电子工业正开始转向无铅过程序和产品，以遵守欧盟减少危险物品的指令。减少危险物品指令要求电子工业的各个领域开发用于印刷电路板锡铅(Sn-Pb)镀涂层的无铅替代换品。对很多引脚铅框架供货商来说，一种简单的制造解决方案就是使用纯锡涂镀层。但是，已知纯锡容易形成针状凸起或针锡晶须，在间隔紧密的电子线路中可能引起电气短路。本文回顾探讨关于锡晶针须的文献，资料并向系统设计人员提供一些可能的解决方案。

Avoiding Tin Whisker Reliability Problems

G.T. Galyon and Ron Gedney

Fighting tin whiskers involves knowing the available mitigation strategies and risk analysis based on lead spacing.

The electronics industry is just beginning a conversion to lead-free processes and products to comply with the European Union's Reduction of Hazardous Substances (RoHS) Directive. RoHS requires some segments of the electronics industry to convert to lead-free soldering, and all segments must develop lead-free replacements for the tin-lead (Sn-Pb) coatings currently used on most component lead-frames and printed circuit boards (PCBs).

A simple manufacturing solution for many lead-frame suppliers is to utilize pure tin coatings. However, pure tin is known to be susceptible to formation of needle-like protrusions, or whiskers (Figure 1), capable of causing electrical shorting in tightly spaced electronic circuitry.[1] Whiskers of tin, zinc, cadmium and silver have caused serious service failures that have been both life threatening and financially disastrous to the people and companies involved.[2,3]

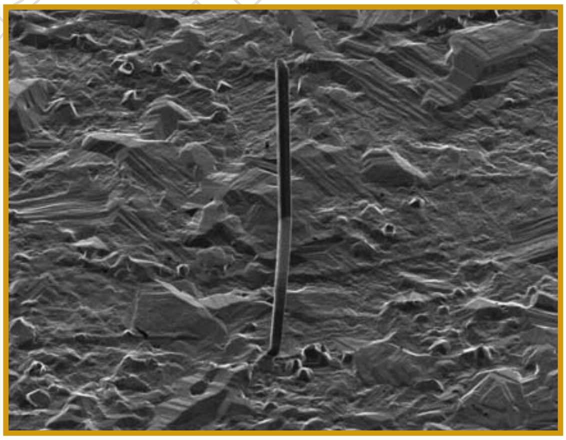

FIGURE 1: A tin whisker approximately 300 microns long.

System developers face two key problems: (1) no consensus exists on a reliability test that can accelerate whisker growth, so qualifying tin-plated terminations is virtually impossible, and (2) no universal consensus exists about the fundamental aspects of whisker formation and growth. As a result, developers, particularly those concerned with high-reliability and/or long design life (greater than five years), do not have sufficient information to safely specify tin coatings for their products.

System designers are bombarded with information about matte tin, alloyed tin, rack plated tin, fused tin, barrel plated tin, mechanically plated tin, tin with an underlay, tin on copper alloy substrates, tin on alloy 42 (i.e. Fe-40% Ni), tin on iron, annealed tin and others. In most cases, a supplier will provide data indicating that its particular offering is *whisker free*. The authors have not found any solution that will guarantee whisker-free products over long periods of time, but some solutions appear to be better than others.

This article examines the literature on tin whiskers and provides some potential solutions for system designers. Military and aerospace systems, which often have unique requirements, are not covered here.

Assessing Risk

Whiskers take a finite time to form and grow. The literature, along with experiments conducted by the National Electronics Manufacturing Initiative (NEMI, Herndon, VA), show that whiskers, once started, tend to grow quickly but not indefinitely. In many cases, whiskers never appear; in others, whiskers appear several years after the component has been fabricated. These inconsistencies leave system designers in a difficult position with respect to accepting pure tin (Sn) lead-frame finishes on componentry.

Prevailing theory is that whiskers are caused by compressive stress buildup in the tin plating. This stress can increase with time, perhaps due to the growth of intermetallic layers at the film/substrate interface. Possible mitigation practices to relieve this compressive stress include use of a nickel underlay, annealing or reflow of the plating, thicker tin (greater than 15 microns) and/or use of an additive such as bismuth.

Designers for applications that have considerable temperature cycling may decide not to allow use of any tin-based finish because whiskers readily form under conditions of temperature cycling. But the bottom line is that all system designers should clearly understand that no pure or high tin content electroplated film is risk free with respect to whisker formation, despite any claims to the contrary.

Of course, a risk-free decision is to not use any high tin content finish. Nickel-palladium-gold (NiPdAu) lead-frames are not prone to whiskers and have been in common use for over 10 years. They currently satisfy a relatively small percentage—about 10%—of commercially available electronic components. These NiPdAu films do not have the innate corrosion resistance of high tin content films, but system designers can easily assess whether a particular application needs significant corrosion resistance capability. Mission and life critical applications should make every effort to utilize NiPdAu finishes.

System designers must be aware of accepted mitigation practices and their limitations. Table 1 summarizes the commonly accepted mitigation practices, based on a study of the available literature in this field, as well as data from the experimental matrices carried out by NEMI projects.

Unfortunately, very few electrical component manufacturers utilize any of the mitigation practices listed in Table 1. Many current commercial lead-free finishes involve *matte* tin, and test data usually indicates that matte tins are preferable to *bright* tins with respect to whisker formation. Matte tin is an electroplated tin with a relatively large (1 to 10 micron) grain size and hopefully low built-in internal stress. Unfortunately, industry data show matte tin is not whisker free. Nonetheless, suppliers have rushed to implement pure matte tin finishes, and only a few of the larger firms have implemented any of the mitigation practices shown. A component user often has to make a risk evaluation on a pure tin finish because no alternative is available.

Mitigation Practice	Description	Comments
Nickel Underlay	Use of nickel plate (0.5-5.0 microns) between the electroplated tin film and the substrate.	• Over 50 years of history on Cu substrates. • Not effective with iron-based substrates. • Rarely available on surface-mount devices. • Common on connectors/bus bars/heat sinks and can packages.
Fused (Reflowed) Tin	Fused tin is a process commonly available in plating shops.	• Over 50 years of history. • Rarely utilized today.
Hot-Dipped Tin	Galvanized sheet steel, etc.	• Rarely used on lead-frames. • Commonly used on sheet steel.
Immersion Tin	Chemical displacement process; very thin (0.5 micron) films.	• Not used in lead-frame industry. • Commonly found on PCBs. • Not a historical mitigation practice, but specific industries have long-term experience without whisker formation.
Annealed Tin	150-200°C for 2-8 hours	• A historical mitigation practice. • Commonly used in the 1960s. • Gradually supplanted by Pb-Sn alloys. • Recently resurrected for lead-frames.
Tin Alloys	Relatively small amounts (2-10%) of some alloying elements are recognized as a mitigation practice. Bi is one such alloy; Ag may be another. Cu is generally recognized as a whisker enhancing additive to Sn films, although some investigators[4] report that they have specific SnCu plating formulations that mitigate whiskers.	• Sn-Bi is not a historical mitigation practice. It has been offered recently as a lead-frame finish by some suppliers. There is some supporting data in the technical literature.

TABLE 1: Common mitigation techniques.

FIGURE 2: Typical quad flat pack with 250-micron gap between lead-frame tabs.

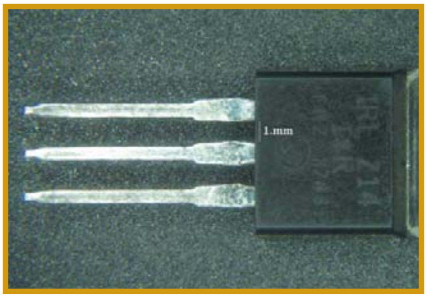

FIGURE 3: A TO-220 package with a 1,000-micron gap between adjacent lead-frames.

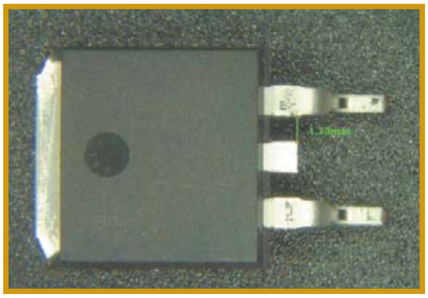

FIGURE 4: A surface-mount D2 package with a 1,130-micron lead-frame spacing.

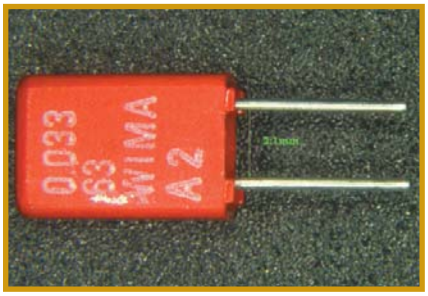

FIGURE 5: An axial-leaded device with a 2,100-micron spacing between adjacent leads.

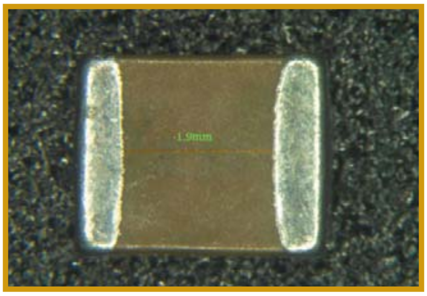

FIGURE 6: A typical surface-mount multi-layer-ceramic (MLC) capacitor with end caps, which has large lead spacings.

The authors describe below a personal risk decision roadmap. Risks are assessed as minimal, marginal and unacceptable based on the following criteria:

- For a mission critical or life threatening application, any high tin content film should be defined as a marginal, possibly even unacceptable, risk.
- For mechanically agitated applications such as automobiles, fan and blower assemblies, any component that does not utilize one of the Table 1 practices should be defined as a marginal risk.
- For applications where the temperature will be cycled between zero/sub-zero and high temperatures (85 to 140°C), any tin-rich films should be defined as a marginal risk. These applications include products such as cell phones, laptops, personal digital assistants (PDAs) and cameras.
- For all other applications, the risk decision should be based on the impact of failures. Special attention must be paid to metal can packages. Whiskers growing from internal or external surfaces can short out to a voltage plane within the device structure and cause a failure.

Lead-Frame Spacing

Finding whiskers more than 300 to 400 microns in length is unusual, and the majority of matte tin film whiskers are 50 microns or less. There are examples of tin whiskers several hundred microns long,[3] but these seem to be in the minority. Exploiting this fact in system design may be possible by using component lead spacing to develop mitigation practices.

We examined several typical lead-frame configurations used for electrical component packages to determine how lead spacing could be used for mitigating whisker effects. These package types are shown in Figures 2 to 6. Figure 2 is a quad flat pack (QFP) with a 250-micron gap between adjacent lead-frames. Similar component packages have lead-frame spacings as small as 50 microns. Figure 3 is a TO-220 package with lead spacings of 1,000 microns.

The D2 surface-mount package shown in Figure 4 has a center stub lead that should have been cut flush to the molded plastic housing. However, in this case, the center stub contact protrudes from the molded plastic housing. As a result of this protruding stub, the lead-frame spacing is 1,130 microns rather than 3,000 to 5,000 microns. Axial leads (Figure 5) are commonly used with resistors, optics packages and certain types of capacitors. Figure 6 shows a surface-mount multi-layer-ceramic (MLC) capacitor with end cap terminations. Both of these package types have large lead spacings.

Risk assessments based on lead-frame spacings are difficult, and the type of device and lead-frame substrate material must be taken into account. Surface-mount and pin-through-hole devices (Figures 2 to 5) typically utilize copper or iron-nickel alloys. Axial-leaded devices use iron or copper-plated iron wire for the leads. Surface-mount bricks (Figure 6) generally use tin over nickel end caps, although some bricks utilize pure tin end caps. Some components use tin-plated brass (CuZn) alloys, which are the worst substrates with respect to tin whisker formation. Table 2 summarizes our risk decision matrix.

Problems at High Frequency

Whisker protrusions affect circuit performance even if shorting of adjacent lead-frames does not occur. Whiskers act as antennas in high-frequency circuits and become an issue at 6 GHz (RF) and

Lead-Frame Spacing (microns)	Comments
50-100	• Ultra fine spacings not commonly used. • Non-tin finishes strongly recommended. • Mitigation practices strongly recommended for tin finishes.
100-500	• Common fine-pitch spacings. • Non-tin finishes strongly recommended for critical applications: military, medical, automotive, mission critical hardware, aerospace, etc. • Mitigation practices strongly recommended for tin finishes.
500-1000	• A fairly long gap for a tin whisker on matte tin finishes. • Long-term reliability (> 5 yrs.) requires mitigation. • Short-term (< 3 yrs.) may use pure tin without mitigation. • Special care is recommended to not use pure tin on iron substrates without either an underlay or an anneal.
1000-2500	• A very long Sn whisker, longer than any matte tin whisker to date. • Common spacings for pin-through-hole (PTH) devices. • Pure matte tin over alloy 42 or Cu a minimal risk. • Mitigation is recommended for critical applications.
2500-5000	• Whiskers this long have been reported, but they are extremely rare, and all known to these authors have been on bright tin deposited onto an iron substrate. • Common spacings for pin-through-hole (PTH) devices. • Mitigation recommended for critical applications where there is either mechanical shock or temperature cycling.
>5000	• There are no matte tin whiskers of this length in the known technical literature. • There is at least one recorded bright tin whisker >10.0 mm in length known to these authors.[5] • Mitigation is recommended for critical applications where there is either mechanical shock or temperature cycling.

TABLE 2: Risk analysis based on lead spacing.

above. For a digital circuit, analysis shows that the effect on circuitry is a function of rise time. The rule of thumb for the effective operating frequency as a function of rise time is:

$$f\ (\text{freq in GHz}) = .35/t_r\ (\text{rise time in nsec})$$

Working backward, a t_r of 58 psecs would be the equivalent rise time for the effect to be significant. This number is becoming more common as device geometries get smaller, integrated circuits (ICs) get faster and buss speeds increase. The total effect is a function of whisker length, whisker density and frequency. To simplify the issue, analysis shows that the tin whisker needs to stay below 75µm in length to avoid affecting a high-speed circuit.

Conclusion

A methodology for protecting long life, high-reliability systems against failures due to tin whiskers has been suggested. Given the complexity of this topic, any system designer who does not have relevant technical experience and know-how should seek expert advice. NEMI has active projects working to develop accelerated testing techniques as well as a greater understanding of basic whisker fundamentals. The organization is also working with groups in Japan and Europe to attempt to develop acceptable solutions worldwide.

The reader is cautioned that any high tin content finish has some associated risk. *Caveat emptor* (and good luck)! ■

References

1. K.G. Compton, A. Mendizza and S.M. Arnold, "Filamentary Growths on Metal Surfaces-Whiskers," *Corrosion*, 7: pp. 327-334, 1951.
2. J.R. Downs, "The Phenomenon of Zinc Whisker Growth and the Rotary Switch (or How the Switch Industry Captured the Abominable Snowman," *Metal Finishing*, pp. 23-25, August 1994.
3. J. Brusse, G.J. Ewell and J.P. Siplon, "Tin Whiskers: Attributes and Mitigation," *Proc. Of the 22nd Capacitor and Resistor Technology Symposium (CARTS)*, pp. 67-80, March 2002.
4. J.C. Bing-Lee, Y.L. Yao, F. Y. Chiang, P.J. Zheng, C.C. Liao and Y.S. Chou, "Characterization Study of Lead-Free Sn-Cu Plated Packages," *Proc. Of the 2002 Electronic Components and Technology Conference (IEEE ECTC), pp. 1238-1245*, 2002.
5. Private communication, J. Smetana, Alcatel Corporation, 2003.

__George Galyon__ is a senior technical staff member for IBM, Poughkeepsie, NY; email: Galyon@us.ibm.com. He chairs the NEMI Tin Whisker Modeling Project and organized the NEMI Tin Whisker User Group. __Ron Gedney__, email: rgedney@nemi.org, is retired from NEMI and continues to consult on several of the consortium's lead-free projects. For additional information about NEMI's tin whisker and lead-free activities, visit www.nemi.org/projects/ese/index.html.