# MITIGATING AND PREVENTING THE GROWTH OF TIN AND OTHER METAL WHISKERS ON CRITICAL HARDWARE

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## ABSTRACT

With the current international requirements to limit the use of lead, plating with pure tin is likely to become more and more prevalent. Although most space systems (and other high reliability systems) generally prohibit the use of pure tin plating, mandating requirements alone have proven to be insufficient to preclude use of tin plating. Experience has also demonstrated that the risk is significant, not only for low voltage application shorting, but also for higher voltage/amperage applications which may be susceptible to metal vapor arcing. Examples of several significant failures are readily available that demonstrate implications for space systems and space control systems. Fortunately, steps can be taken early in the design process and throughout implementation that can reduce or eliminate the tin whisker threat.

## 1. WHAT ARE TIN (OR METAL) WHISKERS?

Tin whiskers are thin protrusions, like hairs, that extend out from tin plated surfaces. Only microns in diameter, they can grow up to tens of mm long over varying periods of time, though most are much shorter (<1mm) and are generally formed from a single crystal of tin. They can grow straight or curl in a variety of styles, often side by side (see Fig. 1). Given that they are made of pure tin, they are very conductive and have been shown to grow in the direction of electrical fields, such as high voltage sources. They grow in a multitude of environments that vary in pressure, temperature and humidity [1]. Electroplated tin seems to be particularly susceptible, and many different factors, such as plating chemistry and processes or substrate are believed to be factors to some extent, but tin whiskering cannot be precluded on most tin plated surfaces. Experiments to help determine the limiting factors have often led to contradictory results, with the only consistently demonstrated method of precluding tin whiskers is a minimum percentage of lead in the solder.

Tin whiskers are not a new phenomenon. Tin whiskers have been reported as early as the 1940's and no small amount of effort has gone into trying to determine what exactly causes them, what conditions make them grow faster (or slower) and what can stop them from growing (such as a small amount of lead added to solder).

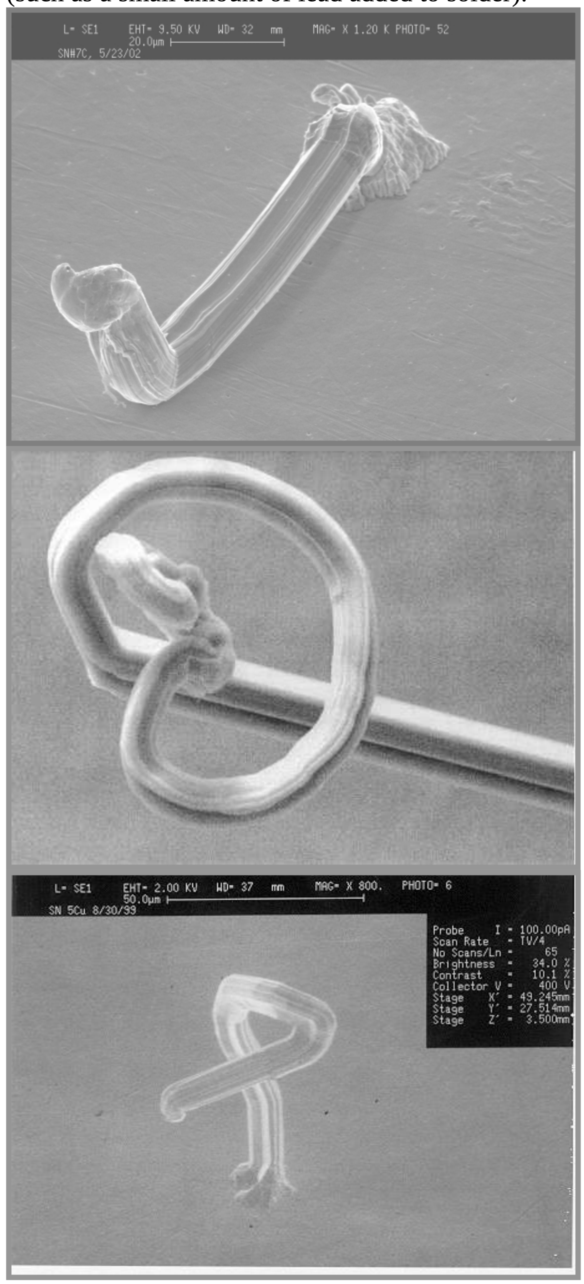


*Figure 1: Scanning Electron Microscope (SEM) photography for some of the curling shapes tin*

*whiskers can grow into, besides straight. Photo Courtesy NASA Electronic Parts and Packaging (NEPP) Program http://nepp.nasa.gov/whisker.[1]*

Theories on what causes these whiskers are not universally accepted, but many theories focus on stresses of some sort that lead to their growth, such as residual stresses within the tin plating itself or externally applied stresses. Other theories include whiskering being the result of nicks or damages, recrystallization, or grain growth processes. No single process has been conclusively proven just as no environment has been found that precludes tin whisker growth, nor any reliable way of predicting when tin whiskers will grow, how fast they will grow and how long they will become. There is often a dormancy period before whiskers begin to grow, but with dormancy periods ranging from days to years, and with no hard data to predict the length, it is very challenging to predict when whiskers will grow, even from items of identical design and usage [1]. Figs. 2-4 show some examples of tin whiskering.

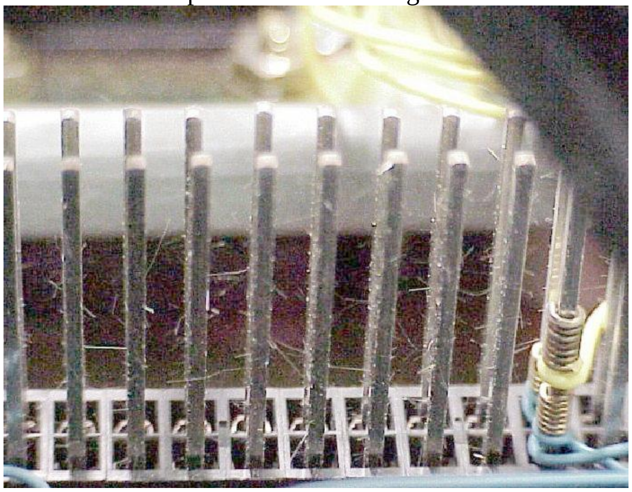

*Figure 2: Tin whiskers growing from pure tin plated connector pins after ~10 years. Courtesy of GE Power Management [2].*

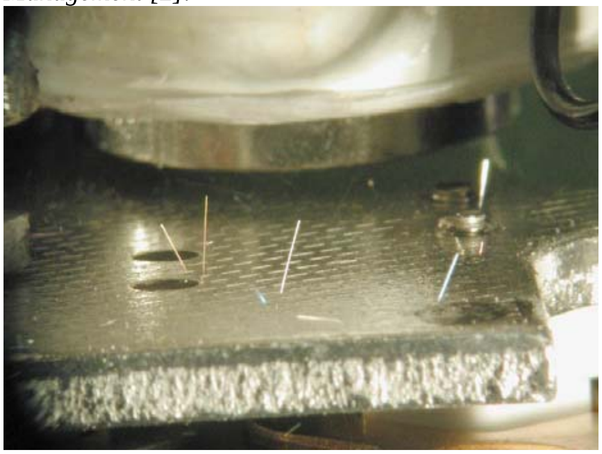

*Figure 3: Tin whiskers growing in a hermetically sealed relay that was pure tin plated, but was not supposed to be. Courtesy of Northrup Grumman [3].*

Although whiskering is a phenomena noted several decades ago, this issue has gained more notice due to some high-profile failures in recent years. Part of the reason there have been more high-profile failures has been from the advances in electronics that are allowing more densely populated circuit boards with closer leads.

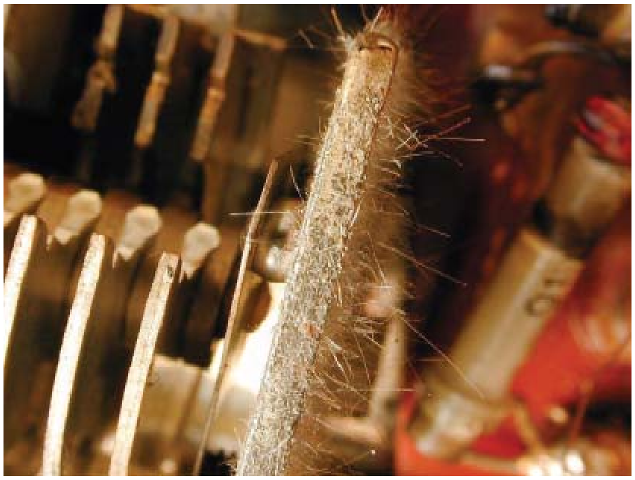

*Figure 4: Tin whiskers on the tin plated housing of a variable air capacitor. Some whiskers are ~ 10 mm long. Courtesy of NASA Electronic Parts and Packaging (NEPP) Program [4].*

Another key development involves the manufacturing changes as electronics companies worldwide move away from the use of lead in solder in response to the European Union's Restriction of certain Hazardous Substances (RoHS) and the Waste Electrical and Electronic Equipment (WEEE) directives to eliminate lead from electronic equipment by June 2006 [5]. Tin whiskers have been avoided for several decades by adding a small amount of lead to the solder. The new restrictions that prohibit the use of lead for most electronic applications are driving electronics manufacturers to the use of pure tin plating and rediscovering the all-but-forgotten issue of tin whiskers.

When pure tin, which has favorable solderable characteristics, was explored by electronics suppliers as an alternative (in some cases, many years ago), many manufacturers were not aware of the tin whisker phenomena and many are just now becoming aware of the issues possible from tin whiskering, especially for high reliability components. Unfortunately, that also means that many components may have been changed to a pure tin-coating without notification and may be in place today.

Even though defense and space applications are exempt from RoHS and WEEE, implications affect these high reliability industries. Components for commercial use outnumber these specific applications, which can push electronics manufacturers to charge more for those needing "high reliability" parts or, worse, even discontinue making the high reliability alternatives. Finding alternative products for future projects that do not contain pure tin may be very challenging, expensive and, as leaded products are discontinued, even impossible.

It should also be noted that, until the process for tin whiskers can be understood, predicting the effectivity of various mitigation techniques, even those called forth by JEDEC (formerly the Joint Electron Device Engineering Council) to address tin whiskers, cannot guarantee prevention of tin whisker formation which is why JEDEC specifically recommends against the use of pure tin (and some tin alloy) plating in high reliability applications such as space and defense [6].

Nor is tin the only plating metal prone to whisker growth. A number of plating metals, including zinc, cadmium, silver and even gold, can whisker. Although silver "whiskers" have been linked with particular environments (sulphur), the speed with which silver whiskers grow is remarkable, much faster than the growth of tin and zinc whiskers, and can be a serious reliability issue for equipment in that kind of environment (See Fig. 5) [7].

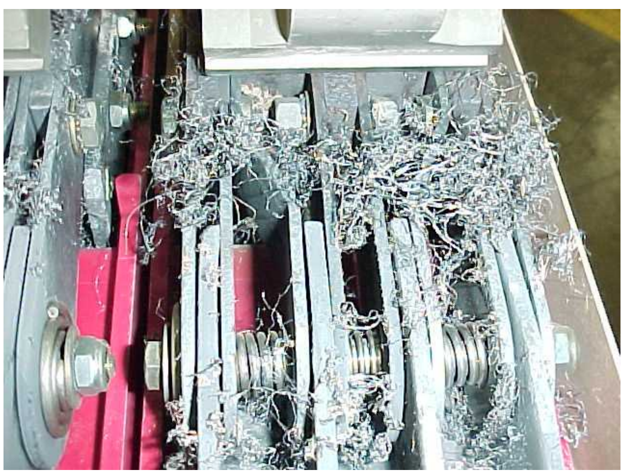

*Figure 5: Silver whiskers appear to have a different formation mechanism than tin and zinc whiskers, but can grow extremely fast. These whiskers (shown here on a circuit breaker) can grow 60-80 mm in a month or two with even a low concentration of hydrogen sulfide. Courtesy of Dr. Bella Chudnovsky (Schneider Electric/Square D) [7].*

However, the mechanism for silver whiskers appears to be different from whatever causes tin and zinc whiskers and is unlikely to be an issue for space applications (except in high-sulphur environments). Zinc, however, grows whiskers much like tin does and has implications not only for space hardware but also for computer environments where facility surfaces are often plated with zinc (galvanized steel); see Fig. 6 [1]. In this case, hot-dipped galvanization is generally believed to be considerably less prone to whisker growth than electroplated surfaces [1].

*Figure 6: SEM photography of zinc whiskers growing from the bottom of a raised (aka "access") computer floor tile, courtesy of NASA Electronic Parts and Packaging (NEPP) Program http://nepp.nasa.gov/whisker.[1]*


*Figure 7: Tin whiskers on Tin-Plated Kovar Terminal having a Nickel Barrier Plating. Whiskers formed on region that was NOT encompassed by the Tin-Lead (Sn-Pb) solder applied during hot solder dip operation. Photo shows how solder dip can help reduce tin whiskers, but also demonstrates one of the limitations as mitigation with whiskering still prevalent on the undipped portion.*

*Courtesy of NASA Electronic Parts and Packaging (NEPP) Program [http://nepp.nasa.gov/whisker](http://nepp.nasa.gov/whisker) [1].*

## 2. PROBLEMS METAL WHISKERS CAN CAUSE

Whisker metals, like tin, zinc, and even gold, are all conductive materials, making whiskering a significant concern. As tin is a plating metal common to electrical connections, so tin whiskers growing in place can often cause considerable problems depending on the particulars of the individual circuits. In low voltage, high impedance circuits, a stable short circuit can develop where tin whiskers grow between physically close surfaces of different potentials. Unless the current is high enough to fuse the whisker (generally more than 50 mA), this short can remain in place indefinitely, disrupting electronic functions or causing unwanted functions to occur. Even a transient short (enough current to fuse the whisker) can cause problems, especially to sensitive circuits, including data and computer systems.

One of the most destructive potential problems, however, is metal vapor arcing (MVA). In high power applications, a tin whisker can bridge a gap where sufficient power exists that the vaporized tin creates an arc across the gap that allows current to flow. The metal vapor arc can carry a large amount of current and, under the right circumstances, can continue to sustain itself by pulling tin from the contacts until either the power is cut off or the arc runs out of conductive material to feed itself. Metal vapor arcing is easiest to start and sustain in a vacuum, and has been demonstrated at voltages as low as 4 V direct current (DC) [8]. Aside from the short itself, the arcing is very hot and can destroy electronic components, either through exposing them to high current/voltage or high temperatures, can trip protective devices like circuit breakers and fuses and can physically destroy components, cases, fittings and structure.

In a vacuum environment, like space, MVA is a serious concern, but even pressurized environments can allow a sustained MVA. It may even be that a whisker does not have to bridge the entire gap between terminals of high potential difference. There are some who think MVA in a pressurized environment is all but precluded at voltages below 100 VDC; however, depending on the current available and the protective circuitry, even pressurized systems at 28 VDC have been shown to sustain a destructive MVA. The pictures below are from an Aerospace 28.1 VDC test performed by Eng and Mason with an extruded tin wire of 27.3 micron diameter in 1 atmosphere of nitrogen. Although power was shut off after 0.5 s, the arc blew a 10 A fuse, and then melted over to reach a current of more than 70 A (see Fig. 8) [9]. Damage in 1 atm of air was even more destructive [8].

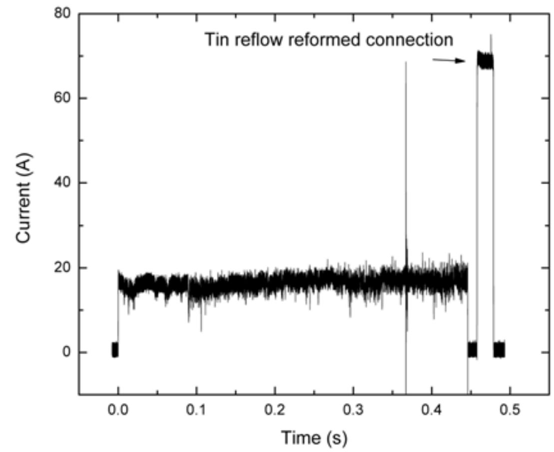


*Figure 8: Current signature from plasma test 2. The plasma sustained itself at about 17 A for approximately 450 ms before blowing a 10 A fuse. Tin reflow reformed a connection between the electrodes which carried approximately 70 A current until the system power was shut off [9].*

The following photos (Fig. 9) show the wire before, during and after the test, including the melted tin that fractured after it cooled. It is this molten/vaporized material that feeds the arc. (Note: Although extruded wires are used for most tests, rolled down to 25-50 microns in diameter, actual tin whiskers have been used without an appreciable difference in result; wires are much easier to handle and obtain than harvested tin whiskers.)

Earlier tests in this same facility (done at vacuum) had arcing that reached the chamber walls and necessitated changes to the test fixtures to preclude damaging the test facility.

Detached whiskers are also a concern. Although whiskers are fairly tough and are not easily dislodged, a whisker that comes loose can be transported to critical areas either through air handling or, with low/zero gravity, just random movement. Since zinc as a coating is rarely used for electronics, detached zinc whiskers represent the bulk of the risk from zinc, but there have been failures from detached zinc whiskers. Zinc is commonly used in facilities where computer networks are housed, particularly as shielding (via galvanized plates) on floor tiles, that can be invisibly dislodged during maintenance and then disrupt even redundant computer systems as thousands of conductive whiskers make their way into power supplies.

Even attached tin whiskers that do not cause a short can disrupt digital circuits by becoming antennae in high-frequency circuits with a frequency above 6 GHz. It has also been noted that whiskers can bend under the force of electrostatic attraction, increasing the likelihood of contact [10].

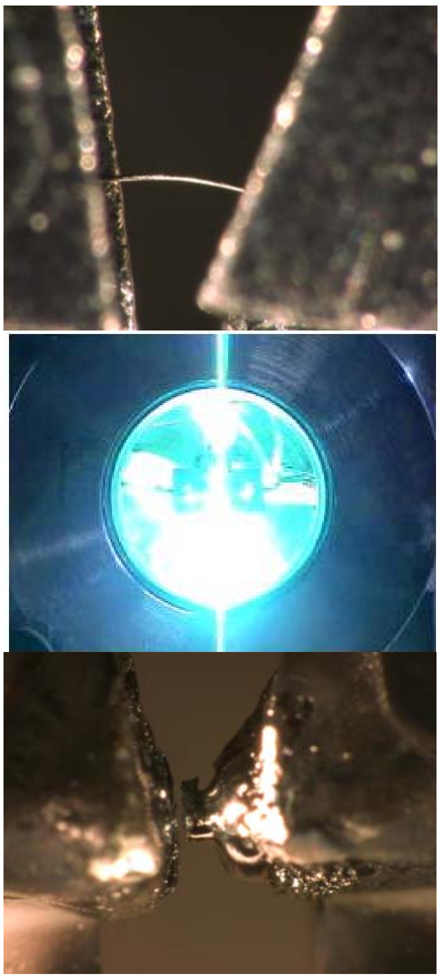

*Figure 9: Before, during and after test pictures showing the original wire, the energy of the metal vapor arc and the destruction that took place in ~0.5 s [9].*

**2.1 Examples of failures**

A number of commercial satellite failures (and redundant system failures) have been linked to tin whiskers. Three commercial satellites have lost both primary and secondary satellite control processors—failures attributed to tin whiskers that grew on latching tin plated relays, bridging the distance to their metal cases. These shorts resulted in blown fuses that disabled the system control processors. Another satellite lost its secondary system to tin whiskers in the same manner (the primary system had been lost to a cause unrelated to tin whiskers). All four of these satellites were complete losses. Three other satellites of the same design have lost their primary systems and are relying on their secondary system as a result of these failures, just one whisker away from total failure [1].

A number of missile and aircraft failures have been linked to tin whiskers, including rather spectacular relay failures in aircraft documented in an article by Davy [3]. It should be noted that requirements precluded tin plating in this application; however, tin plated surfaces ended up shorted as tin whiskers grew toward terminals. See Fig. 3 and Fig. 10 for pictures of a similar relay and the whiskers growing on it.

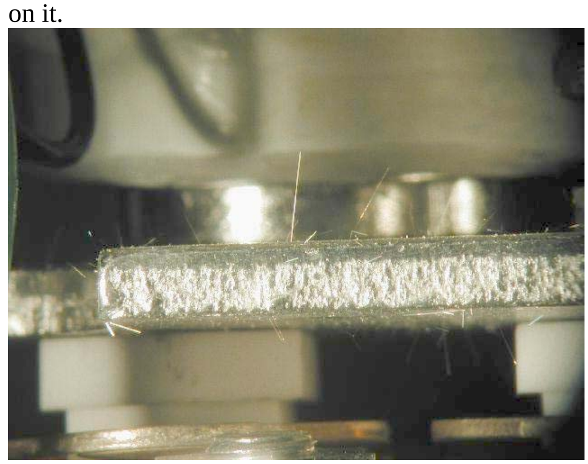

*Figure 10: Whiskers are shown here on a relay similar to the one that failed on an aircraft. Courtesy of Northrup Grumman [3].*

After ten years at considerably less capacity than their rating, these relays failed, burning through their casings until control circuitry shut them down. The relays should have been good for 70 years as designed. Fig. 11 shows the relay after the MVA incident [3].

*Figure 11: Relay destroyed by a metal vapor arcing event. Courtesy of Northrup Grumman [3].*

In 2001, zinc whiskers on a zinc-plated yellow chromate steel bus rail bridged a 1.1 mm gap to the aluminum chassis during a thermal vacuum test at a space contractor facility, causing a MVA that lasted 4.7 s and was only extinguished after blowing 20 A fuse pairs on eleven different boards within the electronic box. Aside from the damage to electronics, the current was sufficient to melt the bus rail, a portion of the housing and some nylon [4].

Several models of pacemaker using tin-plated parts were recalled after failures as a result of low-power shorts. The US Food and Drug Administration issued a recommendation against tin-plated parts in low voltage, high reliability applications and required the manufacturer to use testing independently of the vendor to ensure compliance, as noted in FDA ITG-42 (1986) [11]. Apnea monitors, commonly used for monitoring babies considered at high risk for Sudden Infant Death Syndrome (SIDS), were discovered susceptible to a switch problem that would cause the alarms to fail. Eventually, the failures were traced to the switch and the zinc whiskers that caused them to fail, a fact that led to a costly legal battle, and failure of the apnea monitor company [12].

Tin whiskers on cards, relays and potentiometers have caused failures (trips) at nuclear power plants. Zinc whiskers have disabled several significant data handling facilities, including those computer facilities with substantial redundancy. Air handling systems, which commonly flow under floor tiles where cables are run, gather detached zinc whiskers released from galvanized floor tiles during maintenance and short out power supplies with the tiny filaments. A National Aeronautical and Space Administration (NASA) data center, for example, experienced at least 18 catastrophic power supply failures in a one month period in a new mass memory unit. Problems like these serve as a risk for ground facilities that support critical space functions [1].

The risk posed by tin whiskers is pervasive and extends to non-critical applications. For example, Swatch asked for an exception to the lead-free rule when, within months, their production was halted by reliability issues in their newly manufactured watches [13]. Other consumer electronic companies may also struggle with reliability concerns that can have adverse effects on image and consumer confidence. Many electronic items are not expected to function for more than a couple of years; however, expensive industrial equipment or high-cost premium equipment may be just as susceptible to down-the-road issues as tin usage becomes more ubiquitous.

## 3. METHODS OF MITIGATION AND THEIR LIMITATIONS

There are a number of mitigation techniques documented in different sources including the International Electronics Manufacturing Initiative (iNEMI) organization and JEDEC [6] [14]. However, in both cases, these mediation methods include disclaimers that explain that many methods cannot remove the risk of tin whiskers and may merely reduce the risk. The effectiveness of many methods has not been thoroughly established or verified because of the uncertainty in understanding the growth mechanism, the vast differences in dormancy and growth rates, and the varying environments these components may be exposed to. Additionally, in all cases, use of tin plating is considered inadvisable for defense and aerospace applications, largely because of the long lifetimes and mission critical aspects of those uses.

Methods highlighted by JEDEC and iNEMI are, not surprisingly, quite similar. The most effective method for precluding tin whiskers simply dictates not using pure tin finishes (the preferred method for all high reliability/critical applications) including using tin-lead alloys instead, or plating materials devoid of tin. Additional methods expected to be effective include nickel as a substrate to reduce tin whiskering, a method which is believed to be fairly effective (and which has no noted limitations except in where it can be used), and adding bismuth or silver to the tin which may reduce whisker growth. Heat treating (reflow, annealing, hot dip, etc) a tin plated surface is another method that can reduce the tin whisker risk and often can be performed after the fact on existing hardware. Unfortunately, reflowed or hot dipped plating surfaces are not necessarily immune to tin whiskers, unless tin-lead solders are used. Also, the geometry of the surfaces being hot dipped, for example, may still leave some of the original tin surface susceptible to whiskering as shown in Fig. 7. Other methods that have the potential to reduce whisker growth include thicker platings, silver underlay, controlling grain structure, or etching copper underlayments. Some of these methods or materials have non-whisker-related limitations such as susceptibility to a corrosive environments or being too brittle for high stress or vibration environments. Many of these methods have little data to validate them, though they may hold potential. Of course, finding definitive data with the variations in whisker growth may take considerable time and still involve uncertainty.

Most of the methods listed in these guides are intended for electronics manufacturers and are of relatively limited use for the end user, although hot dipping can be done in certain circumstances. For an end user who finds tin plated components inside their critical devices, choices available to address the problem may be limited to component replacement, conformal coating, physical geometry, control circuitry, frequent inspections (specifically geared to look for whiskers) and, sometimes, living with the potential risk.

Tin-plated components are generally disallowed for all critical defense, space and possibly aerospace uses (as well as critical medical uses), so contractors providing this hardware are unlikely to knowingly include pure tin-plated components and may even specify parts that are not tin plated. Unfortunately, regulations precluding the use of tin plating will not be sufficient to assure compliance. The first recommendation for critical hardware providers/end users would be to perform independent testing of all components (even non-critical ones that can have whiskers that might become detached and move elsewhere) in critical hardware to ensure that pure tin plating (or cadmium or zinc) is not in use. This is the recommendation from the FDA for critical medical equipment [11] and it seems to be a good practice for critical space applications.

Testing by the end user can be performed by an independent laboratory or, especially for existing built-up hardware, can be simplified by using a hand-held device that performs portable X-ray fluorescence which can be used to identify a number of metal alloys. If, after testing, such hardware is found, then the hardware provider/end user is generally limited in choices: replace the erring component or try some other method of mitigation. But those available mitigation methods have significant limitations. Conformal coating, for example, is commonly used, partially because it is a simple low-cost procedure and can be used on built up hardware like populated circuit boards or complex electronic devices without requiring dismantling. For space applications, conformal coating is often standard practice for reasons beyond tin whiskers, so it is a mitigation that is already within the scope of normal procedures.

Conformal coating is believed to generally slow development of tin whiskers and limit the potential harm from a tin whisker by limiting metal to metal contact when a whisker does grow through the conformal coating. However, experiments have shown that no conformal coating precludes whiskering and that, in some case, the whiskers even delaminate the conformal coating, potentially reducing its effectiveness. Or, as noted for one conformal coating, while slowing the rate of growth, the conformal coating appeared to reduce the dormancy period, speeding up initiation of the whisker growth [15]. One possible way to enhance the usefulness of conformal coating is to fill empty volumes with potting materials or something else that challenges the growth of whiskers or limits travel of detached whiskers. Unfortunately, thermal necessities can limit where this method can be used effectively, especially in low gravity environments where convection does not aid in cooling hot electrical components.

Geometry can also be used as a mitigation strategy, but, as circuit boards become more tightly packed, inevitably leads and traces will get closer together. If long lead distances are possible, they can reduce risk, though several tin whiskers have now been discovered in excess of 10 mm and even longer. For many applications, short distances between significant potentials may not be avoidable. Additionally, in several cases, tin whiskering from the metal enclosure, rather than an electronic component, was the culprit, adding uncertainty into the mitigation that can be made worse if the whiskers become detached and can float into other areas. It should also be noted that, between points of high potential difference, it is conceivable that the whisker might not have to bridge the entire gap, but might initiate an arc that has sufficient power to sustain itself on the metal vapor.

Control circuitry can also be used to help mitigate risk, but it can also be an imperfect control. In the test described earlier at 28.1 VDC, the arc enabled a current of up to ~70 A for ~450 ms before a 10 A fuse blew [9]. Depending on the speed of the control circuitry, considerable damage can result, as did the bus failure [4] where the arc was maintained for nearly 5 s before eleven pairs of 20 A fuses blew. A great deal of damage can occur under those circumstances. Even if the circuit can restart, components may have been overstressed and may not be as reliable, which can complicate failure analysis when the root cause is sought. The control circuitry itself can disable a level of redundancy or a primary system, even if it is successful in preventing any other damage from the short or metal vapor arc. A blown fuse does not repair itself.

Inspections are often cited as an assurance of confidence that tin whiskers are not an issue. However, those assurances should be taken with some misgivings. First, examining similar, even identical, hardware may not assure that the actual hardware in place is free from whiskers. Whisker growth is not an exact science, so variations in environment, usage, lot designations, etc. may cause significant variations in whisker growth between "identical" items that may not easily be predicted. The understanding for whisker growth is sufficiently vague that even hardware under identical conditions cannot be assumed to respond identically. Given the differences in dormancy, hardware inspected in the past, even months previously, cannot be assured to be free of whiskers, at least short ones. If an inspection was performed years previously, considerable uncertainty can be attached to any estimates of whisker growth.

Inspections that were not specifically looking for tin whiskers should not be accepted as absolute assurance that no whiskers existed. Inspections without magnification can easily miss tin whiskers. Even at magnification and under good lighting conditions, tin whiskers are often very challenging to spot. Often indirect lighting is required and magnification of at least 10X. Other inspection recommendations can be found at the NASA Tin Whisker (and Other Metal Whisker) website [1].

Following these inspection recommendations, as the webpage directs, will not guarantee that whiskers will be found or that they will even be characterized identically. In 2004, HP evaluated the effectiveness of their tin whisker inspection training using JEDEC methods and discovered that there was a great deal of variation even between inspectors looking at identical hardware. The standard deviation for the length of whiskers was 18-26 µm, which, with a JEDEC fail criteria of 40 µm, can be significant. There were also variations in the assessment of whisker density, particularly for those deemed "medium" [16]. Whiskers are so short, so small in diameter, so hard to spot, even inspection by trained inspectors of the same item can vary widely. There is a great deal of subjectivity in the inspection process.

**Conclusion**

Metal whiskers are a considerable problem, particularly in today's environment where many manufacturers are actively working to remove lead from their equipment in response to new regulations addressing both consumer electronics and waste disposal [5]. Although some manufacturers may continue to build components for defense and aerospace applications, which are generally exempt from these regulations, they may do so at a higher cost. Other manufacturers will likely discontinue those product lines altogether. This poses a concern, not just for future space hardware, but also for ground support facilities and support and test equipment.

(Note: It does not appear that defense and aerospace applications are specifically exempted; however, the wording of RoHS includes article 5(b) "exempting materials and components of electrical and electronic equipment from Article 4(1) if their elimination or substitution via design changes or materials and components which do not require any of the materials or substances referred to therein is technically or scientifically impracticable, or where the negative environmental, health and/or consumer safety impacts caused by substitution are likely to outweigh the environmental, health and/or consumer safety benefits thereof…" Additionally, WEEE lists the types of equipment covered under RoHS in Annex IA and aerospace/defense equipment and implanted medical equipment are not included on that list, though some of the systems listed could be included in aerospace/defense equipment [5].)

The most effective method to avoid metal whiskers is to use platings that do not support their growth; i.e., avoid pure tin and tin-copper alloys or add lead to the tin to retard whisker growth. However, requirements and specifications that restrict pure tin usage have not historically been sufficient to preclude their use. Objective verification to ensure compliance is the only way to be certain that whiskers are precluded in high-reliability critical applications. For those circumstances where tin plating cannot be avoided, steps to mitigate the risk may be needed, with an understanding of the limitations of those mitigating steps. Providing effect control for potential metal vapor arcing everywhere tin plating remains could be critical in preventing a critical result.

Fortunately, this issue is gaining a great deal of visibility and, hopefully, more information and research data will become available to allow us to better mitigate or, at least, predict risk. Programs pursuing these goals should certainly be encouraged.

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