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Tin Whiskers Are Real and Complex

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Abstract: "Tin whiskers" is not an imaginative, fanciful term for some aspect of electronics manufacturing. Tin whiskers are real. They are microscopic conductive fibers emanating from pure tin surfaces, and they pose a serious problem to electronics of all types. These whiskers can form electrical paths, which affect the operation of the subject device. This article discusses the problems caused by the removal of lead from electronics and describes some techniques to mitigate tin whiskers.

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Introduction

This article discusses tin whiskers: what they are, where they come from, and what we know about them. The discussion covers the problems caused by the removal of lead from electronics, not the least of which is the tin-whisker problem, our subject. Finally, ways to mitigate tin whiskers are suggested.

An Overview of the Problem

Briefly, "tin whiskers" is not an imaginative, fanciful term for some aspect of electronics manufacturing. Tin whiskers are real. They are microscopic conductive fibers emanating from pure tin surfaces, and they pose a serious problem to electronics of all types. Tin whiskers are not a new phenomenon resulting from the switch to lead-free electronics. In fact, they were first reported in papers written in the 1940s.

Lead (chemical symbol Pb) has been banned by the Restriction of Hazardous Substances (RoHS) directive. Although RoHS originated in Europe, its directive now affects virtually every piece of electronics gear manufactured today or planned for the near future. Connectors, passive and active components, switches, and relays now must all be lead-free.

Why such a restrictive mandate? The impetus does not originate with electronics and semiconductors (ICs), but with perceived public safety. European safety agencies determined that it was necessary to prevent lead from entering landfill dump sites, because it is a hazardous substance. Lead is recognized as a neurotoxin, and is known to inhibit hemoglobin production and affect brain development. Children are clearly more at risk than adults. Wonderfully, the removal of lead from paint and gasoline has measurably improved our environment and been especially beneficial for children.

A Closer Look at the Culprit

Tin whiskers are almost invisible to the human eye and are 10 to 100 times thinner than a human hair. They can bridge fairly large distances between electrical device leads, and in so doing, can short out the conductors. They can grow fairly rapidly; incubation can range from days to years, according to the NASA backgrounder on whiskers.[1] There is no set timetable for when they commence growing. A scanning electronic microscope (SEM) photograph of a needle-like tin whisker is shown in **Figure 1**.

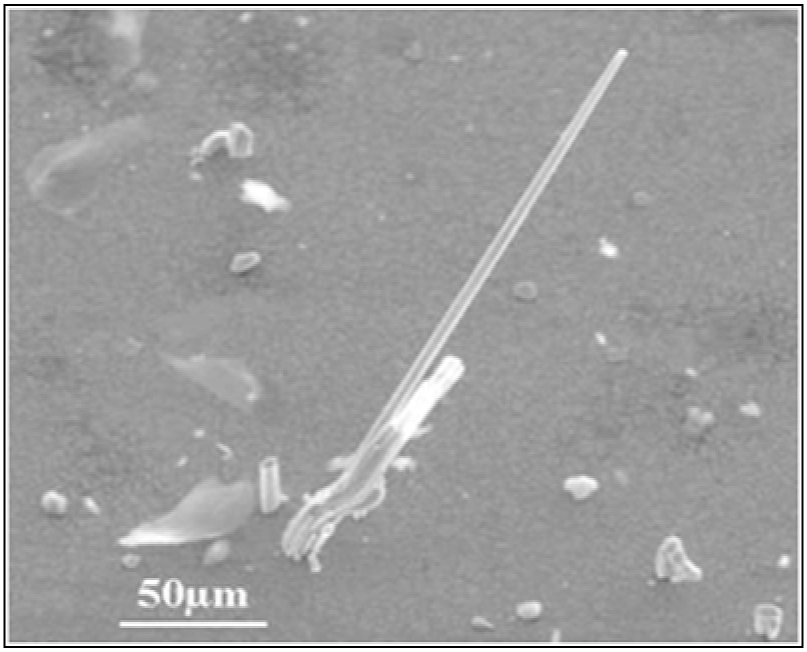

Figure 1. An example of a needle-like tin whisker. Courtesy of CALCE/University of Maryland.

When a whisker grows between two conductors, the whisker usually "fuses" (disappears), creating a momentary short circuit. In some cases it forms a conductive path, creating false signals at an incorrect location which can, in turn, cause improper operation of the device in question. In very rare cases, rather than disappearing like a fuse link, the whisker can instead form a conductive plasma capable of carrying over 200 amps!

Whiskers can also break and fall into contact with printed circuit board (PCB) traces and other conductive pieces where they interfere with electrical signals. In optical systems they can disrupt or diminish the transmitted light; in MEMS they can interfere with the intended mechanical function.

Whiskers are real and they cause real problems. But they are also random. How big an issue are they really? Pure, tin-plated electronics have become ubiquitous in modern society over just the past five years. These electronic systems are the backbone of our communications and financial systems, our manufacturing and transportation systems, and, of course, our power plants (nuclear and conventional). Tin whiskers have created conductive paths and other destruction in unintended places. In 2005, a random "full turn-off" signal at the U.S. Millstone nuclear plant in Connecticut was attributed to a tin whisker.[2]

Because of the potentially dangerous and unpredictable risks of pure tin, it is not presently used in medical devices. Lead is allowed for use in external medical devices until 2014 and for internal medical devices until 2021.

How and Why Do They Grow?

Industry does not really know what causes tin whiskers, nor do we really understand how they are formed. We cannot predict them other than to say whiskers are *likely to form* on pure tin. Studying them with accelerated life tests has proved useless, because they do not grow any faster or sooner in the simulated environment.[1]

So tin whiskers grow at random and interfere with system/subassembly performance. What can you do? To develop a mitigation strategy, the first thing needed is an understanding of what causes tin whiskers. Unfortunately there is no accepted explanation of how they form, but a number of theories exist.

Some postulate that the whiskers form in response to residual stresses within the tin plating and are caused by the chemistry of the plating. They point to the residual stress which results from the bright (small grain) electroplate process finishes as prone to whiskers. Yet the large-grain finishes (matte) are also known to grow whiskers. Others suggest that recrystallization and abnormal grain growth may impact the lattice spacing leading to whiskers.

Stresses can come from many places and are accepted in the "lead" world. But these same stresses seem to induce whiskers in the pure tin world. Sources of stress include compressive forces from external activity like tightening a fastener; bending or stretching that might occur in the formation of the leads; even nicks or scratches created in normal handling. Finally, a seemingly mundane difference in the coefficient of thermal expansion between the lead-frame base material and the tin-plating material has been cited as a possible source for stress that causes the whisker problem.[1] Annealed matte tin seems to be the most successful finish for reducing stress and thus is often used by component companies as a lead-free finish.[3]

Where does that leave us? Many experiments have been conducted with inconsistent results. The present consensus is that influences that increase the stress or promote diffusion tend to induce whisker formation. So in summary, industry really does not know what causes tin whiskers to form.

Is Lead Really the Problem?

Changing pace just a bit, consider the lead question from a different perspective. How much lead is really being consumed each year? According to the International Lead and Zinc Study Group, worldwide usage of lead increased slightly in 2010 to 9.595 million metric tons from 8.966 million metric tons in 2009.[4] (This increase is understandable, given the slowed economy in 2009.) Of that lead usage, 80% is consumed in lead-acid batteries. Note also that before the RoHS directive, only 0.5% was consumed in electronic solder and a mere 0.05% was consumed in electroplate for ICs!

What do all these statistics tell us? The 2010 usage of lead, in all applications, was approximately 21 billion pounds. Of that, 16.8 billion pounds was consumed in batteries and only about 10.5 million pounds *would have been consumed* in IC lead finish if the RoHS directive were not in force for electronics. By the way, the lead in lead-acid batteries remains exempt from the RoHS directive.

Recall that the expected environmental harm from lead in electronics was the impetus behind the RoHS legislative action. Lead was feared as a contaminant to groundwater. But many well-intentioned people overlook one important fact: elemental lead is *not* water soluble. Other sources concur: "Lead does not break down in the environment. Once lead falls onto soil, it usually sticks to the soil particles."[5] When burned in an open-fire recycling operation, lead was feared to cause a poisonous vapor if inhaled. From NASA,[6] the facts are:

1. An open-fire temperature is approximately 1000°C, but Pb boils at 1740°C.
2. Thus, the vapor pressure of Pb would be negligible, presenting little possibility of Pb vapor poisoning.
3. Workers who solder with SnPb do not have high Pb levels in their blood.

In the end, there is no evidence that lead in electronics presents a health risk or causes environmental harm. However, many of the proposed lead-free solutions *do* pose environment problems and many are much worse for the environment.

Options for Lead-Free Electronics

The move to lead-free products meant that the electronics industry has had to develop lead-free solders and terminal finishes compatible with those solders. A number of different lead-free alloys and some very sophisticated binary, ternary, and quaternary alloys were tried. These alloys were expensive and hard to use. Additionally, several tin-silver alloys like tin-silver-copper, tin-silver-bismuth, tin-silver-copper-bismuth, and various other combinations were also investigated. Bismuth-209 is slightly radioactive, so it posed its own set of issues. There were many, serious problems converting to lead-free electronics, but I will not go into a diatribe on all of them today. There are, however, two solutions worth mentioning.

- **Pure Tin (Sn)** is inexpensive and readily available, is not chemically hazardous, and is easy to use. Most lead-free terminal finishes today are annealed matte tin (also called large grain tin) as compared to bright tin or small grain tin. The known and anticipated issue with pure tin has been presented above: whiskers. They will form over time, grow at random, and can eventually cause shorts or worse. Whiskers grow fairly slowly on the ground, but more rapidly at higher altitude. There are mitigation techniques which I will discuss momentarily.
- **Nickel Palladium Gold (NiPdAu)** is a popular lead-free finish material being used more and more widely. Maxim Integrated Products offers it on over 5000 different part numbers today. It is more expensive than pure tin and requires high-temperature lead-free solder.

When considering the finish on components, it is also important to evaluate the ultimate required reliability versus risk. Work presented at the 2010 International Symposium on Tin Whiskers at the Center for Advanced Life Cycle Engineering (CALCE) at the University of Maryland groups the ultimate reliability into three categories and suggests the level of risk for different lead finishes:[7]

- Level I: the product has an expected field life of less than five years.
- Level II: the product requires a very high level of reliability; a failure may be tolerable where redundancies exist or if the failed component/subassembly can be repaired or replaced.
- Level III: the product must be ultra-reliable; there is no easy way to repair or replace a component/subassembly which must have a long planned service life.

Table 1. Finish Material and Reliability Risk

Finish Material	Level I	Level II	Level III
SnPb > 3%	Low	Low	Low
Pure Sn	Medium	High	High
Sn Matte	Low	Medium	High
Sn Matte/Ni Underlayer	Low	Medium	High
Sn Matte/Ni and Annealed	Low	Medium	High
SnBi	Low	Medium	High
SnCu	Medium	High	High
SnAg	Low	Medium	High
NiPdAu	Low	Low	Low

Manufacturing Problems and Surprises

Of course, when the electronics industry moved to eliminate lead problems were anticipated, like the tin-whisker effect. Nonetheless, there were also some complete surprises.

Electronics manufacturing engineers knew that if they mixed leaded and lead-free parts in assembly, they would have to use two passes through the solder machines. Yes, a problem, but not a surprise. However, they were surprised when the thin PCBs sagged at the higher temps required for the lead-free solders. They had acknowledged the possibility of tin whiskers and it still remains a major concern. But they did not always think about the additional thermal load created by the higher temperature pass and the number of cycles through the reflow hardware.

A real surprise was the fracturing of the lead-free solders in high-vibration environments. SnPb solder is not brittle, but many of the newer lead-free options are. Aircraft, for example, have both many frequencies of vibration and fairly rapid temperature cycling as they move from the earth's surface (at perhaps +25°C to +40°C) to 30,000 feet (at -60°C). Fractures were experienced with the lead-free solders and that, in turn, caused intermittent contacts in circuits. And to be sure, that is not a good idea on a fly-by-wire airplane, is it?

Finally, satellites grow whiskers very rapidly. (Recall that the higher the altitude, the more rapid the whisker formation.) Consequently, the various satellite agencies now require a minimum of 3% Pb in the finish of the leads. Most IC makers actually supply a more conventional 85/15 SnPb finish.

Mitigation, But *Not* Elimination

At the outset, let me state the obvious: mitigation is not elimination. It is merely a reduction in severity. Tin whiskers will still grow. In fact, many metals including zinc, cadmium, indium, silver, aluminum, gold, and yes even lead, grow whiskers. But the most damaging and the most prevalent are tin whiskers, which can grow up to 10 millimeters.[1]

Here are some suggestions for reducing the risk of tin whiskers:

1. Do not use pure tin. That seems simple enough. Instead use a tin-lead alloy with at least 3% Pb. Yes, even SnPb has been shown to grow whiskers, but they were observed to be much smaller than pure tin whiskers.
2. Do not rely on the order paperwork. Use an XRF to verify finish on all critical parts.
3. Refinish a pure tin-finished part with a hot-solder dip. Maxim offers this as an option on all of its lead-free devices, and all those devices carry the full Maxim warranty.
4. Use some type of encapsulation or conformal coating. NASA has shown that Arathane 5750 (formerly Uralane 5750) can be effective in preventing tin-whisker shorting when applied with a nominal thickness of 2 mils to 3 mils on the pure tin surface.

Benefits of Conformal Coating

Conformal coating is, just as the name implies, a coating with an inert material which can protect electronic circuit boards from the problems related to tin-whisker growth: shorts, plasma arc, and debris. In defining the requirements for a conformal coat consider the following:

1. It must slow the formation of tin whiskers. We acknowledge that tin whiskers cannot be stopped until we understand how they form in the first place.
2. It must prevent the outward escape of any tin whiskers which do nucleate.
3. It must prevent the penetration of whiskers formed outside the conformal coat.
4. It must protect the coated circuit board from loose whisker debris.

Many types of conformal coatings have been studied over the years by Boeing, Schlumberger, Lockheed, Raytheon, The National Physical Laboratory (UK), CALCE, and NASA among others. A summary of the studies[7] in **Table 2** shows that no conformal coating meets all the criteria outlined above. However, the Arathane coating seems promising when applied sufficiently thick, and the conformal coating does prevent shorts from debris. Ultimately, no coating is 100% effective and whiskers still grow. Thermal effects need to be considered if a conformal coating is used on parts which will need to dissipate heat when operating. If necessary, the device may need to be derated.

Table 2. Whiskers and Different Conformal Coatings[8]

Material	Relative Thicknesses	Time	Results
Acrylic	1, 2, 3 mil	5 yr, 50°C/50%RH	1 mil penetrated, tenting
Silicone	1 to 20 mil	150 days	Whiskers penetrated
Parylene C	0.4 to 0.5 mils	Up to 5 yr, 50°C/50%RH	0.4 mils penetrated
Urethane (Arathane)	1, 2, 3 mils	5 yr, 50°C/50%RH and 11 yrs	Penetration of 1 mil; none of 2 mil at 11 yrs
Urethane Acrylate	1 and 3 mils	Ok after 150 days; 25°C/95%RH	Penetration of 1 and 3 mils

Conclusion

When considering finish material for electronics, the SnPb solution is still the best because industry has more experience working with the material. Additionally, SnPb has been shown not to have a whisker problem and to be very resilient in high-vibration environments.

NiPdAu is a reasonable alternative since it has also proven resistant to whisker formation. However, the suitability of NiPdAu for a high-vibration environment is still being evaluated. Its solder material is a higher temperature solder and may, indeed, be less ductile than traditional SnPb solder.

When a tin-bearing finish is used, conformal coatings have been somewhat effective and may also be suitable. Either non-SnPb solution above adds cost. The NiPdAu finish is plated to the entire lead frame before die bond and encapsulation. (In contrast, SnPb is electroplated to the lead frame after plastic encapsulation.) Although the whiskers are contained, the conformal coating adds processing steps, possible thermal issues, and cannot totally prevent whisker formation.

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