

LEAD-FREE COMPONENT FINISHES – PROBLEMS AND MITIGATION

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ABSTRACT

The worldwide movement towards lead-free (electroplated pure tin) electronic component lead finishes re-introduces a familiar problem to the high reliability electronics community, tin whiskers. This movement to eliminate lead from electronic assemblies is driven by legislation in the EU (WEEE and ROHs) and in Japan to eliminate lead from electronic products by 2006.

While electroplated pure tin is a component surface finish that has existed in the electronics industry for decades, there is a well-known phenomenon related to pure tin plating, known as “tin whiskers.” Tin whiskers are conductive, pure tin crystals that spontaneously “grow” from an electroplated pure tin surface. The growth mechanism for whiskers is not well understood and can be characterized as unpredictable in many cases. Tin whiskers can bridge to near-by conductors causing a range of failures in critical systems.

As the availability of high reliability electronic components with tin-lead terminations continues to shrink, high-reliability equipment manufacturers are being forced to use commercial products (COTS) in many applications. These are precisely the types of components targeted by the lead-free movement. More and more pure tin is finding its way into high-reliability electronics.

COTS components can be tested for performance and reliability using industry and government test methods. Unfortunately there is no accepted test method to determine if a component will exhibit tin whiskers in a specific application or environment. This has led to a number of mitigation strategy initiatives in industry and various consortia investigating methods such as conformal coating, matte tin plating and hot solder dip. This paper will focus on the latter and the capabilities of current technology to efficiently and effectively replace lead-free electro plating with hot dipped solder.

Key words: lead-free, tin whiskers, pure tin, robotic solder dip

TIN WHISKER HISTORY

Tin whisker growth on pure tin finishes has been reported in the electronics industry since the 1940's. Since then, there have been countless research studies on the tin whisker effect. Following a series of tin whisker related failures in the late 1980's and early 1990's the U.S. Military sought to eliminate pure tin from all of its systems. Between 1992 and

1993, language was introduced into most MIL specifications to specifically prohibit the use of pure tin plating. Since the mid-1970's, the United States military, NASA and other high reliability users have preferred and in many cases required tin-lead based finishes instead of pure tin due to documented failures resulting from whisker growth on tin-plated components.

LEAD-FREE INITIATIVES

Legislative and market pressures in recent years (particularly in Japan and Europe) have pushed the electronics industry to consider methods of eliminating lead from their products and manufacturing processes. These initiatives have developed in response to the belief that there are potential environmental and health hazards that may result from the manufacturing and disposal of consumer products bearing lead and other hazardous materials. It is important to note that no direct evidence has been published linking the disposal of electronic equipment containing lead and lead contamination in the environment.¹ Although the U.S. Federal government is not currently introducing similar legislative restrictions, the international pressure has prompted many U.S. electronic component manufacturers to announce conversion of lead bearing plated finishes to lead free (typically pure tin) component lead finishes to remain globally competitive. Pure tin plating is, in the majority of cases, the candidate to replace widely used tin/lead finishes. The ease of converting existing tin-lead plating systems and straightforward (although not without challenges) conversion of existing assembly methods, in addition to years of successful commercial use, pure tin plating is seen by many in the industry as a reasonably simple and cost effective alternative to tin lead.

The problems related to increasing use of lead-free (pure tin) finishes on component leads are compounded by the growth of the use of COTS components in high reliability electronics systems. Most of the initial concern over COTS focused on an electronic component's ability to perform reliably in critical applications and survive and operate in harsh environments such as wide operating temperature ranges, high humidity, vibration and radiation. To address this concern component up screening and system level reliability testing have become a common method to assure performance.

Unfortunately there is no generally accepted test or screening method to determine if a particular component will exhibit tin whiskers in a specific application or

environment. This lack of whisker propensity test protocols, coupled with the unpredictable nature of whisker growth results in a high risk of failure for systems that incorporate pure tin plating on electronic components.

WHISKER FORMATION

Whiskers “grow” in a wide range of shapes, sizes and densities. Figure 1⁶ shows examples of different whisker growth on a variety of components.

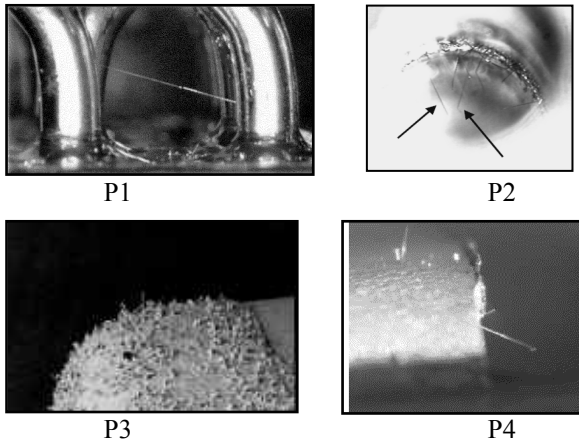


Figure 1. Examples of tin whiskers. P1. Whiskers growing across relay terminals. P2. Whiskers growing inside a plated feed-through. P3. Whisker growth on chip capacitor. P4. Whisker growing from corner of IC lead.

As there is no universally accepted mechanism for the formation of tin whiskers the following is based on observations of many industry consortia experimentation as well as anecdotal reports from industry.

Tin whisker formation is frequently attributed to internal stress in the surface plating, with external stress, electrical fields and environmental conditions sometimes considered to be contributors. Recent studies, including those from NASA, found that external stress can play a very limited part and that the existence of electromagnetic fields does not contribute to whisker formation.² However, NASA did find that a whisker can “bend” toward a surface of different potential and possibly increasing the chances of shorts. The formation of tin whiskers seems to be dependent on a number of conditions in the tin coating. These include:

Plating Chemistry/Process

- Electroplating Current Density
- Higher Current Density --> Higher Residual Stress

Tin Grain Size and Shape

- Submicron Grains
- >0.5 μm and <8 μm appear more prone

“Matte” vs. “Bright” Finish

- Use of “Brighteners” and Presence of Impurities
- Plating Thickness

Alloy composition

- Pure Sn, Sn-Cu, Sn-Bi, and rarely Sn-Pb

- Substrate (Including Base Metal and Barrier Plating Layers)
- Material (Copper, Brass, Nickel, others)
- Substrate Preparation (Stamped, Formed, Annealed)

Other Factors in Whisker Development

- Intermetallic Compound (IMC) Formation
- Environmental Stresses
- Elevated Temperature
- Temperature Shock/cycling (CTE Mismatches)
- Humidity (High RH Observed to Increase Whiskering)
- Applied Pressure (Torque on Fasteners)

Much of the literature supports the theory that growth of tin whiskers is related to internal stress. It has been shown that the external application of compressive stress can cause the growth of the whiskers. To understand the development of whiskers it is important to consider all aspects of the total system. For example, how are the leads on an electronic component formed? The process of lead forming may cause stress on the tin finish on the component. If the internal stress already present in the finish is slightly below the “activation” energy required, the new energy provided by the forming of the electronic component may well be enough to supply the additional energy required for tin whisker growth.

It is important to note that many experiments show contradictory results for these factors. In particular, the time over which whisker form seems quite variable. While whisker formation has been historically believed to be long term (8 to 10 years) there are instances where whiskers develop over much shorter periods of time.

TIN WHISKER FAILURE MODES

A number of government and industry notices have been issued relating to whiskers for aerospace, defense and medical industries.^{6,8,9,10} Tin Whiskers can contribute to a number of potential failures in electronic hardware. These problems include:

- Short circuits, hard and momentary
- Plasma arc (in a vacuum)
- Fragments / contamination

Hard short circuits are a problem for circuits where there is enough current to fuse the tin whisker to form a permanent short circuit. Pacemakers have had this problem.⁹ An F-15 radar failed because of a tin short from a tin plated component. Another failure mode resulting from a hard short circuit is a change in circuit operating parameters. These failures can be much more difficult to identify and may lead to erroneous problem diagnosis.

Momentary short circuits occur when there is sufficient current to exceed the fusing current of the whisker and the circuit experiences only a momentary short circuit.

In the vacuum of space a whisker can vaporize causing plasma that can conduct many hundreds of amperes.⁸ The Galaxy IV and VII satellites failed because of this issue.

The unpredictable nature of whisker growth results in a significant risk of failure in critical electronic systems. The risk is increased by the random nature of whisker growth meaning that a short circuit could occur anywhere over a wide area of an electronic assembly. This has major implications for reliability and safety

Fragments and contamination is caused when a tin whisker breaks loose due to some environmental event. These loose whiskers can interfere with other exposed circuits. This is again another unpredictable failure mode.

MITIGATION STRATEGIES

There are many possible mitigation techniques that can be implemented for dealing with the risk of tin whisker related failures in an electronic system. To evaluate these mitigation techniques, two major factors must be evaluated relative to the cost of the mitigation technique; first, the consequence of a failure in the application; second, the amount of mitigation the technique will provide. As shown in figure 2¹¹, as the consequence of a whisker failure increases, so does the

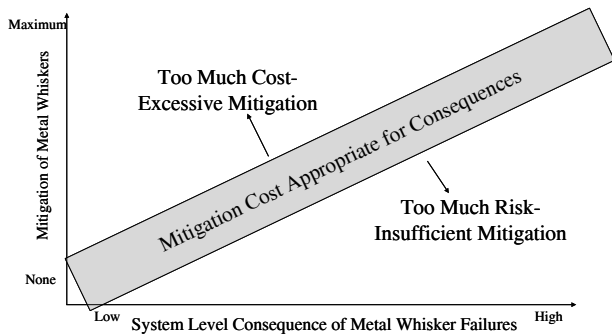


Figure 2.

Pure Tin Prohibition

Prohibition of pure tin lead in a design is the best way to avoid tin whiskers. Unfortunately this technique is becoming impractical due to the lack of availability of components with tin lead plating. In addition, for some component types the surface finish of cases and interconnects is not considered a critical issue in the components intended application. This means that surface finish may not be specified or available from the component source.

Case by Case Risk Assessment (use as is)

By analyzing the components on a circuit board, the physical layout of those components, the assembly environment and application, a case can be made that the risk of tin whisker growth is low enough to be discounted.

The major challenge to this strategy is in the development of a risk assessment metric that is more than qualitative. As part of a case-by-case risk assessment, there also needs to be some way to determine a risk tolerance level for the design being evaluated. Table 1¹¹ shows an example of the type of levels that could be considered in high reliability applications. In the extreme, these tolerance levels would range from no risk being acceptable as is a medical implant or space application to a high level of risk being acceptable as in consumer electronics or office equipment.

Description	Controls	System Types
Complete ban on pure Sn and Zn finishes	No pure Sn or Zn, no exceptions	Space-based Strategic Missiles Implanted Medical Devices
Use of Sn and Zn finishes as last resort	Permit use on a case-by-case basis, if no alternative, if risk is negligible	Avionics Tactical Missiles
Use of Sn and Zn permitted under pre-set conditions	Blanket permission for classes of use, and on a case-by-case basis, if risk is minimal	Surface-based Radar and Communications Hi-Rel Commercial (Automotive, Medical, Industrial, Maritime)
Use of Sn and Zn restricted only under pre-defined conditions	No general restrictions. Use may be banned in limited high-risk places	Non-deliverable Test Equipment Ground-based non-tactical
No Restrictions	None	Consumer Electronics

Table 1. System risk levels

Conformal Coating

Conformal coating has been in use for some time to reduce the risk of failures due to tin whiskers in electronic assemblies. There are, however, documented cases where conformal coat has been shown to be ineffective as a whisker mitigation technique. It is clear that the nature of the components being coated, the coating process and coating material all contribute to the effectiveness of conformal coating to reduce tin whisker growth.

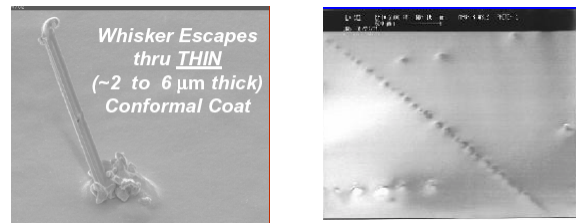


Figure 3. Whiskers growing through and under conformal coat.

One potential problem with conformal coating, is its propensity to “thin-out” at sharp corners and edges. In the case of an electronic component, this thinning would occur in a high whisker risk area on the edge of plated leads. Tin whiskers have been observed growing through conformal coatings. (Figure 3⁶) The ability of the coatings to protect nearby circuits is also valuable but it is providing secondary protection at best.

The use of conformal coatings to prevent the growth of tin whiskers is not practical in all cases especially where access to the components on a circuit board for repair or adjustment is necessary after final integration.

Robotic solder dip

In robotic solder dipping of tin plated leads, a Sn/Pb based solder is used to replace the existing tin finish. This process will help reduce whisker formation by:

- Relieving stress in the tin layer through reflow
- The addition of an alloying element (Pb)

State of the art robotic solder dipping equipment can effectively solder coat the finest pitch component leads, formed or unformed. The use of nitrogen blanketing and dynamic solder waves are keys to successful and consistent coating. To avoid problems related to heating the component there are several requirements for the solder dip system. (See Table X)

1. Pre-Process moisture bake-out capabilities for plastic encapsulated microcircuits (PEMs)
2. Accurate control of the temperature profile during processing.
 - This requires pre-heat and cool down stations to minimize temperature shock. (Fig. X1)
3. Precise positioning capability to ensure that the component package is not exposed to excessive contact with the molten solder. (Fig. X2)

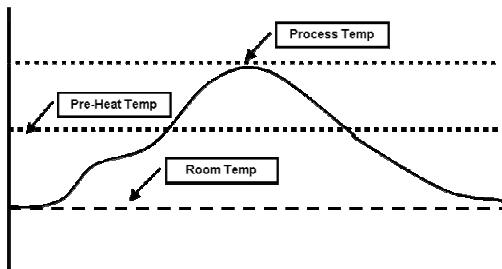


Figure 4. The temperature profile of a component processed in a robotic solder dip system can be controlled to minimize thermal shock.

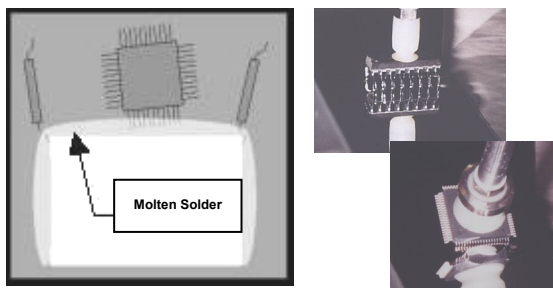


Figure 5. The dynamic solder wave system allows for a wide variety of component insertion angles to facilitate solder coverage and, minimize solder defects.

System Feature	Benefits				
	Process Repeatability	No Artifacts, bridging, icicles	Thermal Shock Reduction	No physical lead damage	No excessive solder contact
Pre-bake facility to eliminate moisture	✓		✓		
Computer control of system operation	✓	✓		✓	✓
Hands free operation through all stages	✓			✓	
Vision assisted component alignment	✓			✓	✓
Pre-heat stage immediately prior to solder dip	✓		✓		
Dynamic solder wave with precise temp control	✓	✓			
Nitrogen atmosphere over solder	✓	✓			

Table 2. Robotic solder dip features and benefits.

Solder dip alone may not be applicable to all component types, especially where a glass bead is used to seal the lead to the package as the temperature of the solder may compromise the glass seal. In these cases the combination of robotic solder dip and conformal coating may provide the highest level of protection.

Robotic solder dip can be a cost effective method for mitigating tin whiskers as state of the art systems can operate at throughputs from hundreds to thousands of components per hour.

Diffusion of lead into pure tin

Recently there has been an example has been shown where a pure tin termination on a passive SMT device has had lead “added” to the tin plating. This technique is currently being adopted in several high reliability applications for tin whisker mitigation. Figure X¹² shows the before and after results of this technique. In both micrographs the right most edge is the plated terminal finish. The Left hand micrograph is before lead addition. The right hand micrograph is after lead addition. The lead shows up in the micrograph as the bright areas.

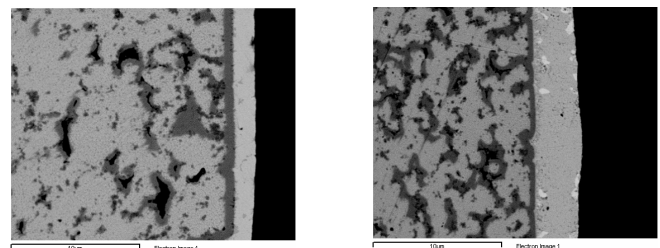


Figure 6. Backscattered SEM micrographs showing absence and then presence of lead.

CONSORTIA WHISKER MITIGATION EFFORTS

There are several consortia in industry, academia and government looking at solutions to the lead-free and tin whisker problem. Some of these efforts are not open to the public, while some are. Table 3 lists several organizations actively researching tin whisker development and mitigation techniques.

CALCE (University of Maryland)	
	Investigating the whisker growth mechanism. Developing whisker test protocol.
CALCE (University of Maryland)	
	Tin Whisker Team
	Evaluating solder dip, conformal coat.
NEMI (National Electrical Manufacturers Initiative)	
	Investigating the whisker growth mechanism. Developing whisker test protocol.
GEIA G-12	
	Published a tin whisker mitigation guideline.
JCAA - JG-PP	
	Evaluating reliability of lead-free alloys.
IPC/JEDEC	
	Establishing guidelines for lead-free assembly, inspection and repair.

Table 3. Tin whisker/lead free research initiatives.

SUMMARY

As a result of political and environmental pressures, electronics components manufacturers' are increasingly adopting pure tin as a standard lead finish. This action is causing a reemergence of the problems associated with pure tin lead finishes, tin whiskers and finish contamination. The announcement, by many electronic component manufacturers, of a switch to pure tin as an "environmentally friendly" alternative to tin-lead alloys, coupled with the move toward increased usage of COTS components has the potential to make tin whiskers a serious problem for high reliability electronics industries such as military hardware, medical devices and space systems.

With no widely accepted method to determine if tin whiskers will grow and no published and accepted model for tin whisker formation many questions remain unanswered. Tin whiskers can develop in a short time period or after many years. The success of any mitigation strategy such as new plating chemistries, conformal coat, lead diffusion and robotic solder dip needs to be evaluated for each type of application. There is clearly more research needed to answer the questions raised in this paper and by other researchers. In the mean time, the risk of tin whisker related failures is real and increasing in high reliability applications. System design and reliability engineers need to evaluate the potential impact of a whisker related failure in high reliability systems where failures can impact mission success and safety and chose an appropriate mitigation strategy.

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