

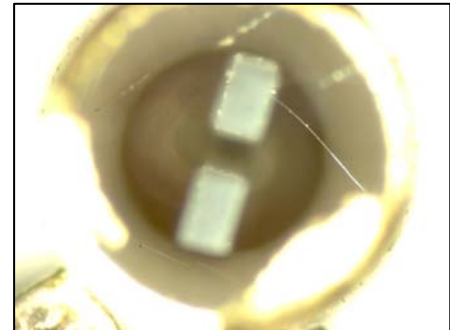
A New (Better) Approach to Tin Whisker Mitigation

Craig Hillman, Gregg Kittlesen, and Randy Schueller

*Environmental testing can only take the industry so far.
A return to fundamentals promises better mitigation at lower cost.*

Introduction

Most of the electronics industry by now knows about tin whiskers. They know whiskers are slim metallic filaments that emanate from the surface of tin platings. They know these filaments are conductive and can cause shorts across adjacent conductors. And they know that these shorts can cause some really bad failures (see nepp.nasa.gov/whisker/ for a list longer than you need). But, with all of this knowledge, the industry is still struggling on how to predict and prevent these “Nefarious Needles of Pain”.



A good start to solving this problem is to admit that the formation of tin whiskers is not such a mystery. It does not arise due to ‘bad karma’, ‘the black arts’, or ‘voodoo economics’. Whiskering occurs because of the presence of a compressive stress (or, more accurately, a stress gradient). This compressive stress drives the preferential diffusion of tin atoms. A few more things then have to occur for whiskers to form and grow, but in the absence of such stress, whiskering does not occur.

The issue to date has been the electronic industry’s excessive focus on the indirect causes of whisker formation (there is a healthy dose of blame to go around for this *faux pas*¹). The use environment (ambient temperature, thermal cycling, elevated humidity, and bending) simply initiates or accelerates the stresses present within the plating. It is the stress itself that should be modified, measured, and tracked over time to capture whisker behavior. The inability to capture and quantify the stresses present within the tin plating and to clearly delineate the sources of these stresses is stifling the eventual prevention (not just mitigation) of whisker-induced failures.

Background

The stresses that drive whiskering derive from five sources

- Base metal (intermetallic formation)
- Base metal (differences in coefficient of thermal expansion)
- Bulk plating conditions
- Oxidation/Corrosion
- External pressure

Whiskering occurs when one or more of these sources induce stresses of a sufficient magnitude. The magnitude of these stresses can be fixed at the time of production or can evolve over time.

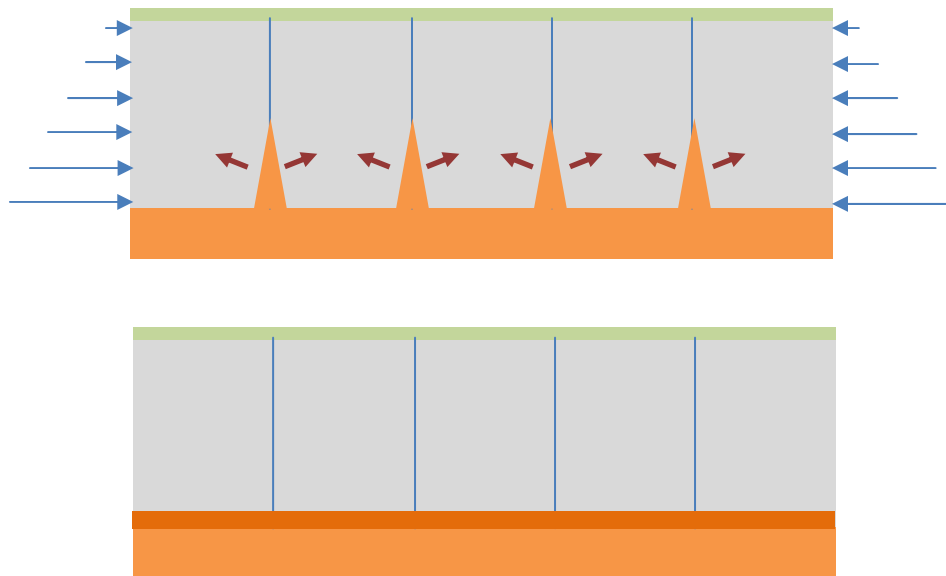
¹ Authors’ note: This is most equivalent to the questionable use of ‘pull testing’ to capture the risk of pad cratering. Pad cratering is a fracture mechanics issue that could be resolved through the measurement of laminate fracture toughness and flaw population to determine the critical fracture strength. Pull testing seems to continue the path of ‘test-in reliability’, which rarely provides the protection and value it’s proponents claim

Base Metal (Intermetallic Formation)

Because of significant differences in the diffusion rate of copper (Cu) through tin (Sn) grains and grain boundaries at room temperature, copper-tin intermetallic (Cu_6Sn_5) will tend to grow preferentially into the grain boundaries. The volumetric expansion of 58% (molar volume of Cu and Sn compared to Cu_6Sn_5), will result in large compressive stresses within the plating.

The use of an underplate such as nickel (Ni) prevents interdiffusion of the Sn and Cu and thus formation of the Cu_6Sn_5 intermetallic. The resulting Sn and Ni intermetallic compound, Sn_3Ni_4 , is relatively thin, uniform, and is self-limiting due to the low dissolution rate of Ni in Sn compared to Cu^2 . This morphology does not create compressive stresses in the tin plating and actually induces a slight tensile stress. For this reason a Ni underplate of > 1.2 micrometers is often used to mitigate growth of tin whiskers.

Annealing the tin coating immediately after plating at a temperature from 150 – 170°C is also commonly used to mitigate whisker growth. At temperatures over 60°C³ the intermetallic that forms is Cu_3Sn . In addition, at temperatures above 75C⁴, bulk and grain boundary diffusion rates in Sn become roughly equivalent. The resulting intermetallic morphology does not induce compressive stresses and provides a uniform layer that reduces the rate of diffusion and intermixing of Cu and Sn. It is essentially a poor man's Ni layer.



² Cu = 4.1 microinches/sec vs. Ni = 0.05 microinches/sec; Printed Circuits Handbook, 6th Edition, Clyde Coombs, 2008

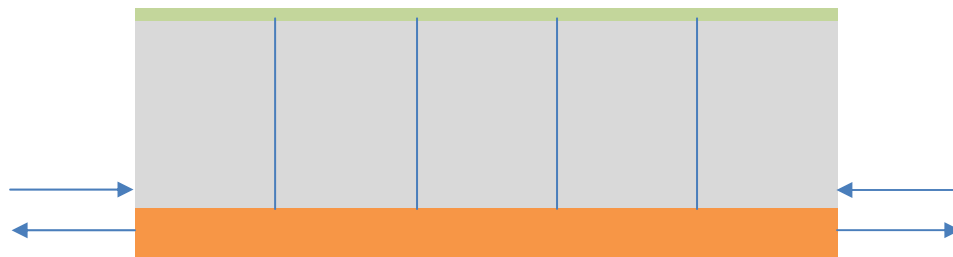
³ K.N. Tu experiments found Cu_3Sn at temperatures above 60C [34. K.N. Tu, Interdiffusion and Reaction in Bimetallic Cu-Sn Thin films, Acta Metallurgica, 21(4): pp. 347-354, April 1973]; other studies have indicated 75C, 100C [Lead-free solder interconnect reliability, edited by Dongkai Shangguan, Chapter 6: Tin Whisker Growths on Lead-Free Solder Finishes, K.N. Tu, et. Al.], and 140C as appropriate temperatures to induce Cu_3Sn growth.

⁴ Lead-free solder interconnect reliability, edited by Dongkai Shangguan, Chapter 3: Fatigue and Creep of Lead-Free Solder Alloys, Paul Vianco

Base metal (differences in coefficient of thermal expansion)

Compressive stresses can also arise when the base metal (copper, Alloy 42, steel) has a lower coefficient of thermal expansion (CTE) than tin plating and the plated component is subjected to repeated changes in temperature.

Material	CTE
Tin	23 ppm/C
Copper	17 ppm/C
Brass	19 ppm/C
Bronze	10 ppm/C
Nickel	13 ppm/C
Alloy 42	5 ppm/C
Steel	11-17 ppm/C



Bulk plating conditions

The process of plating tin can introduce compressive stresses into the bulk plating. This is typically through conditions that can cause grain texturing or the incorporation of plating elements such as organic brighteners

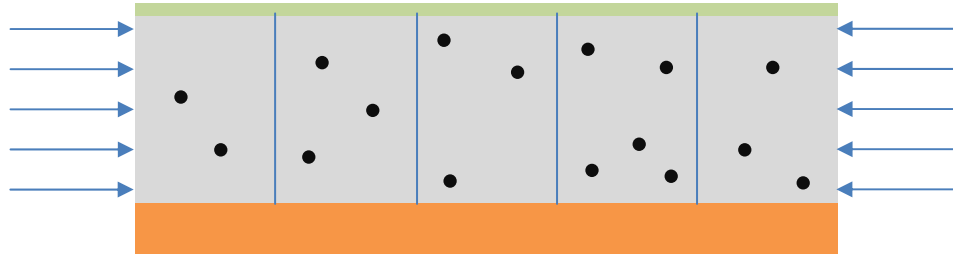
Brighteners are typically used for two reasons: ensure a uniform plating surface and to reduce the grain size. Brightener is attracted to points of high electro-potential, temporarily packing the area and forcing metal ions to deposit elsewhere. By continuously moving with the highest potential, the brightener prevents the formation of large clumps of tin, giving a smooth, bright deposition. Organics used as brightening agents also provide a nucleation site for grain growth of tin. Without such nucleation sites, the tin added during plating will more readily settle into its low energy state and form large grains. The smaller grains from brighteners provide a high and uniform reflectance from the plated surface.



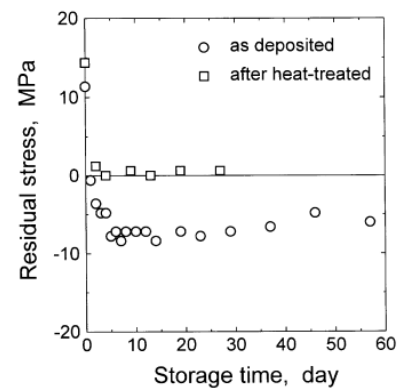
Tin whisker growing from a bright tin coated connector shell

The incorporation of the organics can cause compressive stress in the tin deposit and the smaller grains provide more grain boundaries for rapid interdiffusion of Sn and Cu and faster diffusion

of Sn to form whiskers. For this reason bright tin (grain size < 1 μm) is typically not allowed on electronic components.

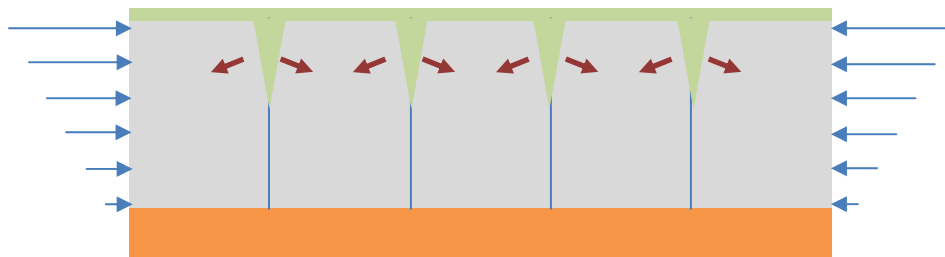


Intrinsic stresses can also arise simply due to variations in the plating process. While the effects of all drivers are not always well quantified, it is believed that degree of texturing plays a critical role. Texturing is the phenomenon of preferred, rather than random, orientation of the crystal lattice of the grains. High organic brightener content and high current densities⁵ can also introduce texturing into the plating. As carbon content or plating rates rise, the tin atoms are unable to rearrange to a low-energy state. This can introduce orientations that are ‘whisker friendly’ and increases the compressive stresses within the plating⁶.



Oxidation/Corrosion

Just as with intermetallic formation, the process of tin oxidation can also induce compressive stress states. Because of significant differences in the diffusion rate of oxygen (O) through tin (Sn) grains and grain boundaries at room temperature⁷, tin oxide (SnO₂) will tend to grow preferentially into the grain boundaries. The volumetric expansion can result in large compressive stresses within the plating. Similarly, certain conditions can cause corrosion on the surface of the tin plating and the corrosion product will induce compressive stresses within the tin.



⁵ Classic engineering tradeoff. The faster you want to build something, the greater the risk of problems. High current densities allow for faster plating, higher throughput

⁶ The cause and effect are not always clear: do stresses drive texturing or does texturing drive stresses?

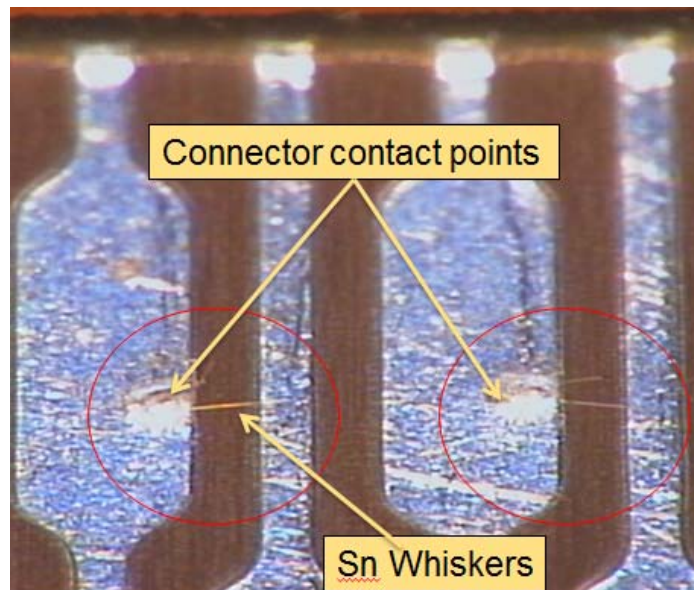
⁷ Microcracking at grain boundaries could also potentially play a role. As microcracking can be accelerated by elevated levels of stress within the plating, it can produce a challenging ‘which came first’, the chicken or the egg, conundrum

There are some indications that exposure to elevated temperature / humidity conditions could exacerbate this behavior by overcoming the self-limiting behavior of tin oxide at room temperature.

External pressure

While the majority of sources for stresses in tin plating are intrinsic, extrinsic sources can also introduce compressive stresses into the plating. One of the first studies on tin whiskers was triggered by a serendipitous finding that tin-plated steel mounted in a ring clamp grew whiskers⁸ and the amount of whiskering increased as the clamping pressure increased.

Common external pressure points within electronic products include connectors (on-board and press-fit), standoffs, card guides, washers/terminals, and separable shielding. Of particular concern is contact pressure on tin plated flexible circuits. The compliancy of the polyimide substrate results in localized areas of high contact pressures and therefore high stresses. The larger the stresses in the tin, the longer the whiskers must grow to relieve the stress.



⁸ Fisher, Acta Metallurgica, Accelerated Growth of Whiskers

A New Approach to Mitigation

Mitigations can fail, will fail, when only one source of stress is addressed. For example, two of the most popular mitigations, nickel underplate and annealing, only entirely resolve stresses due to intermetallic formation (they can also provide some mitigation to bulk plating stresses). They provide no assistance in regards to stresses that arise due to oxidation or external pressure points. It is believed that this inability to protect against all stresses was the reason for the tin whisker failures on nickel plated connectors reported by DfR Solutions in 2008⁹.

Given this reality, DfR Solutions proposes an alternative to the current approaches for tin whisker risk mitigation put forward by the iNEMI and GEIA organizations. This new risk mitigation process proposal relies on two basic activities: a checklist and process control.

The checklist, used in multiple industries as an extremely effective tool for eliminating failures (think airlines and medical surgery), is to confirm that all the sources of stress that can induce tin whiskers have been accounted for and are adequately controlled. The proposed checklist would be as follows (at least one Yes required per question).

Are stresses due to intermetallic formation adequately controlled?

- Yes, through annealing (150°C for an hour within 24 hours of plating)
- Yes, through use of an appropriate underplate (nickel, silver, etc.)
- Yes, the base metal is treated to limit anisotropic intermetallic growth (i.e., surface roughening)
- No

Are stresses due to differences in coefficient of thermal expansion adequately controlled?

- Yes, the base metal is copper
- Yes, the coefficient of thermal expansion is greater than or equal to nickel (13 ppm)
- No

Are stresses in the bulk plating adequately controlled?

- Requirement: The supplier measures in-plane stresses on a monthly basis and ensures the stresses are tensile or mildly compressive
- Yes, the supplier only uses low carbon/organic content tin plating
- Yes, the plating is subjected to reflow temperatures that melt the tin
- No

⁹ Maximum Whisker Length: A New Paradigm, LEAP, Melbourne, FL, September 2008

Are stresses due to oxidation or corrosion adequately controlled?

- Requirement: The device is not directly exposed to corrosive conditions (residual aqueous flux residues, corrosive gases, salt spray, etc.)
- Yes, the device will be used in a vacuum
- Yes, the application has sufficient power dissipation to drop the humidity below 40%RH and the application is always on
- Yes, the device is covered with conformal coating or potting material¹⁰
- No

Are stresses due to external loads adequately controlled?

- Yes, the tin plating does not have separable mechanical load being applied
- No

Just as plating measurements (ductility and yield strength) in the printed board industry have become commonplace and are now performed on a monthly basis (if not more often) to prevent failures of plated through holes (PTHs), stresses in connector and component tin platings should be measured in a similar manner. While instituting stress measurements industry-wide may seem daunting, the reality is that a relatively small number of contract packagers and connector manufacturers supply the bulk of the world's parts.

High volume, high reliability OEMs, and the industry organizations they belong to, should require component manufacturers to report on tin plating stress measurements. These measurements are common in other industries and there are a number of methodologies available, including spiral contractometer, bent strip, and the I.S. meter. Prior work has clearly shown that plated tin with stresses close to the yield strength (7 to 15 MPa) tend to drive severe whisker behavior. The electronics industry should determine if only platings with tensile stress are acceptable, or if some minimal level of compressive stress still provides sufficient risk mitigation.

Conclusion

DfR believes that the simple, but authoritative checklist in combination with industry implementation of stress measurements through process control, will result in a more effective and lower cost mitigation activity than the current scattershot approach with its excessive focus on environmental testing.

¹⁰ DfR believes that in nominal outdoor environments (not test chamber conditions), a number of conformal coatings are effective moisture barriers and would tend to prevent the preferential growth of oxide along the grain boundaries