers.

Experiment

The literature reports that the bright tin plating process is most susceptible to whisker formation and suggests that this is caused by residual stresses in the surface material [5], [6]. The thickness of the tin plating plays a significant role to whisker formation as well. Tin plating that is too thin (less than 0.5 µm) or too thick (more than 10 µm) does not promote whisker formation [8], [9]. For this experiment, several brass substrates (some with copper flash) have been plated using a "bright" tin finish. The brass substrates were coated with 5 µm (0.2 mil) of tin plating, which has been suggested to be the optimum thickness for whisker formation [8]. To further promote whisker formation, the plated samples were scratched using a knife blade, since scratches also create localized stresses that may promote whisker formation (Figure 1).

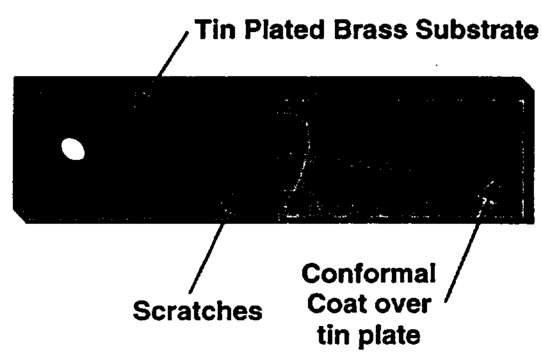


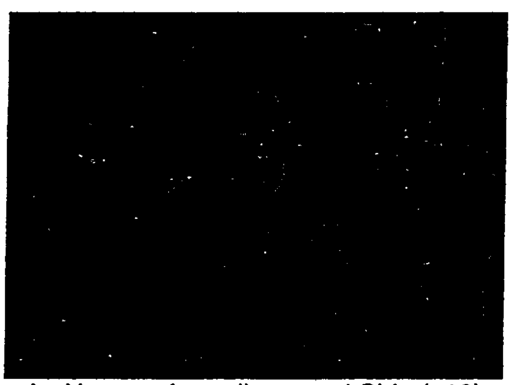
Figure 1. A specimen

The samples were segregated into two test groups. Portions of each sample were coated with Uralane 5750 conformal coat material. Uralane 5750 was selected because of its widespread use in NASA systems. The Uralane coating was applied by spraying it directly onto the specimens. The thickness range of the coating was measured to be 25 to 75 µm (1 mil to 3 mils). The thickness was measured using an optical microscope. Since the coating is optically transparent, we were able to focus on the coating surface and then on the underlying tin surface. The difference in the two values was multiplied by the uralane index of refraction (n=1.61) to get the true thickness. One test group is stored in an oven at 50 °C because the literature suggests that whisker growth is greatest at this temperature. The other test group is stored at room temperature. Table 1 summarizes the conditions of each specimen.

Table 1. Sample Preparation

Sample	Storage Condition	Conformal Coating Status	Appearance Condition
4 Brass with Copper Flash	At 50 °C	3 sprays (half of the specimen)	A straight line and a circle scratch in the center of each specimen
4 Brass without Copper Flash			
3 Brass with Copper Flash	At Room Temperature		
2 Brass without Copper Flash			

All samples are periodically examined using both an optical microscope and a Scanning Electron Microscope (SEM). The inspection was performed every two weeks for 3 months, and then once a month. Both tin nodules and tin whiskers were observed in less than a month following plating. Surprisingly, more nodules formed under the coating than on the non-conformally coated side. Figure 2 shows the nodule density on the coated side and the non-conformally coated side.



A. Non-conformally coated Side (x13)

B. Conformally Coated Side (x13)

Figure 2. Density of Nodules

The tin surface under the coating has been protected from oxidation whereas the exposed surface has been free to oxidize. Based upon our observations that more tin nodules formed under the conformal coat than on the exposed tin surface, we hypothesize that oxidation of the tin surface (exposed side) increases the incubation period for whisker formation.

Using a Scanning Electron Microscope (SEM), the whisker nodules were observed in more detail with high magnification. These nodule photos were taken of the non-conformally coated side. It was impossible to observe nodule formation on the metal surface on the coated side, since the coating is opaque to electrons. Furthermore, the insulating properties of the coating caused the specimen to charge up when exposed to the electron beam; thus distorting the SEM image. However, a quick scan of the coating surface was made to see if there was any evidence of whisker penetration through the coating. Later in the experiment, two specimens were vapor deposited with Gold (Au) to prevent charging. These specimens do not show any signs of tin whiskers penetrating through the coating.

On the non-conformally coated side, nodules formed in various shapes, shown in Figure 3. Most of these nodules formed along surface scratches in the tin plating. These thin, tiny scratches are not the scratches that were made intentionally. In fact, relatively few whiskers were observed from the scratches that were made intentionally. Rather, the thin, tiny scratches, possibly resulting from abrasion by the paper within which the specimens were wrapped for shipping by the company that performed the electroplating process, promote almost 90% of the whisker formation observed.

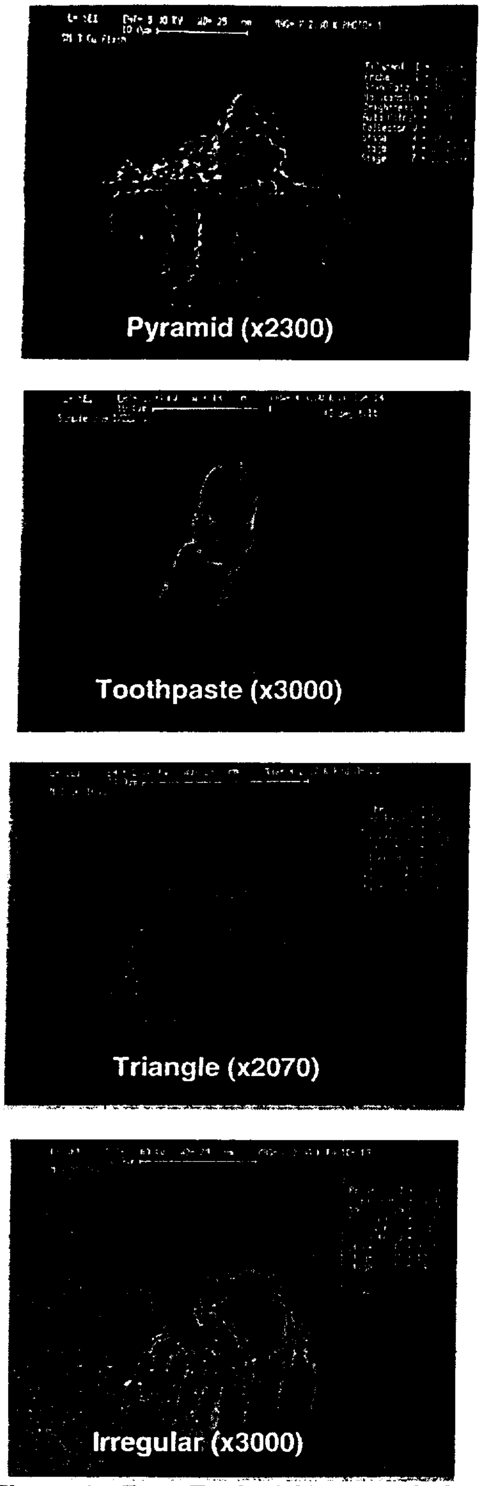


Figure 3. Four Typical Shapes of Tin Nodules

Selected nodules were reinspected on a regular basis to determine the growth rate and to monitor the nodule formation process. Figure 4 depicts several stages of the formation of one specific tin whisker nodule.

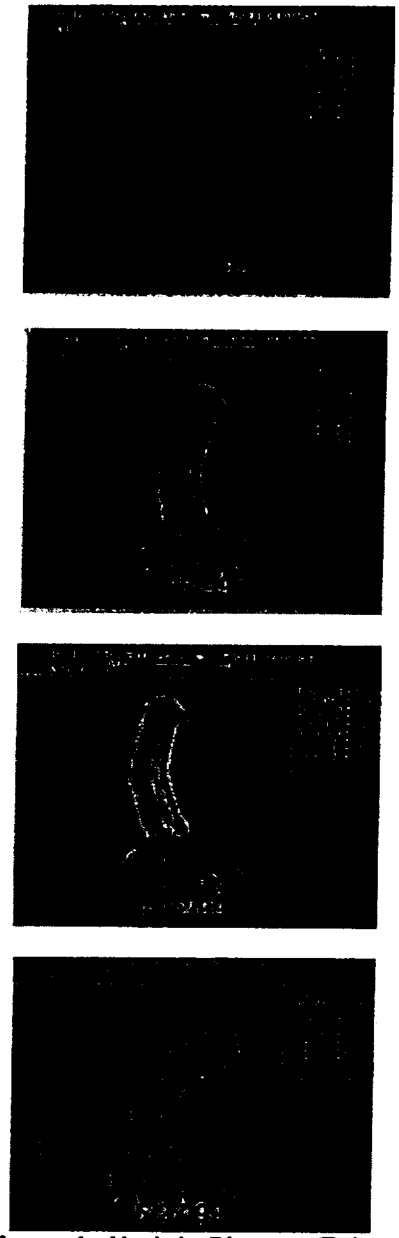
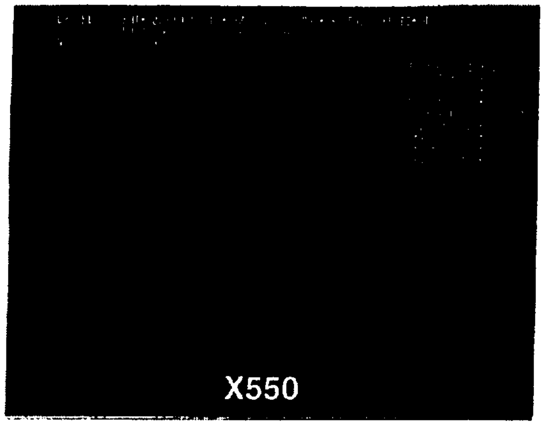


Figure 4. Nodule Pictures Taken Periodically (x1700)

This particular nodule had an average growth rate of 0.06 mm/year measured at 6 months, which can be compared to the reported growth rate value of 0.92 – 7.3 mm/year [4]. This nodule stopped growing after 6 months.

Some of these nodules are growing straight whiskers while other nodules grow whiskers with kinks (Figure 5).



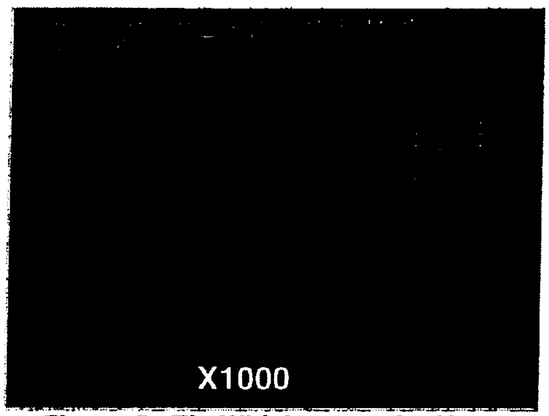


Figure 5. Tin Whiskers on the Non-conformally Coated Side

We now turn our attention to the possibility that a whisker growing out of some other surface until it contacts the conformally coated surface, will cause a discharge through the coating, or will push through it to contact the conducting surface. Two main concerns were addressed:

- Voltage breakdown strength (dielectric strength) of Uralane
- Buckling force when the whisker comes in contact with Uralane

The dielectric strength of Uralane 5750 was reported to be 1500 V/mil by the manufacturer. However, this is for a uniform applied electric field. The field around the tip of the whisker is non-uniform, and so we performed some new breakdown tests. To simulate a tin whisker, a tungsten carbide probe tip (6 µm in diameter) was brought into contact with the Uralane conformal coat. The DC voltage was increased until dielectric breakdown was detected. The breakdown voltage from the experiment was measured to be higher than the value reported (see Figure 6). The Uralane coating would have to be extremely thin (less than 1/10 mil) for the breakdown voltage to even approach 50V, which was the application voltage in the commercial satellite that failed.

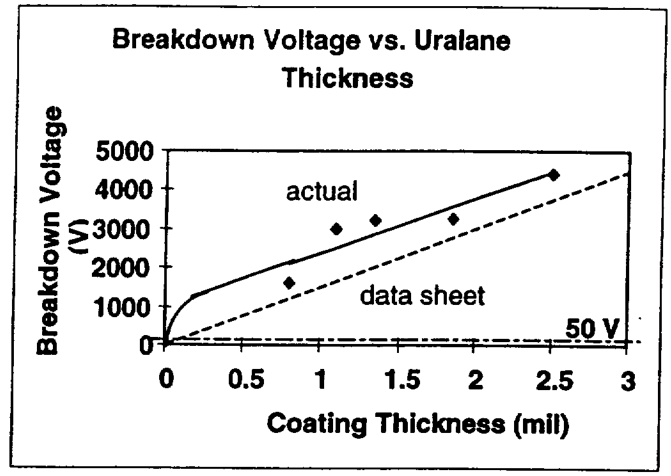


Figure 6. Breakdown Voltage from the Experiment

Since the thickness of the Uralane coating on the NASA boards would be approximately 50 to 75 µm (2 to 3 mils), dielectric breakdown will not happen even when the whisker touches the surface of the coating, so long as the potential difference is less than a few thousand volts. Furthermore, the tin whisker will buckle when it pushes against the coating, rather than penetrate it. This is shown by comparing the buckling force with the force required to dimple the surface of the coating.

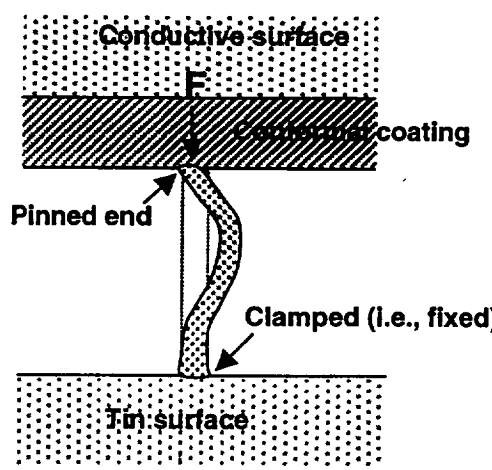


Figure 7. Diagram of Hypothetical Analysis of Buckling

The force that buckles a tin whisker is:

$$F_B = \frac{2\pi^2 EI}{L^2}$$

where: F_B = Buckling Force
E = Young's Modulus of tin
I = Inertia
L = Length of the whisker

Figure 8 shows the buckling force of the tin whisker as a function of diameter and length.

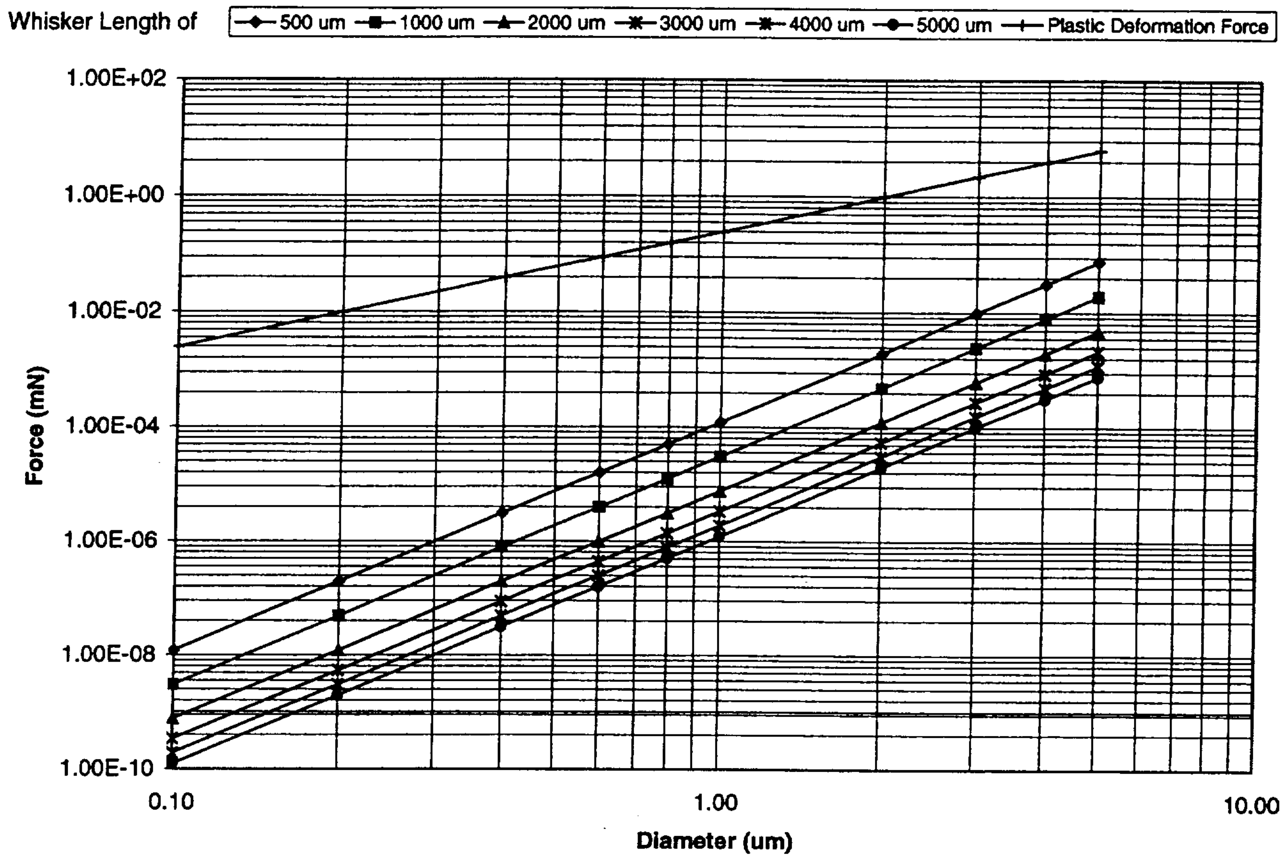


Figure 8. Tin Whisker Buckling Force Calculation

Clearly, a long thin whisker would buckle more easily than a short, thick whisker. When the tin whisker tip is pushed against the Uralane, the coating will elastically dimple before it punctures.

The displacement of the surface due to the whisker pushing against the coating is:

$$D = \frac{(1-\nu^2)F_B}{E \quad d}$$

Where

D = Displacement of the surface
ν = Poisson's ratio for Uralane
E = Young's Modulus for Uralane
d = Diameter of the tin whisker

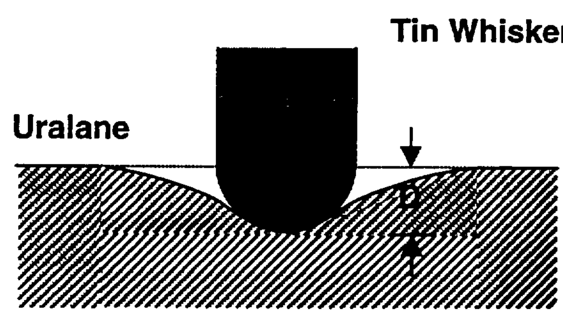


Figure 9. Diagram of Tin Whisker Contact against Uralane

According to Figure 10, even a short, thick whisker would make a dimple that is 2 orders of magnitude less than the minimum coating thickness of the specimen. Consequently, the tin whisker would only make a small dimple on the coating before buckling occurs.

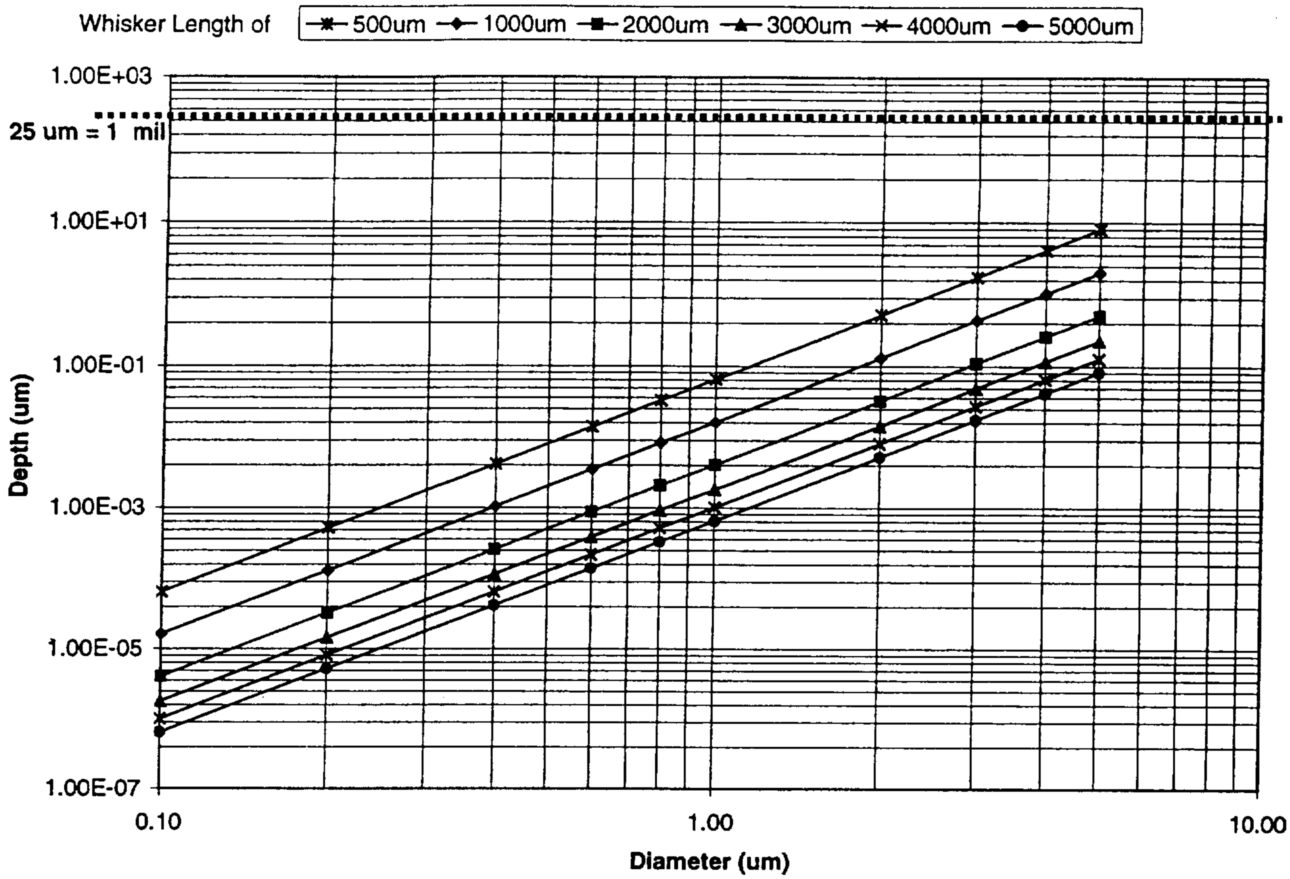
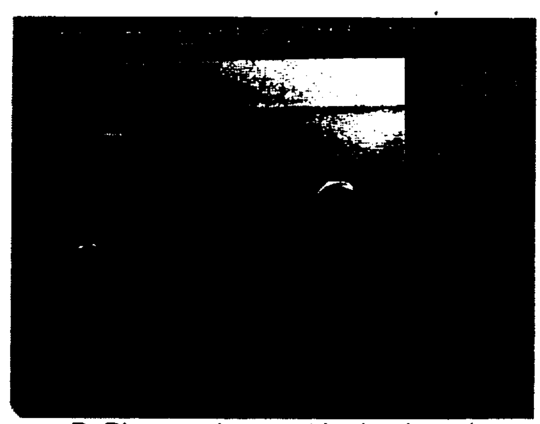


Figure 10. Penetration Depth before Buckling

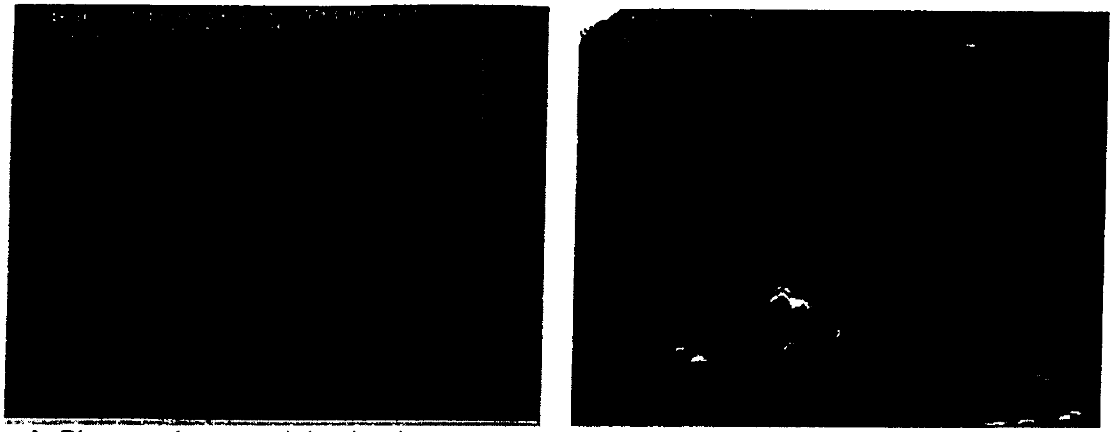
The latest observations indicate that tin whiskers under the conformal coat are pushing their way outward, causing dome shapes in the coating. As time progresses, these dome shapes are becoming larger and narrower at the top, which suggests that the whisker tips are approaching the outer surface of the conformal coat. Figure 11 shows tin whiskers from the same location: Figure 11A is taken a year before Figure 11B. Similarly, figures 12A and 12B are photos of a whisker field taken 6 months apart.

A. Picture taken on 3/11/99 (x139)



B. Picture taken on 3/15/00 (x140)

Figure 11. Whiskers Forming Under Coating



A. Picture taken on 8/5/99 (x50) B. Picture taken on 3/15/00 (x50)

Figure 12. Whiskers Forming Under Coating

Among 13 samples, only three specimens show these dome shapes. One is stored in the oven at 50 °C and two are kept at room temperature; one is copper flashed and the other is just pure tin over brass substrate.

Figure 13 shows whiskers from a bare metal surface, without coating: some whiskers are growing faster than others. This one particular whisker grows at a rate of 0.64 mm/year. This whisker, which measured 0.8 mm in length (~31 mil) when the photo was taken, is long enough to cause short circuits between two leads having a standard 0.635 mm (25 mil) pitch.

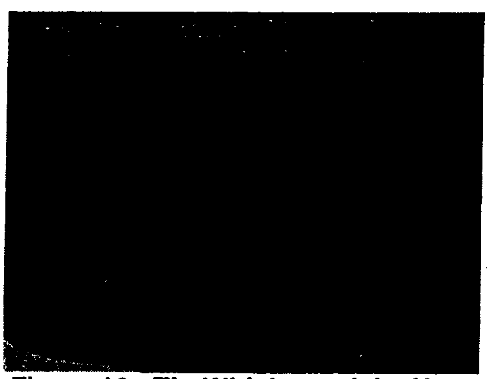


Figure 13. Tin Whiskers of the Non-conformally Coated Side (x95)

The experiment is ongoing. Please visit our web site for further updates. Updates will be reported and documented on the NASA Goddard Space Flight Center Code 562 web site:

http://nepp.nasa.gov/whisker/

Conclusions

The purpose of these experiments was to document what protection a Uralane provides from tin whisker-induced failures in space flight electronics. Three main topics were addressed: Does conformal coating prevent, or inhibit tin whisker growth? Does conformal coating prevent penetration of whiskers growing from other surfaces? Does conformal coating protect against arcing from whisker to adjacent surface?

For the first year of the experiment, nodules formed more rapidly and in greater numbers under the conformal coated side than the non-conformally coated side. Later, the density of nodules was essentially equal on both sides. One possibility is that tin oxidation actually delayed initial nodule formation. However, once the nodules are formed on the non-conformal-coated side, they grow at a faster rate than the coated side. After eighteen months, none of the whiskers under the conformal coat have broken through the coating surface. This finding mitigates concerns for short duration space missions (days to months in duration), but is not conclusive regarding long term protection (years to decades in duration).

The other two points were addressed by determining the properties of tin whiskers and the Uralane coating through tests and then applying recognized analytical techniques. It was shown that the whisker would buckle before penetrating the coating on an adjacent surface and that for common NASA spacecraft voltages, the conformal coating provides adequate dielectric breakdown protection. Our findings differ from other investigators who have reported the optimal temperature for tin whisker growth to be 50 °C. Our results show more and longer whiskers on specimens kept at room temperature, compared with those kept at 50 °C.

Even though penetration of whiskers through coating is not yet observed, it is definite that the coating is slowing down the whisker growth. What has not yet been addressed in this study is the real possibility of whiskers growing from two conformal-coated surfaces having different electrical potentials and then coming into contact through electrostatic attraction. The question is whether or not the conformal coat would limit the supply of tin enough to prevent a catastrophic plasma arc.

Finally, It must be noted that nothing in this study is meant to relax prohibition against the use of pure tin surfaces for space flight use. As stated, this test is to determine if tin whisker protection can be added to the many benefits of conformal coating.

Acknowledgements

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