CARTS 2002: 22nd Capacitor and Resistor Technology Symposium, 25-29 March 2002

TIN WHISKERS: ATTRIBUTES AND MITIGATION

Jay A. Brusse, Gary J. Ewell, and Jocelyn P. Siplon

QSS Group, Incorporated
NASA Goddard Space Flight Center (Code 562)
Greenbelt, MD 20771
Phone: 301-286-2019
FAX: 301-286-9778
Jay.A.Brusse.1@gsfc.nasa.gov

The Aerospace Corporation
P.O. Box 92957, M4-986
Los Angeles, CA
Phone: 310-336-6003, 310-336-6572
FAX: 310-336-6914
Gary.J.Ewell@aero.org, Jocelyn.P.Siplon@aero.org

ABSTRACT

The movement to eliminate lead (Pb), especially active in Japan and the European Union, has resulted in an increasing use of pure tin (Sn) coatings on leads and other external and internal surfaces of capacitors, resistors, and other passive components. This paper discusses the issues of tin whisker growth with respect to passive components. It also presents both a critical analysis of existing published documents on tin whisker nucleation and growth and a summary of very recent experiments that provide further understanding of the potential means of whisker formation mitigation. Many of the proposed mechanisms for mitigation, including control of the immediate underplating material, use of conformal coating, regulating the thickness of the tin coating, use of matte tin electroplating, and annealing or fusing of the tin layer, are inadequate. They likely reduce the incidence of nucleation or growth but do not provide an absolute guarantee of lack of whisker formation.

"Lead-Free" Movement

Electroplated and dip-coated finishes are applied to electronic components primarily to protect the base metal (conductor) from corrosion and to enhance solderability. The benefits of many tin and tin alloy electroplating processes also include excellent control and uniformity of plating thickness (especially critical in miniaturized, fine-pitched components), good electrical conductivity, and non-toxicity [1]. In addition, tin finishes, especially "bright" finishes, which use organic additives in the plating bath, maintain an aesthetically pleasing shiny surface. For these purposes, a wide assortment of electroplated finishes have been used with much success, including many tin-lead based alloys (ranging from 2% - 50% Pb) as well as 100% pure tin [2].

In recent years, legislative pressures (particularly in Japan and Europe) have forced the electronics industry to consider methods of eliminating Pb from their end products and manufacturing processes. These legislative regulations are being developed in response to potential environmental and health hazards that may result from the manufacturing and disposal of consumer products bearing Pb and other hazardous materials [3]. There have also been reports that Japan’s computer makers will start charging fees from consumers for future recycling/disposal of these computers.

Although the U.S. is lagging Japan and Europe in introducing similar legislative restrictions, the U.S. electronics industry is reacting to these initiatives, by considering alternative solders and coating systems in order to remain competitive in the world market. With respect to factors such as ease of converting existing tin-lead plating systems, ease of manufacture and compatibility with existing assembly methods, pure tin plating is seen by many in the industry as a potentially simple and cost effective alternative to SnPb-based systems [4]. Many manufacturers have been offering pure tin coated components as a standard commercial (and in some cases high reliability) product for years while others are just now exploring use of Pb-free alternatives, such as pure tin, for the very first time.

Despite all of its benefits, there is one major impediment to an across-the-board adoption of pure tin as the solution to pending Pb-free legislative requirements: *many pure tin electroplates develop tin whiskers.* This possibility, in combination with the lack of accepted methods for testing whisker growth susceptibility, gives rise to major reliability concerns!

Concern Over Tin Whiskers

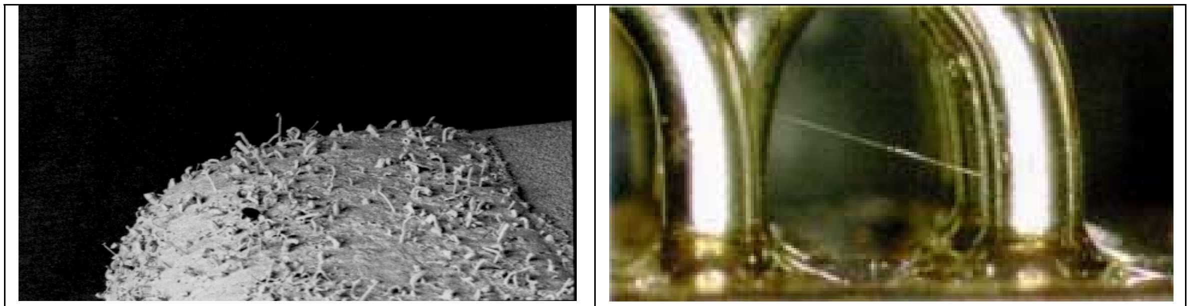
Tin whiskers present two reliability issues for equipment manufacturers and users. The first is electrical shorting. Whiskers can grow between adjacent conductors of different potential and cause either a transient short as the whisker is burned open, or a permanent short. Second, whiskers can be broken loose from their substrate and as debris cause mechanical problems with slip rings, optical devices, microelectromechanical devices (MEMS) and similar components.

Examples of Components that Have Grown Tin Whiskers

Many types of pure tin coated components have been shown to be susceptible to spontaneous growth of tin whiskers. Given time (days or months to years) whiskers may grow to lengths capable of causing electrical shorts in densely packed circuits. The first report of such whiskers on electronic components dates back to 1946 [16]. Since that time whisker-related problems have been reported consistently. Today the concern is for the likelihood of <u>increased</u> whisker-related problems due to circuit geometry reductions, lower application voltages and the probability of more suppliers (rapidly) introducing pure tin plated alternatives to comply with pending Pb-free legislation.

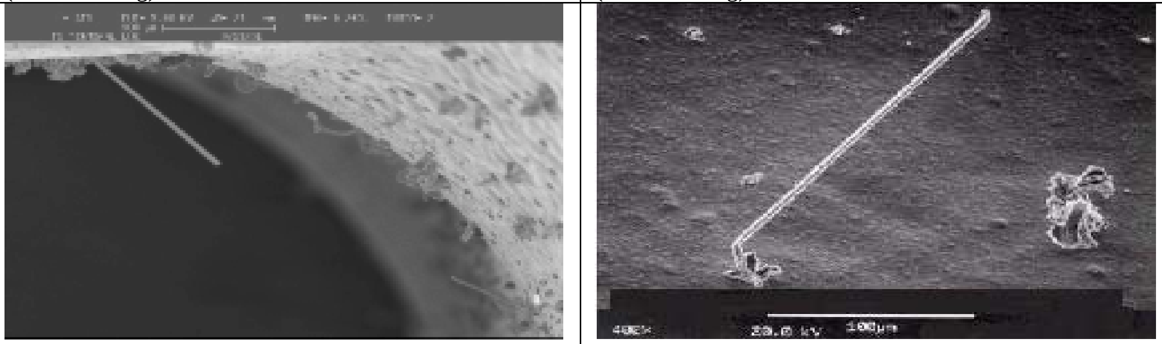
Although the authors of this paper are focusing on whiskers from tin electroplates, it must be noted that other metal electroplates may also be prone to whisker formation (most notably zinc and cadmium). Arnold offers an excellent overview of several component applications where whisker problems have occurred [5]. Arnold's review, and more recent problem reports, shows that whisker formation is not restricted to any particular family of electronic components. Among the pure tin plated components that have exhibited extensive tin whisker formations are electromagnetic relays, IC leadframes, transistor and diode packages, hybrid microcircuit lids, connector shells, terminal lugs, metal washers, printed wiring board traces and plated through holes and very recently ceramic chip capacitors. Figure 1 provides a few examples that the present authors have encountered during the past few years.

The most concern is with chip-style resistors, inductors, and capacitors that have pure tin plated terminations. The concern arises from their very small physical dimensions and the lack of established tests to demonstrate immunity to whisker formation.



Ceramic Chip Capacitor: Termination
(>0.2 mm long)

Electromagnetic Relay: Hook terminals and case
(>2.0 mm long)



Terminal Lug: Inside crimp barrel
(> 0.25 mm long)

Hybrid Microcircuit: Package Lid
(> 2 mm long also reported)

Figure 1: A few examples of pure tin-plated components that have exhibited tin whisker growth, courtesy of NASA-Goddard.

Whiskers and Passive Parts

There are only a few papers that directly discuss whisker growth in passive components such as surface mount resistors and ceramic capacitors [32, 30, 31, 44]. To date such papers have generally proclaimed these device types to be relatively immune to whisker formation based on a number of apparent beneficial characteristics of their termination structure such as the use of a nickel barrier to minimize diffusion, tin grain size and shape factors and post-plating annealing practices]. In 1997, Endo (Murata) reported 18 years worth of whisker-free observation of multilayer ceramic chip capacitors (MLCC) stored at 50°C [31]. However, the authors of this paper have recently observed moss-like whisker growths on MLCCs as long as 0.25 mm (see Figure 1) after thermal cycling. Such apparent contradictions are evidence that proclamations of whisker "immunity" are extremely difficult to validate given the vast array of user application conditions and the absence of industry-accepted test methods to judge whisker propensity.

Reportedly, tin whiskers have been observed growing from “tin-rich” areas of the end metallization (90% tin) on military-grade polycarbonate capacitors [50]. These whiskers caused electrical shorting on production lots from which spacers designed to help improve vibration capability were inadvertently left out in one case, and purposely eliminated for a wholly different reason in another. Such incidents are examples of a general class of concerns where a tin-rich area is otherwise formed in an alloyed tin matrix, and the tin-rich area has the potential for whisker formation. Tin-rich areas can be formed through recrystallization and grain growth, selective oxidation, diffusion, and other mechanisms.

Failure Mechanisms and Field Problems Associated with Tin Whiskers

Tin whiskers pose a serious reliability risk to electronic assemblies. The most likely hazard is referred to as an "electrical short", but a refinement of that terminology is warranted to clarify the shorting behavior in terms of application conditions. It is tempting to expect that these tiny conductive filaments will fuse open at the instant of shorting, creating perhaps an unnoticeable "glitch" to the circuit performance. However, the miniaturization of electronics and advances in low power, low voltage circuitry as well as the unique environmental conditions of space application demonstrate that such "glitches" can become catastrophic events. Table 1 defines some common failure modes attributed to tin whiskers.

Table 1: Equipment Failure Modes Induced by Tin Whiskers

Failure Mode	Description
1. ***Permanent short circuits***	In low voltage, high impedance circuits there may be insufficient current available to fuse the whisker open and stable short circuit results. Depending on a variety of factors including the diameter and length of the whisker, it can take more than 30 milliamps (mA) to fuse open a tin whisker [14].
2. ***Transient short circuits***	Under normal atmospheric conditions, if the available current exceeds the fusing current of the whisker (normally less than 30 mA, but perhaps as high as 75 mA [35]), the circuit may only experience a transient glitch as the whisker fuses open.
3. ***Metal vapor (Plasma) arcing in vacuum***	In vacuum (reduced atmospheric pressure) a much more destructive short circuit phenomenon can occur. If currents of above a few amps are available and the supply voltage is above approximately 18V, the tin whisker may vaporize creating a plasma of tin ions that can conduct hundreds of Amperes. An adequate supply of tin from the surrounding plated surface can help to sustain the arc until the available tin is consumed or the supply current is interrupted such as occurs when a protective fuse or circuit breaker interrupts the current flow [43]. This phenomenon is reported to have occurred on at least three on-orbit commercial satellites since 1998 resulting in blown fuses that have rendered the spacecraft non-operational [26].
4. ***Debris/Contamination***	Mechanical shock, vibration or handling may cause whiskers to break loose from the plated surface. Once free to move about, these conductive particles may then interfere with sensitive optical surfaces or the movement of microelectromechanical systems (MEMS). In addition, the debris may also bridge isolated conductors resulting in short circuits (see 1-3 above) [29].

Several instances have been publicly reported where tin whiskers have caused system failures in both earth and space-based applications affecting the military, medical and telecommunications industries. Table 2 presents a few such incidents to emphasize the significance of the inherent risks of tin whiskers.

Table 2: Reported Field Problems Induced by Tin Whiskers

Application	Impact	Reference
Medical		
Heart Pacemaker	Class I Product Recall: Tin whisker shorts from pure tin-plated housing of crystal cause complete loss of pacemaker output.	[45]
Military		
F-15 Radar	Tin whisker shorts inside hybrid microcircuit. Whisker from pure tin-plated hybrid microcircuit lids.	[29]
U.S. Missile Program	Tin whisker from pure tin plated relays	[24]
U.S. Missile Program	Tin whisker growing from pure tin plated TO-3 transistor can shorts collector to case. Short sends a false command to turn on an electrical unit.	[20, 23]
Phoenix Air to Air Missile	Tin whisker shorts inside hybrid microcircuit. Whisker from pure tin-plated hybrid microcircuit lids.	[47]
Patriot Missile II	Tin whiskers from pure tin plated terminals	[46]
Space (Satellite)		
GALAXY IV	Complete loss of satellite operations. Tin whisker short (metal vapor arc in vacuum) from pure tin plated relays.	[25, 26]
GALAXY VII	Complete loss of satellite operations. Tin whisker short (metal vapor arc in vacuum) from pure tin plated relays.	[26]
SOLIDARIDAD I	Complete loss of satellite operations. Tin whisker short (metal vapor arc in vacuum) from pure tin plated relays.	[26]
Additional Satellites	Three additional satellites of the same general design as above have lost one of two redundant satellite control processors due to tin whisker shorts.	[25, 26]
Energy		
Nuclear Regulatory Commission	Tin whiskers from pure tin plated relays	[34]

What are Tin Whiskers?

Tin whiskers, as the name implies, are hair-like growths of near perfect single crystalline structures of tin that grow from some electroplated tin surfaces. Tin whiskers are believed to grow in order to relieve mechanical stresses acting within the tin layer. Over time (days or months to years), some whiskers have reached lengths capable of creating electrical short circuits between closely spaced conductors (see Table 1).

Whisker growths are frequently defined as "spontaneous", to distinguish them from a completely different phenomenon known as "dendrites" which require the presence of moisture, an ionic species and an electric field in order to form. On the contrary whiskers require none of these conditions to form. Indeed, they have been observed to grow in inert atmospheres and in vacuum with or without the presence of electric field [5]. Almost all research conducted to date agrees that electric field has little to no effect on initiation of tin whisker growth. However, NASA Goddard has demonstrated the ability of whiskers to "bend" in response to forces of electrostatic attraction [7]. Such behavior is significant, when considering the probability of a whisker shorting scenario where whiskers growing from a surface at one electrical potential will bend towards a surface at a different potential, especially if those whiskers are relatively long.

Whisker Growth Mechanism

Experts in the electronics and electroplating industry still have not reached a consensus upon a single accepted explanation of the mechanism(s) that drives whisker formation. However, there are some commonly accepted factors involved in tin whisker formation. Generally speaking, there is agreement that whisker growth occurs from the base of the whisker (not the tip) [17] and that some form of long range diffusion of tin atoms supports the growth. Long-range diffusion theories are supported by the lack of material depletion in the immediate vicinity of the whisker base [21].

Today most agree that a process of stress relief within the tin layer drives whisker nucleation and growth. More precisely, many researchers postulate that the development of "compressive" stresses within the tin layer provides the fundamental driving force for whisker growth [2, 9, 18].

Of the more recent studies of whisker growth mechanism(s), Lee and Lee [9] have described one model for whisker growth that is heavily reliant upon the processes of diffusion and intermetallic compound (IMC) formation occurring between the tin layer and the underlying substrate. In this model atoms with high diffusivity in tin (i.e., copper, zinc) migrate from the substrate material (phosphor bronze in their study) into the tin layer, preferentially along the tin grain boundaries. These diffusing elements and the resulting IMCs (Cu_6Sn_5), produce a compressive stress in the tin layer. The stress that builds over time can shear the surface tin oxide layer approximately along the boundaries of grains having orientations different from the majority. Once the oxide layer has ruptured, tin grains (whiskers) may then be extruded in a continuous fashion through the oxide layer as a means of relaxing compressive stresses. As growth proceeds, the resultant localized compressive stress tends to reduce until the stress level is no longer sufficient to support further growth (equilibrium). Additional stresses, such as those arising from thermal cycling, might initiate further growth. One implication of this is that whisker nucleation is not needed, as pre-existing grains are whisker nuclei, and that growth occurs after there is sufficient stress to overcome the obstacles of pinning the boundaries of a particular grain, which then becomes a whisker.

Table 3: Factors reported to contribute to the development of compressive stress in plated tin layers

Factor	Description
Plating chemistry and process [18]	• Higher current density produces higher residual stress • Co-deposited organics (carbon) from "brighteners" in the plating bath • Co-deposited hydrogen • Grain size and shape. Smaller grained finishes (submicron) appear to be more prone to whisker formation; however, thicker/larger grained surfaces may also whisker • Plating thickness >0.5 μm and <8 μm
Substrate Stress: [12]	Mechanical processes used in preparation of the substrate such as cold rolling, swaging, piercing, stamping can leave the substrate in a highly stressed state prior to plating
Diffusion of substrate elements into tin layer: [9]	Elements from the substrate, such as zinc (from brass) or copper, may readily diffuse into tin. Diffusion may occur preferentially along grain boundaries of the tin layer causing compressive stress.
Intermetallic Formation: [9, 22]	Formation of intermetallic compounds (such as Cu_6Sn_5) may alter the lattice spacing in the tin plating.
Externally Applied Mechanical Stress: [5, 12, 42]	• Compressive stresses such as those introduced by torquing of a nut/bolt assembly. Interestingly, controlled experiments by Dunn [14] failed to show any correlation between applied external stress and whisker growth. • Bending or stretching of the surface after plating such as lead forming or crimping • Scratches, gouges in the plating and/or the substrate material introduced by handling, probing, etc.
Environmental Stresses: [37]	• *Storage temperature:* 50°C reportedly is optimal for growth, but independent researchers have shown higher growth potential at 25°C compared to 50°C [7]. Higher temperatures may introduce competing effects by increasing rate of diffusion while simultaneously relieving stress through annealing/recrystallization of tin grain structure. • *Temperature Cycling:* Coefficient of Thermal Expansion mismatches between the tin plate and substrate material(s) • *Moisture/Humidity*
Surface Tin Oxide: [49]	Formation of surface tin oxide is also reported to contribute compressive stresses to the underlying tin due to the specific volume change on the surface.

Table 3 lists some of the factors most frequently considered to contribute to compressive stress. As such, the majority of whisker mitigation practices being explored today by both electroplaters and users involve attempts to minimize those factors which encourage the development of compressive stresses within the tin electroplate.

Schetty and others have demonstrated experimentally that the use of substrate materials and/or underplatings that are diffusion resistant (such as nickel) can serve to significantly reduce whisker growth as described by the Lee model. However, other researchers still observed significant whisker formation on specimens thought to be diffusion and IMC formation resistant. For example, Dunn [21] observed 2 mm long whiskers growing on a matte tin plated steel (low diffusivity) electronics box, Lal [36] has shown that both matte and bright tin finishes over nickel (diffusion barrier) on phosphor bronze are prone to whisker formation, and the present authors have evidence of whiskers approaching 0.25 mm long on tin plated nickel-barrier layer ceramic chip capacitor terminations (see Figure 1).

Table 4: Common Tin Whisker Attributes

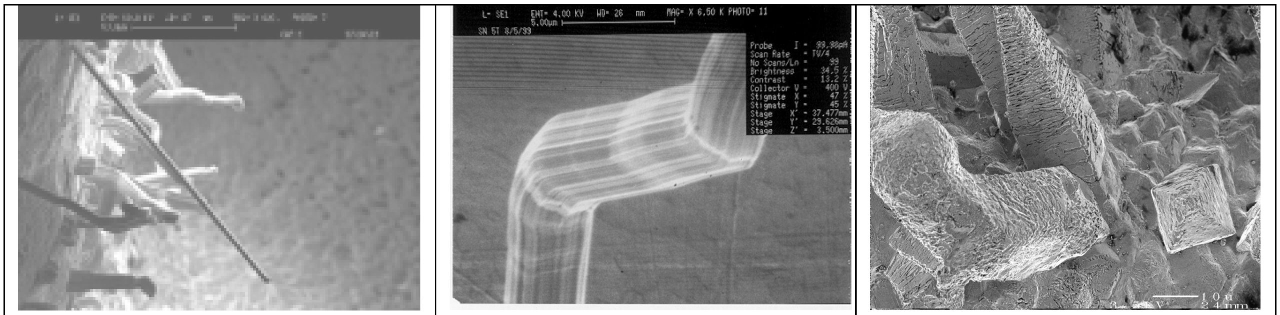
Attribute	Description
Shapes & Surface Features (Figure 2):	• Many different shapes have been reported including very short irregularly *shaped nodules or pyramidal eruptions* (typically no more than a few tens of microns in size). The more concerning longer *needle-like structures* may be straight or kinked with discrete bends along their length. Such whiskers often appear to emanate from nodules, although nodule formation is not a prerequisite for needle like growth. • Some are reported to be hollow [8], though such claims are not generally accepted (see Figure 2). • Close inspection of their surfaces reveals that most whiskers are striated (grooved) along lines parallel to their longitudinal axis giving the appearance of having been "extruded" as if drawn through an irregularly shaped die. [7, 9]
Growth Rate	Growth rates ranging from 0.03 to 9 mm/year have been reported [38]
Whisker Length:	Whiskers a few millimeters long are the most commonly reported, with some experimenters observing whiskers as long as10 mm (400 mils) [1, 11, 12]. Ultimate lengths are dependent on many variables, including the amount of time allowed for growth to occur.
Whisker Diameter:	Typical diameters range from 1 - 4 μm with some reports as high as 10 μm and as low as 0.006 μm [14]. In many instances the diameter of the whisker may be larger than the tin grain size as well as larger than the nominal thickness of the electroplate. [15]
Density of Growths:	Whisker densities up to $10^4/cm^2$ have been observed [15]. There are other cases that showed very sparse growth densities. The less dense growth specimens have sometimes been attributed to unique conditions of highly localized stress in the tin layer such as may result from corrosion of the substrate (i.e., steel) [27], or due to residual substrate stresses resulting from operations such as stamping, cutting or bending [12].
Current Carrying Capacity:	• Current carrying capacities as high as 75 mA before fusing (melting) have been reported for whiskers of 4 μm diameter [35]. Other experiments showed capacity up to 32 mA [14] under normal atmospheric conditions. • More astounding are the documented cases in vacuum (space) applications where tin whisker shorts may cause the whisker to vaporize, forming a plasma of tin ions that may sustain currents of several HUNDREDS of AMPERES! [43]. Such catastrophic events have been reported as the root cause of complete failure of at least 3 on-orbit commercial satellites [25, 26]. Similar plasma arcing phenomenon has also been reported for zinc whisker shorts during vacuum testing. [28]
Mechanical Strength:	Tin whiskers are reported to possess very high mechanical strength in the axial direction due to their near perfect crystalline structure. Experiments using mechanical shock and vibration spectra representing common spacecraft launch environments have shown whiskers to be highly resistant to detachment from such dynamic forces [13]. However, other researchers have observed component failures resulting from detached whiskers that lodged in areas creating critical short circuits [5, 29]. Shear strengths, especially in long whiskers, have been reported as low.

Generally speaking, the whisker growth process may be characterized by 3 distinct stages: incubation (or nucleation), period of growth at a fairly constant rate, followed by transition to growth at a much-reduced rate (or apparent cessation of growth). Perhaps the most insidious trait of tin whiskers is the unpredictable nature of their growth initiation. Several researchers have reported incubation periods as short as a few days from the time of electroplating. Others have observed incubation periods of many years in duration [14, 19]. This attribute of whisker growth is particularly challenging because meaningful experiments to determine the propensity of a particular process to form whiskers may need to span very long periods of time, especially in the absence of industry-accepted test methods proven to accelerate the growth mechanism.

Once the initiation period has been completed and growth begins, average growth rates up to 0.8 mm/year have been reported for a bright tin finish on brass [7]. Growth rate is highly variable and is likely to be determined by a complex relationship of factors including plating chemistry, plating thickness, substrate materials, grain size and structure, and environmental storage conditions [14]. In one extreme case [42] in the presence of high levels of external pressure, a 1mm long whisker was observed to grow within 16 minutes! Some have suggested that the whisker growth period may only last for a period of a few hundred days from the initiation of growth [14]. However, such reports are difficult to confirm, as they require extremely long-term experiments and careful monitoring. The apparent failures of 3 commercial on-orbit satellites due to tin whisker shorting events [25, 26], at intervals between

6 to 8 years after launch, are suggestive that either the growth or initiation periods could have been much longer in duration than a single year.

Some of the commonly reported attributes of tin whiskers are summarized in Table 4.



Classic "needle-like" whisker

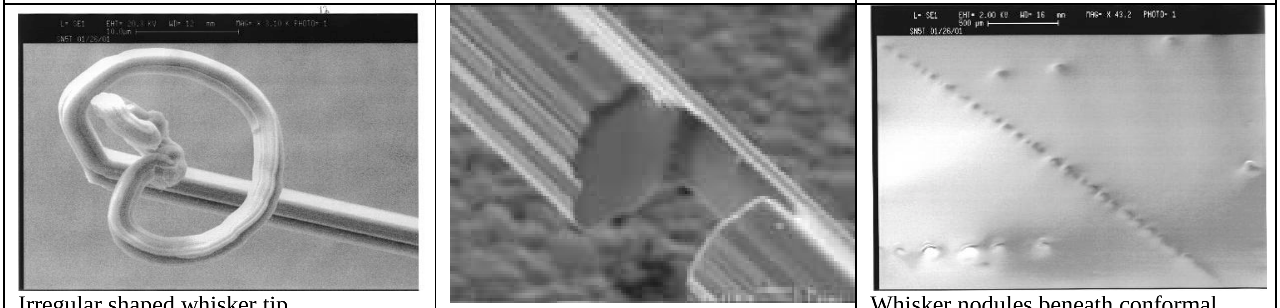
Kinks and striations

Pyramidal shaped whiskers

Nodules (note how it appears to originate from a very fine surface scratch)

Nodules originating along a mechanically induced surface scratch

Whisker growing from a nodule



Irregular shaped whisker tip

Focused Ion Beam "cross section" of a tin whisker. Note the solid (not hollow) structure and striations.

Whisker nodules beneath conformal coat (growing preferentially along the line of a surface defect)

Figure 2. Whisker Shapes (courtesy of NASA Goddard and The Aerospace Corporation)

Factors Affecting Whisker Growth Propensity

The following paragraphs discuss factors reported to contribute to whisker growth propensity. Noted differing views are also cited.

Substrate Effects: Whisker growth has been observed on any number of different substrate materials commonly used in the electronics industry. Most agree that brass substrates are most prone to whisker formation (due to zinc and copper diffusion from the brass and copper/tin intermetallic formation). Copper and copper-based alloys (phosphor bronze, alloy 194) are considered to be the next most sensitive. Whisker formation has also been observed for substrates considered to have low diffusivity into tin such as steel [21] and alloy 42 (iron/nickel alloy) [33]. Despite the diffusion barrier properties of nickel, whiskers have also been observed on passive components utilizing a nickel barrier layer construction such as those used in MLCCs and connectors (see Figure 2 and [36]). Others, however, have observed a general beneficial effect of nickel barriers with respect to retarding whisker growth [18].

Plating Thickness: Most researchers suspect there are threshold thicknesses for tin plating above and below which whisker formation may not be supported. Glazunova reported that thicknesses below 0.5 µm and above 20 µm were less prone to whisker formation while 2 µm - 10 µm thicknesses showed maximum growth rates for tin on steel and tin on brass [40]. Zhang and Schetty have suggested thicknesses over 8 µm tend to be in the "safer" region. [18, 22]. Unfortunately, very thin plating thicknesses may reduce the effectiveness of other characteristics of the plating such as corrosion resistance. Thicker platings are not as commonly used probably for cost reasons. It has been hypothesized that thicker coatings tend to distribute the stresses more evenly, especially those originating at the substrate/plating interface [9].

Grain Size and Shape**:** Kakeshita reported that the grain size and shape play significant roles in whisker propensity. In particular they have proposed that "well polygonized" grains in the range of 1 µm to 3 µm (possibly as large as 8 µm) in size will greatly inhibit whisker formation. Grain sizes of only a few tenths of a micron were found to be much more prone to whisker formation. [39, 30]. Although there are no industry accepted definitions, tin finishes with smaller grains (~ 1 um and less) are commonly termed "bright" because they produce a very shiny, reflective surface, while those with larger grains (over 1 µm) are often termed "matte" because of their somewhat dull gray appearance. Relatively speaking, "bright" finishes are considered to be more prone to whisker formation than "matte" finishes because the processes and materials used in "bright" finishing incorporate more internal stress within the electroplate. However, it must be noted that many examples of whisker growths have been reported from finishes advertised as "matte".

Temperature: If diffusion and IMC formation contribute to whisker formation, it seems logical to suspect that elevated temperatures which encourage such processes will also increase whisker propensity. However, elevated temperatures also tend to relieve residual stresses within the coating, thus, creating competitive forces that may in sum discourage whisker growth [37]. Most experimenters report that ambient temperatures of approximately 50°C [22] are optimal for whisker formation, while others observe that equivalent specimens maintained at room temperature (22°C to 25°C) have grown whiskers faster [7]. Reportedly, whisker growth ceases at temperatures above 150°C [37]. Some researchers have observed whisker growth can still occur at temperatures as low as -40°C.

Barometric Pressure: Whiskers will grow in vacuum as well as earth-based atmospheric pressure [6]. Observations of whisker formation under vacuum conditions tend to rule out oxidation as a necessary condition for whisker formation.

Moisture: Some observe that whiskers form more readily in high humidity (85% - 95% RH). Still others have seen no apparent effect of moisture [37, 41].

Thermal Cycling: Some experimenters report that thermal cycling may increase the growth rate of whiskers, but others report no apparent effect. Experiments have commonly utilized temperatures in the range of -40°C to +90°C [41].

Externally Applied Mechanical Stresses: See Table 3 for discussion of this factor. In addition, some experiments have observed that surface defects in the substrate (minor scratches) that were present prior to plating appear to be preferential sites for whisker formation [7] (see also Figure 2).

Electric Field: Whiskers grow spontaneously without requiring an applied electric field to encourage their growth. However, NASA-GSFC has demonstrated that whiskers can bend due to the forces of electrostatic attraction; thus, increasing the likelihood of tin whisker induced shorts [7].

Whisker Test Methods

Unfortunately, to date, there are no industry-accepted test methods to measure the propensity of a given product/process to form whiskers. Various industry consortia in both the U.S. (National Electronics Manufacturing Initiative -NEMI) and Japan (Japan Electronics Information Technology Industries Association -JEITA) have initiated studies to define and then validate through experimental evidence, the exact mechanism(s) by which whiskers form. Many of these same organizations are simultaneously working to devise accelerated test methods to determine the whisker formation propensity of a given product/process [41]. Such test methods are vital to the development and qualification of plating applications.

Ideally, any whisker test that is developed should enable a product manufacturer or user to determine (within a practical period of time) the inherent risk of whisker formation for a given specimen or process. In addition, development of such tests should include studies that correlate an "acceleration factor" of the test condition to some baseline application environment. Given the extreme variability in the behavior of whisker growth in terms of incubation and growth factors, it may not be reasonable to expect a short duration "accelerated" test can provide adequate assurance of whisker-free performance for applications requiring long term reliability (e.g., undersea cable lines, geothermal wells, etc.).

Recent work at The Aerospace Corporation [48] has focused on encouragement of rapid whisker initiation and growth on commercial and military-grade pure tin plated ceramic capacitors through thermal cycling, using both mounted and unmounted samples. Such cycling appears to produce compressive stresses that accelerate growth. Though the thermal excursions and number of cycles can be related to equipment mission lifetimes, the acceleration factors have not been determined.

What Users Should Know About Part Manufacturers' Tin Plating Processes

Plating baths. Responsible manufacturers who supply passive components with tin-coated terminations are aware of the potential for tin whisker formation, and are active in controlling their electroplating baths to minimize the possibility. A user should query the manufacturer about the controls in place and the baths being used. A "matte" tin bath, or one that produces a relatively dull [non-bright] finish is preferred, because it minimizes the use of additives that are mainly intended to improve leveling and brightness. This, in turn, can produce tin without excessive metallic or carbon contaminants; thus, minimizing internal plating stresses that can lead to whisker growth [18]. Plating baths require process controls to ensure that contamination buildup is minimized, and frequent chemical replacement (not simply replenishment) should be part of these controls. Other plating parameters should also be optimized and controlled in a manner that achieves minimum internal stresses; time, temperature, current density and gradients are critical process parameters. Generally speaking, electroplating process parameters that achieve the fastest tin deposition tend to be more prone to whisker formation.

Underplating/substrate. The tin should be applied over a controlled substrate, nickel being much preferred to copper or brass. The chemistry, thickness, surface finish, grain size, and surface cleanliness and internal stress of the substrate are all important. These factors may affect intermetallic compound [IMC] formation and growth. While a layer of IMCs is necessary for adhesion, the major theory for tin whisker formation indicates that excessive IMC growth, with the concomitant increase in specific volume, increases the stresses on the top tin layer. According to this theory, a layer of minimum thickness IMCs of a chemistry that creates the minimum internal stress is desirable. Similarly, the nickel grain size may also affect the tin grain size. While we may not be able to determine what is optimal, ensuring that the manufacturer controls the nickel plating process closely to produce a consistent electroplate is important.

Hot-tin dipped coating. Hot-tin dipped parts should also come from controlled production lines. While the very process of applying a molten layer minimizes internal stresses, coating application will not be uniform in thickness. Regardless, these parts are still prone to abrasion and contact during subsequent automatic feeding and processing which may reintroduce surface compressive stresses, likely the most dangerous type.

Fusing, annealing and handling. Ideally, tin-plated parts should be subjected to a fusing or reflow process to relieve existing stresses after the parts go through manufacturing and testing. Subsequent handling should strive to minimize introduction of new stresses. High temperature annealing where the tin plated finish is brought to temperatures below the melting point of tin for a short duration may also have beneficial effects because such practices tend to relieve inherent stress and encourage grain growth (intuitively expected but was not observed in recent experiments with MLCCs at The Aerospace Corporation [48]). However, appropriate conditions of temperature and time are not well established in the literature. Contacts with probes, vacuum chuck pickup heads, tweezers, and anything but low-pressure bars should be minimized or eliminated.

Original Equipment Manufacturer (OEM) Mitigation Guidelines

The following items are generally considered to minimize whisker formation. In applications where tin whisker formation cannot be tolerated, users may wish to consider employing as many of the following guidelines as practical for their application. However, even when two or more of the following guidelines are used in concert, they have NOT been shown to completely prevent whisker formation.

Conformal coating. OEMs should consider the use of conformal coating wherever possible. Coating all electrically active surfaces is recommended. While a whisker may penetrate a layer of conformal coating over its originating surface [7]**, a whisker is very unlikely to penetrate two layers of coating. The layer over the surface of a different potential will be reached only when a whisker is very long [and relatively flexible], so that it is likely to impact that second layer at an angle and slide to one side or buckle rather than penetrate it. To our knowledge, there are no documented cases of a whisker penetrating two separated layers of conformal coating.

** Conformal coating or foam encapsulation over the whisker prone surface appears to be beneficial but the limitations are not completely understood. NASA GSFC experiments [7] suggest that use of urethane conformal coat can provide some benefit by reducing the growth rate, but tin whiskers can grow through the coating, and once exposed can then short to other tin whiskers or other exposed surfaces, or break off and lodge in areas where they can cause short circuits. It has also been demonstrated experimentally that conformal coating can sufficiently restrict the availability of tin to prevent plasma formation (a particular concern for space applications) [38]. However, such factors as the minimum thickness of coating necessary to prevent whisker growth or plasma formation have not been determined. Similarly, it has been shown that foam can prevent sustained arcing but the effects of foam type, foam density, pore size etc. have not been reported.

Physical Barriers. Interposition of non-conductive washers, ceramic spacers, staking compound materials, etc. as a physical barrier is a very simple and powerful method of preventing whisker contact.

Solder Dipping. Users may consider hot solder dipping of tin plated leads (surfaces) using a SnPb-based solder. This process will help reduce whisker formation by relieving stress in the tin layer through both reflow and the addition of an alloying element (Pb). If the leads were fused before solder coating and then carefully conformal-coated after connections were made, possibilities of detrimental tin whisker growth would be greatly reduced. The effectiveness of hot solder dipping is limited to those surfaces that can be safely subjected to a hot dipping process without introducing thermal damage. For this reason, solder dipping is frequently limited to areas no closer than 10 to 50 mils from the component body. Devices where the leads pass through glass-to-metal seals are particularly susceptible to cracking of the seal if the dipping process is not carefully controlled. In addition, the portion of the lead that is internal to the device will not be afforded the whisker reducing benefits of the dipping process.

Tin surface reflow. Reflowing the tin surface coating as a last step or next-to-last step in an assembly process both removes the internal stresses and may largely redissolve the surface tin oxide; thus, reducing whisker initiation stresses. The only stresses that would contribute to whisker growth would be those at the substrate interface, due to IMC growth, and those imposed with any subsequent probing, bending or scratching of the new tin surface.

Minimizing elevated temperature exposure. The major current theory of tin whisker growth is that it is a means of relieving the compressive stress of the plated tin layer. A major source of that stress is the tin oxide that forms on top of the layer and the tin intermetallic compounds formed at the interface of the tin and its substrate. Reducing elevated temperature exposures may serve to reduce, but not eliminate, such stresses.

Performing burn-in in an inert environment. Minimizing the growth of surface tin oxide by performing burn-in in an inert atmosphere may help reduce the compressive stress on the tin.

As mentioned previously, the whisker mitigation steps just discussed, even when used in concert with two or more of them, have not been shown to completely prevent whisker formation. Recent experiments at The Aerospace Corporation of USA manufactured commercial-grade ceramic capacitors [48] that have pure-tin plated terminations show many whiskers (some as long as 30 microns) forming after 554 thermal cycles of –40°C to 90°C (5-minute rise time, 5-minute-dwell, 20-minute cool down). A similar experiment was conducted on pure tin plated military-grade capacitors, which grew whiskers as early as after 100 cycles. In both experiments, excess moisture in the thermal chamber was removed by dessicants. These two sets of capacitors have nickel underplating that are at least 5 microns thick, and a slightly thicker (10+ microns) tin layer.

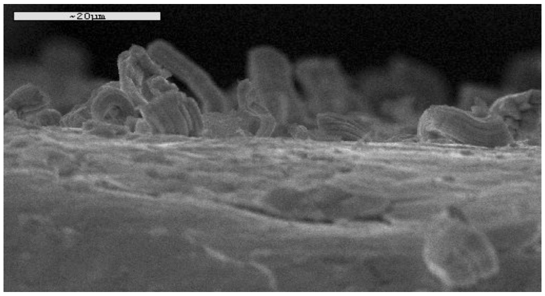


Figure 3. Commercial-grade ceramic capacitor after 554 thermal cycles.

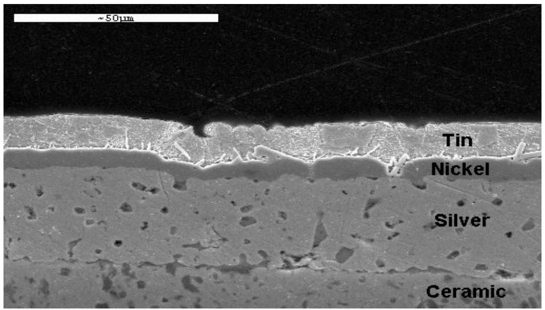


Figure 4. Cross-section of commercial-grade ceramic capacitor with pure-tin termination finish.

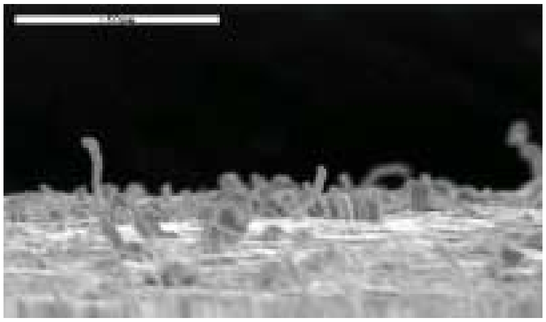


Figure 5. MIL-grade pure-tin plated ceramic capacitor after 100 thermal cycles.

Discussion

It is dangerous to simply rely on the manufacturer's certification that pure tin plating was not used in the production of the part supplied. In several cases, including the FDA pacemaker recall and the aforementioned satellite failures, it was found that the procurement specification required that no pure tin shall be allowed as a plating finish. The authors are aware of many instances where pure tin was prohibited, yet the product supplied was later determined to be coated with pure tin. In some of these instances, tin whisker growths were discovered. Users are advised to analyze directly the plating composition of the products received as an independent verification.

The continuing reports of tin whisker induced failures (especially the commercial satellite failures) coupled with the lack of an industry-accepted understanding of tin whisker growth factors and/or test methods to identify whisker-prone products has made a blanket acceptance of pure tin plating a risky proposition for high reliability systems. This is particularly true in the military, aerospace, and telecommunication industries whose products frequently have reliability requirements extending over five years (sometimes over fifteen years). In these instances, especially if deployed in challenging environments of high moisture, high temperature, or near-vacuum, the use of tin, as well as cadmium and zinc, as structural materials or surface finishes should be completely avoided.

A majority of the so-called mitigation factors whose use manufacturers believe may free them from worry are simply rules-of-thumb that have been gathered. Many have not been adequately verified in the literature or through practice. Other factors, such as use of two conformal coating barriers, one over the tin coatings and one over adjacent conductors, and conductor spacings greater than 0.5 inch, appear to have a documented, experimental basis for their validity, but these approaches may not be practical in all conditions. Specific application reviews are essential in each instance where tin coated hardware is found.

Tin Whisker Literature Review

The authors of this present work have encountered nearly 200 references available in the public domain that are related to whisker growth from tin and other common metal electroplates. The majority of these reports describe whisker growth from pure tin electroplates, including both "bright" and "matte" finishes.

A few reports describe whisker formation from some tin-lead alloys (i.e., 90/10) [4, 10, 18]. Most of these other observations, however, seem to be confined to sparse populations of very small nodular growths that rarely exceed 10 μm or were observed under conditions of high levels of externally applied stress (i.e., compression from torque of nut/bolt). These reports are of major import because one factor believed to dramatically reduce tin whisker formation is to alloy the tin with three percent or more of a metallic element. The amount of alloying material necessary to prevent whisker growth from tin alloys depends upon both the specific alloying metal and the environmental stresses to which the coatings are subsequently exposed. If the compressive stress theory of initiation and growth are valid, then the alloying metals may absorb or reduce compressive stress within the plating. If external stresses are severe, such as a deep surface groove caused by an electrical probe, then whisker nucleation and growth could still occur in such alloyed coatings. Understanding the stress conditions under which whisker formation from such alloyed surfaces may occur should be of high priority.

Viewed collectively the available literature describes a wide range of observations and factors (often contradictory) that affect whisker formation. An extensive listing of whisker-related literature references is provided on the NASA Goddard Tin Whisker www site: http://nepp.nasa.gov/whisker

Conclusions

1. Tin whisker formation and the associated risk for catastrophic electrical shorting continues to be a potential problem, and must be seriously considered as the industry moves to pure tin and other Pb-free surface finishes.

2. Even when prohibited by system requirements, tin-coated finishes continue to appear in

electrical equipment. The authors have participated in several major review teams attempting to determine whether major OEMs have successfully eliminated tin-coated surfaces. In all cases, some instances of components or small mechanical items with pure tin-coated surfaces have been found.

3. The amount of alloying material necessary to prevent whisker growth from tin alloys depends upon both the specific alloying metal and the environmental stresses to which the coatings are subsequently exposed. Whisker nucleation and growth may still occur in such alloyed coatings if the plating stress was introduced mechanically, like when a deep groove or scratch was induced on the surface.

Recommendations

1. For components that are only available in pure tin finishes and must be utilized, buy them from a manufacturer that (a) you have confidence can control its tin plating processes (such that low-stress, matte finishes are produced), and (b) only uses a substrate, such as nickel, that is relatively more whisker-resistant than copper or brass.

2. If a user must use tin-coated parts and the results of whisker-induced failures are critical, then as many whisker risk mitigation practices should be employed as are practical. However, hardware retrofits should always be an option when failures resulting from tin whisker growths severely impact mission life or circuit functionality.

3. Industry must strive to achieve and verify through direct investigation a consensus understanding of the fundamental mechanism(s) of whisker formation. Model(s) must be developed to represent ALL component constructions including active, passive and mechanical devices. Only when such fundamental knowledge is acquired can manufacturers and users confidently utilize materials and processes that will mitigate the risk of whisker induced failures.

4. Industrial societies should strive to develop standardized test methods to judge whisker formation propensity.

5. More studies need to be undertaken to better understand the various stress scenarios under which whiskers will form on alloyed surfaces.

6. The authors encourage continued reporting of whisker-related research and problem experiences via the refereed literature and problem-reporting services such as GIDEP. These media help foster collaboration that can lead to more informed and relevant problem solving initiatives.

7. Handling of pure tin coated components must be very carefully controlled at the equipment manufacturer. Whiskers will form preferentially at high stress areas associated with scratches, probe marks, and other areas of handling damage, where otherwise the coating may be whisker resistant.

Acknowledgments

The authors would like to thank Mike Sampson, Dr. Henning Leidecker (NASA Goddard) and Jong Kadesch (Orbital Sciences Corporation) for their support and contributions to this paper. The authors also wish to thank Gary Stupian and Eric Frasco (The Aerospace Corporation) for contributing photographs of a FIB cross section of a tin whisker and whiskers on ceramic capacitors. In addition, the authors acknowledge Ingemar Hernefjord (Ericsson-Sweden) for providing specimens of ceramic chip capacitors that show clear evidence of tin whisker growth.

References

1. P. Hinton, "Tin-Plating, Tin-Nickel Electroplate and Tin-plating over Nickel as Final Finishes on Copper," PWB Engineering, pp. 806 – 810 (unknown publication date), and Proceedings Surface-Mount International Conference, San Jose, CA, Sept. 10, 1996
2. Y. Zhang, G. Breck, F. Humiec, K. Murski and J.A. Abys, "An Alternative Surface Finish for Tin/Lead Solders: Pure Tin" SMI'96 Proceedings, San Jose, CA, Sept., 1996
3. European Union, "Waste Electrical and Electronic Equipment (WEEE) and Restriction of Hazardous Substances", http://www.lead-free.org/legislation/detail/soldertec-overview.html
4. S. Winkler and B. Hom, "A Look at the Past Reveals a Leadfree Drop-In Replacement", High Density Interconnect (HDI) on-line, March 2001.
5. S. Arnold, "Growth of Metal Whiskers on Electrical Components," Proceedings of Electrical Components Conference, pp. 75-82, 1959.
6. S. Arnold, "Repressing the Growth of Tin Whiskers," Plating, 53, pp. 96-99, 1966.

7. H. Leidecker, and J. Kadesch, "Effects of Uralane Conformal Coating on Tin Whisker Growth", Proceedings of IMAPS Nordic, The 37th IMAPS Nordic Annual Conference, pp. 108-116, September, 10-13, 2000
8. H. Kehrer and H. Kadereit, "Tracer Experiments on the Growth of Tin Whiskers," Applied Physics Letters, 16, no. 11, pp. 411-412, June 1, 1970
9. B. Lee and D Lee, "Spontaneous Growth Mechanism of Tin Whiskers", Acta Mater., 46, No. 10, pp. 3701-3714, 1998
10. K. Cunningham and M. Donahue, "Tin Whiskers: Mechanism of Growth and Prevention," Proceedings 4th International SAMPE Electronics Conference, p. 569, June 1990.
11. P. Key, "Surface Morphology of Whisker Crystals of Tin, Zinc and Cadmium," IEEE Electronic Components Conference, pp. 155-157, May, 1970.
12. R. Diehl and N. Cifaldi, "Eliminate Whisker Growth on Contacts by Using a Tin Alloy Plate", Insulation/Circuits, April 1976 pp. 37-39
13. B. Dunn, "Mechanical and Electrical Characteristics of Tin Whiskers with Special Reference to Spacecraft Systems," European Space Agency (ESA) Journal, 12, pp. 1-17, January 14, 1988.
14. B. Dunn, "A Laboratory Study of Tin Whisker Growth," European Space Agency (ESA) STR-223, pp. 1 - 50, September 1987.
15. K. Tu, "Interdiffusion and Reaction in Bimetallic Cu-Sn Thin Films", Acta Metallurgica, 12, pp. 347 - 354, April 1973.
16. H. Cobb, The Monthly Review", American Electroplaters Soc., 33, 1946. p. 28
17. S. Koonce and S. Arnold, "Growth of Metal Whiskers", Unknown Publisher (only the Letters to the editor at the Bell Telephone Laboratories, Murray Hill, NJ), December 8, 1952.
18. R. Schetty, "Minimization of Tin Whisker Formation for Lead Free Electronics Finishing", Proceedings IPC Works Conference, Miami, USA, 2000.
19. B. Hampshire and L. Hymes, "Shaving Tin Whiskers", Circuits Assembly, pp. 50-53, September 2000
20. M. McDowell, "Tin Whiskers: A Case Study, (USAF)", Aerospace Applications Conference, pp. 207 -215, 1993.
21. B. Dunn , "Whisker Formation on Electronic Materials," ESA Scientific and Technical Review, 2, no. 1, pp. 1-22, 1976
22. Y. Zhang, C. Su, C. Fan, and J. Abys, "Tin Whisker Growth and Prevention", Journal of Surface Mount Technology, October, 2000
23. J. Richardson, and B. Lasley, "Tin Whisker Initiated Vacuum Metal Arcing in Spacecraft Electronics," Proceedings 1992 Government Microcircuit Applications Conference, Vol. XVIII, pp. 119 - 122, November 10 - 12, 1992.
24. K Heutel and R. Vetter, "Problem Notification: Tin Whisker growth in electronic assemblies", Feb. 19, 1988, internal memo
25. R. Dore, "Launches of Hughes HS 601 Satellites Ready to Resume", Hughes Press Release, Aug. 1998
26. Satellite News Digest www site, "HS601 Satellite Failures", http://www.sat-index.com/failures/
27. S. Britton, "Spontaneous Growth of Whiskers on Tin Coatings: 20 Years of Observation," Transactions of the Institute of Metal Finishing, 52, pp. 95 - 102, April 3, 1974.
28. GIDEP, "Zinc Whisker Shorting in Vacuum", LL-U-01-68, July, 23, 2001
29. B. Nordwall, "Air Force Links Radar Problems to Growth of Tin Whiskers", Aviation Week and Space Technology, June, 20, 1986, pp. 65-70
30. A. Selcuker, and M. Johnson, "Microstructural Characterization of Electrodeposited Tin Layer in Relation to Whisker Growth", Proceedings Capacitor and Resistor Technology Symposium : USA, pp. 19 - 22, October, 1990.
31. M. Endo, S. Higuchi, Y. Tokuda, and Y. Sakabe, "Elimination of Whisker Growth on Tin Plated Electrodes", Proceedings of the 23rd International Symposium for Testing and Failure Analysis, pp. 305 - 311, October 27-31, 1997.
32. R. Kuhl and S. Mills, "Assuring Whisker-free Components," Surface Mount Technology, 9, p. 48, 1995.
33. D. Endicott and K Kisner, "A Proposed Mechanism for Metallic Whisker Growth", Proceedings of the 71st Annual AES (American Electroplaters' Society) Technical Conference, New York, NY, USA, July 16, 1984, 21 pp.
34. Nuclear Regulatory Commission www site, "http://www.nrc.gov/NRC/PUBLIC/PART21/1999/1999352.html", 1999
35. Y. Hada, O. Morikawa, H. Togami, "Study of Tin Whiskers on Electromagnetic Relay Parts," 26th Annual National Relay Conference, pp. 9.1 - 9.15, April 25-26, 1978.
36. S. Lal, "An Evaluative Study of Lead-Free Deposits in High Speed Applications", American Electroplaters and Surface Finishers (AESF) SUR/FIN Conference 2001, Nashville, TN.
37. P. Harris, "The Growth of Tin Whiskers", International Tin Research Institute, pp. 1 - 19, 1994.
38. G. Stupian, "Tin Whiskers in Electronic Circuits," Aerospace Report No. TR-92(2925)-7, pp. 1 - 21, December 20, 1992.

39. T. Kakeshita, R. Kawanaka, and T. Hasegawa, "Grain Size Effect of Electro-Plated Tin Coatings on Whisker Growth", Journal of Materials Science, 17, pp. 2560-2566, 1982.
40. V. Glazunova, and N. Kudryavtsev, "An Investigation of the Conditions of Spontaneous Growth of Filiform Crystals on Electrolytic Coatings," Translated from Zhurnal Prikladnoi Khimii, 36, no. 3, pp. 543 - 550, March 1963.
41. Private communications with members of a forum sponsored by the National Electronics Manufacturing Initiative (NEMI). Forum established in 2001 to discuss tin whisker testing and fundamental growth mechanisms.
42. R. Fisher, L. Darken and K. Carroll, “Accelerated Growth of Tin Whiskers”, Acta Metallurgica, 2, pp. 369-373, May 1954.
43. D. Van Westerhuyzen, P. Backes, J. Linder, S. Merrell and R. Poeschel, “Tin Whisker Induced Failure In Vacuum”, Proceedings 18th International Symposium for Testing & Failure Analysis, pp. 407-412, October 17, 1992.
44. G. J. Ewell and F. Moore, “Tin Whiskers and Passive Components: A Review of the Concerns”, Proceedings 18th Capacitor and Resistor Technology Symposium, March 1998.
45. Food and Drug Administration, "ITG #42: Tin Whiskers- Problems, Causes and Solutions", http://www.fda.gov/ora/inspect_ref/itg/itg42.html, March 16, 1986
46. Anoplate www site: http://www.anoplate.com/news/pastnews/fall2000/tin.htm
47. L. Corbid, "Constraints on the Use of Tin Plate in Miniature Electronic Circuits",Proceedings 3rd International SAMPE Electronics Conference, pp. 773-779, June 20-22, 1989.
48. R. Ferro and E. Frasco, The Aerospace Corporation, unpublished work.
49. G. Stupian and T. Hoskinson, The Aerospace Corporation, unpublished work.
50. The Aerospace Corporation Experience Sharing Bulletin #9802, May 1, 1998, “Terminal-to-Case Shorts In Metallized Plastic Film Capacitors Due To Tin Whiskers”.