Tin Whiskers: Capsulization

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Since lead-free implementation, concerns about tin whiskers have intensified. For the past 12 years, studies and research by various laboratories and organizations have delivered burgeoning reports and papers, and my column has devoted an entire series to this subject. This article aims to capsulize the important areas of the subject. (Note: For expression, "whisker" is used as both noun and verb.)

The tin whisker issue and its potential mishaps have been recognized for more than six decades in electronic, electrical and industrial applications. Some metals are prone to whiskering, or protruding from the surface of the substrate. In addition to tin, the metals that have exhibited whiskers include zinc, cadmium, silver, gold, aluminum, copper, lead, and others.

The whiskering phenomenon is distinct and unique. It is the result of a process different from other known phenomena (e.g., dendrites). And tin whisker and tin pest are separate metallurgical phenomena (*SMT Magazine*, May 2013). However, whiskers share commonality with dendrites in two aspects: Both are the result of a physical metallurgical process, thus following the science of physical metallurgy; and both could cause a product failure.

Uncertainty about tin whisker growth is most insidious. Stock markets do not like uncertainty, nor does the electronics industry. Our effort is to alleviate the uncertainty.

Practical Criteria

As some metals can whisker when accommodating conditions are met, the goal should be set with the differentiation between whisker-resistant and whisker-proof.

Overall, for testing or evaluation of the whisker propensity of a system, the key questions to be addressed are, is the system whisker-prone or whisker-resistant (not whisker-proof), and how does the system's whisker resistance stand in reference to the intended benchmark?

To comply with RoHS regulations, Pb-free materials including pure tin (Sn) have been used as surface coating for component leads and metal terminals, and Sn-based alloys as solder materials in making solder joints. Because of its economics, availability, manufacturability, compatibility and solderability, pure tin makes a practical replacement for Sn-Pb as a choice of surface coating. Today, most component manufacturers offer pure tin-coated components.

The evaluation of tin whisker propensity and growth rate needs to be put in the context of relative formation rate under a set of conditions. For the electronic and electrical applications, the renewed concern about tin whiskers are largely the result of conversion from tin-lead coating to lead-free (or tin coating) for component leads or PCB surface finish. Thus, the relative performance in reference to a tin-lead benchmark that has demonstrated satisfactory whisker-resistance is a logical criterion, not the absolute performance. An SAC (SnAgCu) alloy is lead-free, but a lead-free alloy is not necessarily an SAC. This clarity is particularly important as more viable lead-free alloys become commercially available. And tin whiskering is highly sensitive to an alloy composition including impurities.

Phenomena and Observations

Tin whisker reflects its coined name, which has long been recognized to be associated with electroplated tin coating and most likely occurs with pure tin. Its appearance resembles whiskers. However, they can also form in a wide range of shapes and sizes, such as fibrous filament-like spirals, nodules, columns and mounds (Figure 1). Tin whiskers are often single crystals and electrically conductive. They are normally brittle in nature but can be rendered ductile when whiskers are very long and thin.

Whisker formation and its resulting shapes and sizes depend on time, temperature, substrate, surface condition of the substrate, surface morphology, plating chemistry, and plating process. The rate of whisker growth also depends on a list of factors including the abovementioned.

Whiskers sometimes grow up to a few mm long, but usually less than 50 µm, and a few microns in diameter. Whiskers may grow, but they may also be self-annihilating as the electric current can fuse the whisker if the current is sufficient (e.g., typically more than 50 milliamps is often required). The self-annihilation ability varies with the whisker's size in length and diameter. This self-annihilating occurrence further contributes to the observed inconsistent or mythical nature of the events. Furthermore, the highly disparate whisker growth rates have been reported, ranging from 0.03 to 9 mm/year. And whiskers can grow even in a vacuum environment.

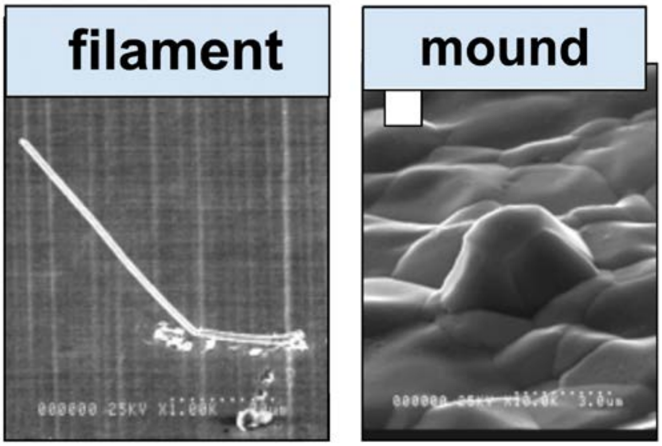


Figure 1: Tin whiskers appearance, from mound to filament.

Among various findings, one experiment indicated that whiskers can be eliminated by controlling the plating process in an equivalent way to controlling stresses in materials. The very sharp decrease in internal stress of tin electrodeposits was observed after plating as quickly as within minutes. It is interesting to note that this fast stress release occurs regardless whether initial stress in the deposit is compressive or tensile. In the case of compressive or tensile stress, the value of the stress drops to very low numbers, but it remains being of the same type as the initial stress form (i.e., high initial tensile stress reduces to much lower stress value but remains tensile and high compressive stress remains compressive).

It has been observed that the inclusion of organic elements in the tin structure promote tin growth. Organic inclusion or the level of inclusion is in turn affected by the plating chemistry[1,2]. And bright tin has exhibited to be most susceptible to whisker formation. Bright tin

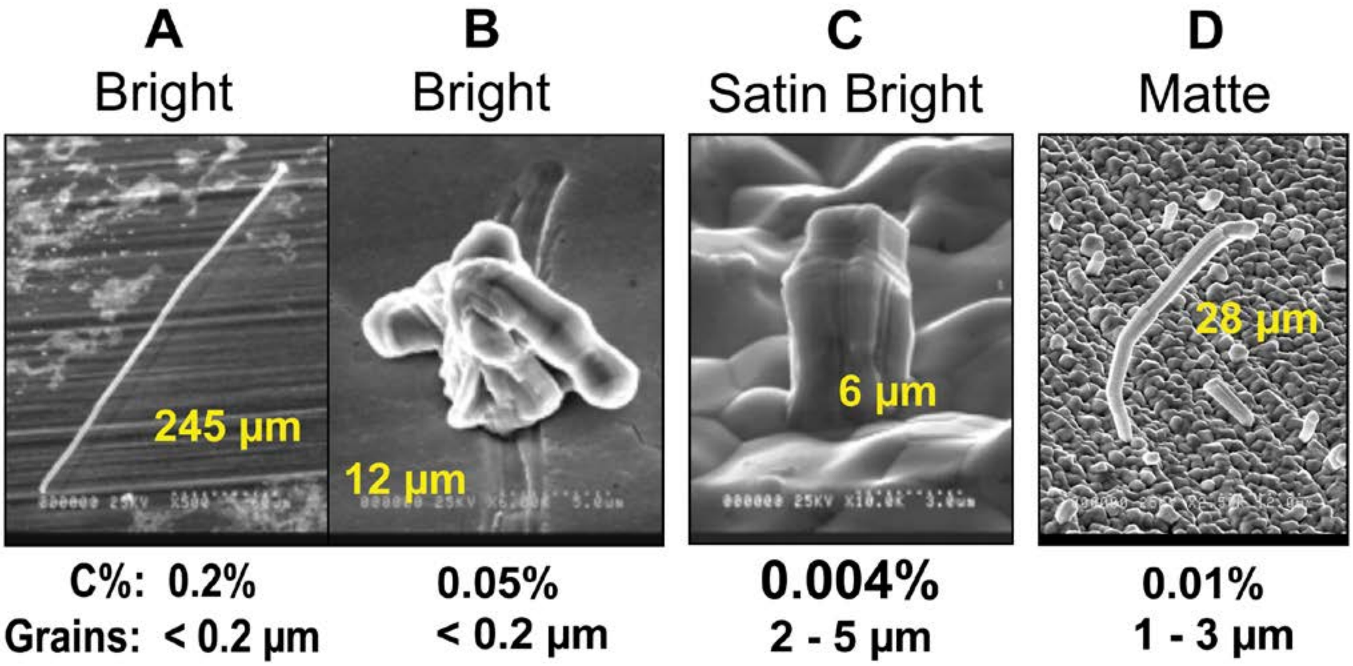


Figure 2: Tin whiskers—organic inclusions and grain size (four months aged at 50°C).

plating chemistry is prone to creating an environment that creates greater organic inclusion and higher stress level in tin crystal structure. The nature of substrate, external mechanical force, and temperature have been found to affect tin whiskering as well.

Concerns and potential impact

If/when tin whisker occurs, concerns and impact primarily fall in the following four categories (*SMT Magazine*, November 2013).

1. Short circuits

When a whisker grows to a length that bridges the adjacent lead or terminal, this conductive whisker can cause an electrical short. However, if a whisker is formed but does not bridge its neighbor, there will not be an electrical short. To complicate the phenomena, there are occasions where whiskers may not cause failure, or a failure may not be detected even when the whisker physically touch the adjacent lead due to lack of electrical current flow.

2. Tin metal arcing

Under high levels of current and voltage that is able to vaporize the whisker and ionize the metal gas, metal arc can occur. A NASA report attributed a satellite failure to tin metal vapor arc as the suspected root cause. It is expected that tin arc is more likely to occur under reduced atmospheric pressures or vacuum environments.

3. Break-off debris

The whiskers, being brittle and conductive, can break off from the base of its substrate surface, which may create functional issues. This is particularly a concern for sensitive electronic devices, such as optical and computer disk driver applications. The break-off behavior varies with the service conditions and the characteristics of the whisker.

4. Unwanted antenna

Tin whiskers can act like miniature antennas, which affect the circuit impedance and cause reflections. In this case, the most affected areas are in high-frequency applications (higher than 6 GHz) or in fast digital circuits.

Causes and Contributing Factors

Regarding causes and factors, physical metallurgy is the place to go to. Fundamentally, tin whisker follows the basic physical metallurgy in its principles on nucleation and crystal growth through the classic theories of dislocation dynamics and of other lattice defects in tin crystal structure. Thus, for whiskers to appear from the tin-based (or coated) surface, the causes and contributing factors should be intimately related to the nucleation site creation and the subsequent growth paths. However, the actual processes of nucleation and grain growth of tin whisker are dauntingly complex.

The nucleation and growth can be encouraged by stresses introduced during and after the plating process. The sources of these stresses come from multiple fronts. This includes residual stresses caused by electroplating and/or additional stresses imposed after plating, and/or the induced stresses by foreign elements, and/or thermally-induced stresses. Specific causes and contributing factors are excerpted from my previous article (*SMT Magazine,* March 2014):

Organic Inclusions

Organic inclusions affect the tin crystal structure by distorting or crowding the crystal lattice, thus creating the internal stress. It is found that tin whisker growth is correlated to the organic inclusions as represented in carbon content in the coating. A test conducted at 50°C for four months on coatings that have similar grain sizes generated the following results: 235 µm whisker was formed from the coating containing 0.2% carbon; 12 µm whisker was formed from the coating containing 0.05% carbon content[1,2].

Surface Physical Condition

Surface conditions, such as notches or scratches on the surface, are the source of atomic irregularity, which could contribute to the driving force of tin whisker formation.

Substrate Surface Morphology

Physically maneuvering the surface morphology of the substrate in the level of roughness was found to alter the tin whisker propensity—a rougher surface being less prone to tin whiskers[3], as shown in Figure 3. It is believed that a relatively rougher surface facilitates the formation of an even interface between the tin coating and the substrate surface that contains a thinner and more uniform intermetallic layer.

Oxidation or Contamination Level

It is postulated that as the oxygen atoms diffuse into tin crystal structure, oxygen can serve as nuclei and can also restrain grain boundary mobility and diffusion. When the lattice structure is oriented in a way that is favorable to the protruding crystal growth,

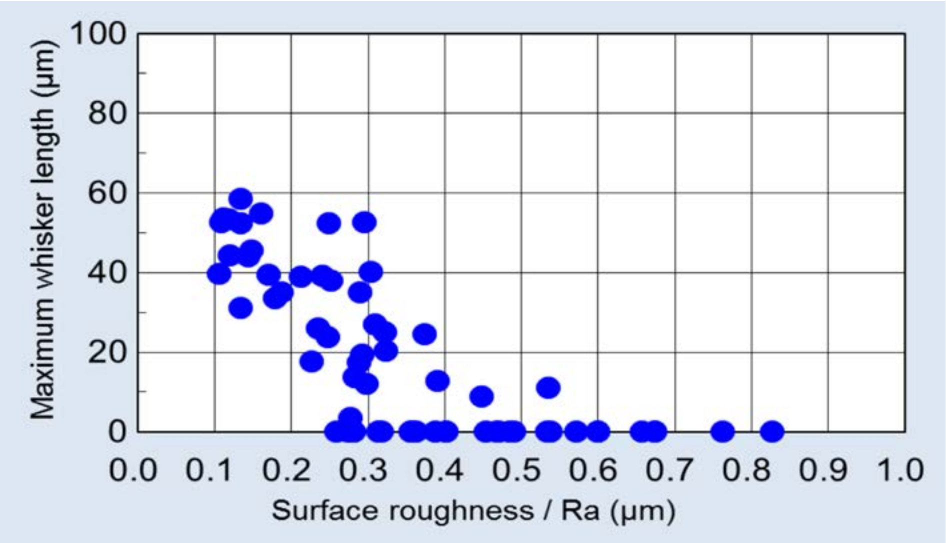


Figure 3: Tin whiskers—role of surface morphology (chemical micro-roughening to produce a set of surface roughness with specific Ra values).

tin whiskers will occur. Other studies found that surface oxide promotes tin whiskers[1,2] and surface corrosion and contamination also contribute to tin whiskers[4,5]. It was also found that whisker growth occurred on SAC305 solder joints on either the copper or the alloy 42 leaded components, and the alloy 42 leads exhibited a delay in long whisker growth[4,5].

External Mechanical Stresses

Externally applied forces such as those introduced by the lead-forming, bending or torque after plating process may affect tin whisker formation. In studying the effect of external mechanical force that is imposed on the coating on tin whisker growth, the relative whisker growth under different levels of organic inclusions with and without an external mechanical force were performed. Under each level of organic inclusions, an external mechanical force (by the means of bending) created an increased rate of whisker growth as shown in Table 1 below[1].

Substrate Base Material

It was found that there is a difference in tin whisker propensity between bronze and brass[6] and between Cu-based and alloy 42 leads, respectively. The differences are primarily attributed to relative inter-diffusion between the substrate material and the tin-based materials, as well as to the relative abundance of intermetallic compounds.

Metallic Impurities

As metallic particles enter into the tin lattice, there may or may not lead to the formation of intermetallic compounds, depending on the metallurgy of the elements involved. These metallic particles can change or distort the lattice spacing in the tin structure.

Intermetallic Compounds

It should be emphasized that intermetallic compounds at the interface of tin coating and the substrate or in the bulk of the tin-based material is not necessary for tin whiskers to form.

However, intermetallic compounds may exert additional effects in grain structure, as these compounds can form in various geometries and morphologies ranging from small, more-rounded particles to long needles. This formation creates either high localized stress or well-distributed stress or both in the tin lattice structure.

It should also be noted that the critical difference between SnPb and SnAgCu alloy is that SnPb does not (should not) form intermetallics in the bulk matrix, but SnAgCu alloys intrinsically contain intermetallics. The presence of intermetallics in SnAgCu and the absence of such in SnPb account for most of phenomenal and property differences between SnAgCu and SnPb, including tin whisker.

CTE Mismatch Between Tin Coating and Substrate

The relative coefficient of thermal expansion between the tin plating and substrate can contribute to the occurrence of tin whisker as the result of additional global stress as well as localized stresses. In this regard, the lead material (e.g., alloy 42 vs. Cu) is a factor. Although the larger mismatch between the tin layer and the substrate causes higher stress levels, the diffusion rate of substrate atoms into the tin-based material layer with or without the companion of the formation of intermetallics may skew the linear relationship between CTE mismatch and whisker propensity.

Plating Process vs. Coating Surface Morphology

Tin plating process parameters control the lattice defects incorporated in the tin layer. It

Organic Impurity	No Mechanical Bend	Mechanical Bend
0.2%, 4 months	245 microns	312 microns
0.004%, 7 months	6 microns	6 microns

Table 1.

also determines the thickness of the coating layer. The organic content, grain size, and surface morphology highly depend on the coating chemistry and process parameters, including the type of electrolyte, additive/brighteners, current density, process temperature, and the process control. For instance, high current density allows faster rate of plating, and a faster rate may impede the tin atoms' ability to rearrange to a low-energy state, which contributes to subsequent whiskering conditions.

Take bright tin as an example, which is reportedly the most susceptible to tin whisker. Its high susceptibility is largely attributable to the high residual stresses within the tin plating caused by the plating chemistry and process. The added brighteners in making tin bright may serve as nucleation sites and may prevent tin from settling into the low energy state to form large grains. The resulting small grains provide more grain boundaries that in turn offer diffusion paths for tin.

Plating Process vs. Coating Crystal Structure

The effect of microstructure in terms of grain size on whiskers has been observed—equi-axed crystal structure (Type C in Figures 4 and 5) and thin IMC minimizes whiskers[3]. It is hypothesized that as grain size reduces below 1 micron, the internal stress and the driving force for recrystallization will be built up. This condition creates high whisker propensity.

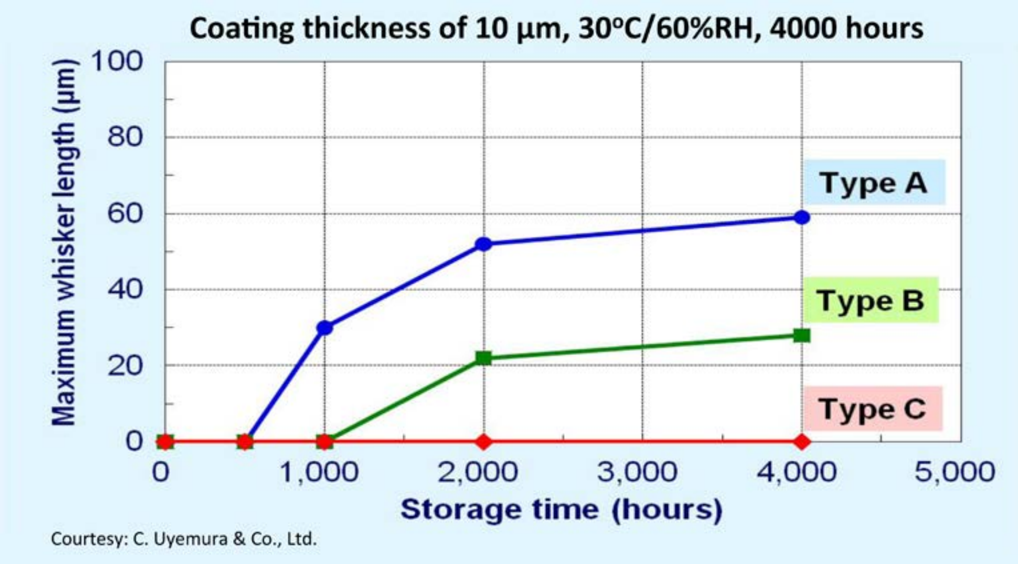
Thickness of Tin Coating

It is postulated that it takes a proper thickness for whiskers to grow. To make a statement on the correlation between the thickness of tin layer and the whisker propensity is indeed oversimplistic. Yet, some results do support that a too thick coating can bury whiskering tendency and a too thin coating can shortchange the materials needed to grow whiskers. The proper thickness also is related to stress distribution ability.

Temperature Effect

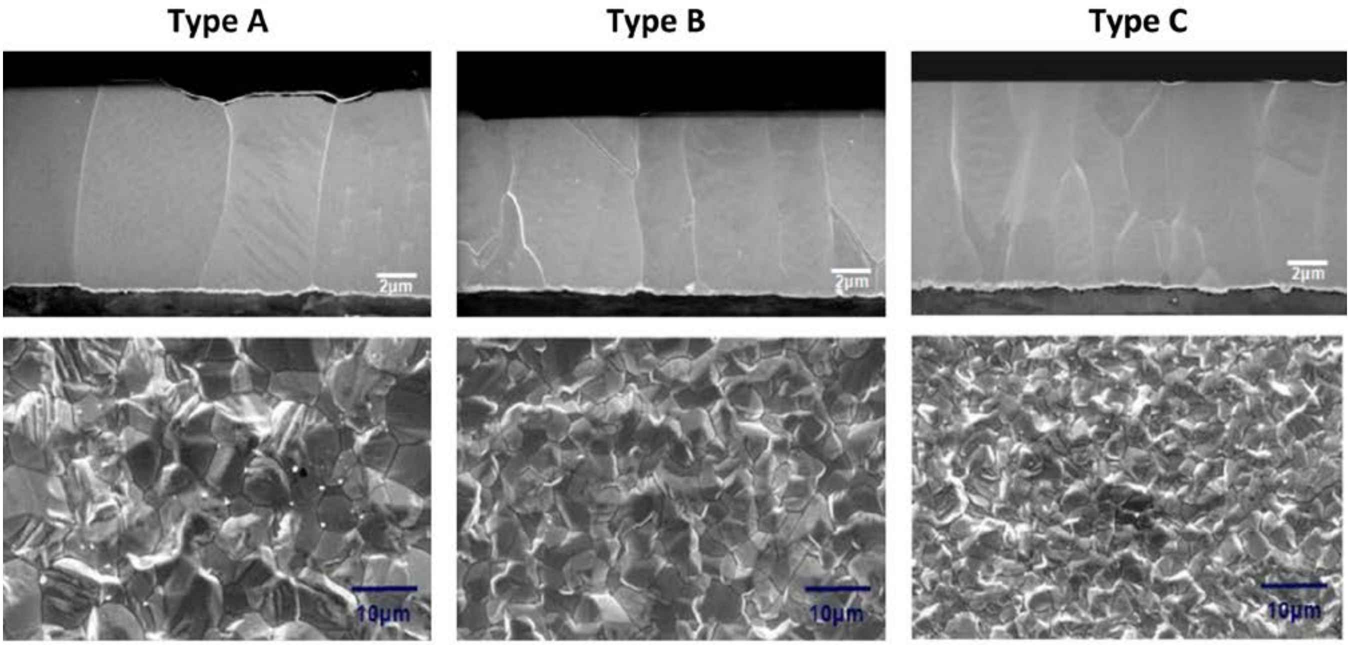
Temperature drives the kinetics of defect dynamics in the tin layer by affecting stress relaxation and atomic mobility-related phenomena. For example, high temperature relative to tin's recrystallization temperature is expected to impede the continued growth along the protruding direction, resulting in short whiskers.

Overall, from the atomic lattice structure standpoint, most of the above sources do not play by itself in the tin coating layer, rather they are intricately interplayed. This is the very challenge imposed to the evaluation of tin whisker propensity based on a set of testing conditions.



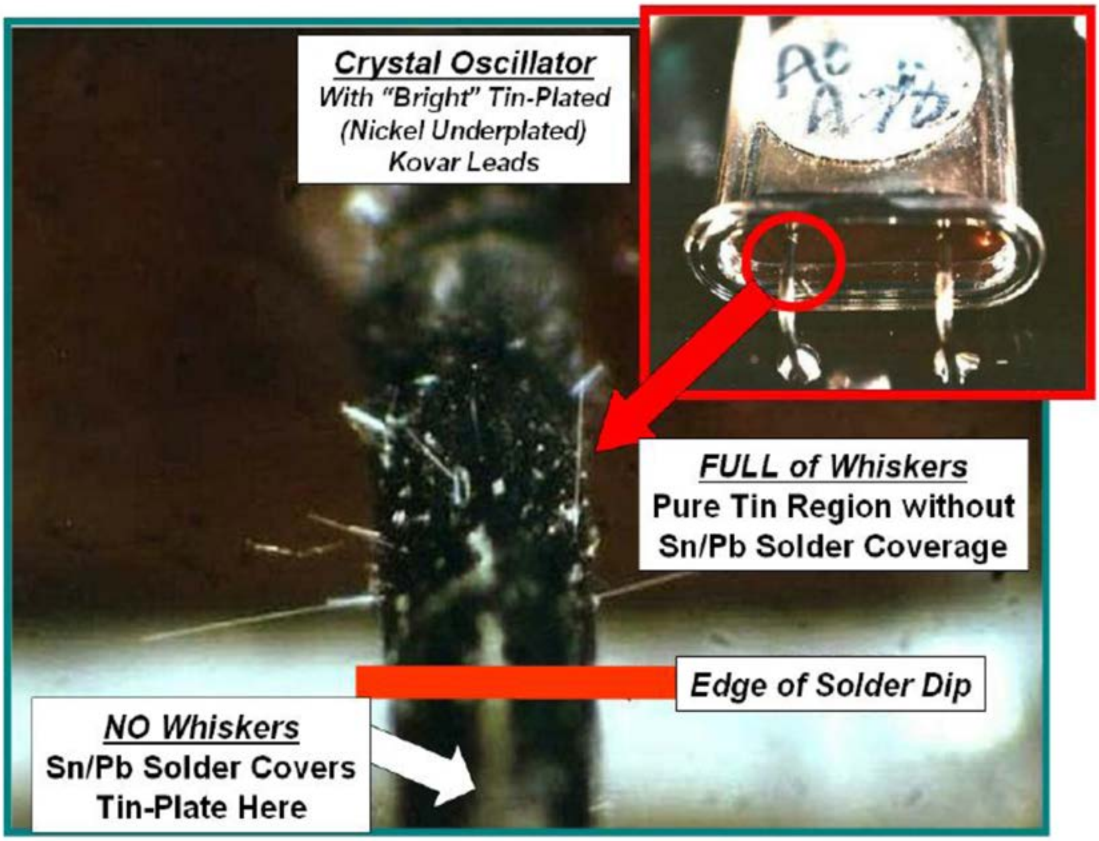
Courtesy: C. Uyemura & Co., Ltd.

Figure 4: Tin whiskers—effect of coating crystal structure.



Courtesy: C. Uyemura & Co., Ltd.

Figure 5: Tin whiskers—coating crystal structure.



Crystal Oscillator
With "Bright" Tin-Plated
(Nickel Underplated)
Kovar Leads

FULL of Whiskers
Pure Tin Region without
Sn/Pb Solder Coverage

Edge of Solder Dip

NO Whiskers
Sn/Pb Solder Covers
Tin-Plate Here

Ref: NASA Goddard Space Flight Center

Figure 6: Tin whiskers—Ni layer.

Impact of Testing Conditions

JEDEC Solid State Technology Association (formerly known as the Joint Electron Device Engineering Council) has published several documents that directly address and/or are related to the testing of tin whiskers, which are good guidelines to start from.

- JEDEC Standard No. 201: Environmental Acceptance requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes, JESD201
- JEDEC Standard No. 22A12: Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes, JESD22A121
- JEDEC Standard No. 22-A104D, Temperature cycling, JESD22-A104D

Primarily three sets of testing conditions are included in the JEDEC documents: ambient temperature storage, elevated temperature storage and temperature cycling.

In contrast to testing the mechanical behavior of solder joints (e.g., thermal fatigue, mechanical shock), the test parameters should be set to monitor the nucleation and growth pattern of tin whiskers or lack thereof. More importantly, the tests for the intended purpose are to gauge the relative susceptibility to whiskering. Testing the absence of whiskers is as meaningful as the presence of whiskers. The end game is to secure a tin-whisker-resistant system or to discern between the tin-whisker-resistant and tin-whisker-prone systems. To this end, one has to define what is deemed to be tin-whisker-resistant in a practical sense (*SMT Magazine*, May 2014).

Tests should monitor:
- First appearance of whisker, if feasible
- Max length of whisker at high T
- Max length of whisker at low T
- Density of whiskers
- Overall pattern and appearance

Desirably:
- Rate of formation over a range of temperature
- Activation energy

Ideally:
- Accelerated test vs. real-life phenomena

The above parameters are "known knowns." Nonetheless, the "known unknowns," such as specific external conditions, application environment either during service or during testing, the uncertainty of tin whiskers remains to be inevitable.

Real-life stresses either introduced at or subsequent to the tin plating or during service life may lead a different tin whisker behavior as in accelerated tests (e.g., temperature cycling, elevated temperature storage). Alloying-making process to achieve homogeneity needs to be taken into consideration. For an impurity system, how the process that adds elements into tin could also affect the whisker propensity.

Testing tin whisker propensity, due to its underlying mechanisms, is a more challenging endeavor than testing solder joint reliability. Not to over-test nor under-test is the gist of the effort. For both theoretical and practical reasons, a reference material incorporated in the test scheme is a must.

Indeed, testing such intricate phenomena of tin whisker formation and growth is not straightforward, not to mention its laborious and costly nature. Nonetheless, a well-thought-out test plan including the properly selected parameters is the prerequisite in order to draw a viable conclusion, positive or negative, from the test results.

As selecting testing parameters that are in sync with the intrinsic properties of the system is a critical step, it is plausible to choose the test parameters based on the anticipated underlying process and/or a postulated theory so that the tests can capture the action.

Prevention and Mitigation Measures

Prevention and mitigation start at the understanding of the causations of tin whiskers. It is indicative that tin whisker phenomenon is both thermodynamically and kinetically controlled process. Based on the test data, field experience, and the material crystal growth theory, a smorgasbord of tactics is listed below, which serves as a guide to prevent or retard tin whisker growth. Discussion will appear in a future column in my series on tin whiskers.

- Organic content
  - <0.05% (a typical military requirement)
- Coating grain size
  - 0.5 to 5 mm
  - (matte Sn 1 -10 mm)
- Coating thickness
  - < / = 2 mm or > 8 mm
- Coating surface morphology
  - Semi-bright
- Coating crystal orientation
- Additional process, e.g.,
  - Fusion
  - Reflow
  - Annealing (150°C, one hour)
- Surface intactness
  - Absence of surface corrosion
  - Free of surface notches, scratches, grooves…
- Minimize deformation
  - Avoid external mechanical force imposed on the coating surface
- Use of underlying barrier for Cu substrate
  - Ni layer with nominally 0.5 to 2 micron thickness
- Minimize CTE mismatch of the system
- Minimize heat excursion
- Choice of conformal coating
- Change to a composition that is less prone to whiskering when needed
- Dipping process
- Use of alloying tactics (vs. SnPb)
- Most effective elements include Bi, In
- SnCu is not a good in whisker-resistance

In order to prevent and retard tin whisker growth, it is highly recommended to exercise the good practice by using aggregate tactics to suppress its driving forces to the level that is below the threshold.

Relative Effectiveness—Use of Alloy Tactic

My anticipated effectiveness of tin-based materials in preventing and mitigating tin whisker formation and growth in descending order is depicted here:

1. SnBi, SnPb
2. SnZn
3. SnAg, SAC
4. SnCu
5. Sn

Plausible Theories

Tin whiskers occur by science. What are the driving forces that initiate the formation of whiskers? What sustain the growth? Can these driving forces be controlled practically and economically?

These are million dollar questions and deserve a deliberate treatment. Overall, disparities in theories and reports abundantly exist. Thus far, there is not a uniform conclusion on the theory and mechanism behind tin whisker occurrence.

Discussion of plausible postulation will appear in the future publication of my column series on tin whiskers. Below outlines some key points to be addressed.

Whisker involves an intricate and complex process. Under accelerated test conditions or in real life services, the understanding of tin whisker calls for a deeper atomic level treatment considering crystal structure, crystal orientation, grain size, grain boundaries, grain boundaries mobility, atomic mobility, and lattice structural changes to foreign elements. This goes to the heart of physical metallurgy theories in crystal nucleation and grain growth, by normal growth and by abnormal (protruding) growth, from a high energy state to a low energy or to a stress-free state.

Driving to the stress-free state involves several stages:

- Forming nuclei
- Nucleation
- Grain and sub-grain growth
- Impingement of grains
- Classical grain growth

Tin crystal structure (body-centered tetragonal, Figure 6) differentiates tin from other metals that are less prone to whiskering. The anisotropic properties of tin result in different surface energies of grains exposed at the surface. This difference and the immobility of grain boundaries pinned by surface grooves is expected to favor "abnormal" grain growth.

Relatively speaking, the energy to drive grain growth is very low and so it tends to occur at much slower rates and is easily changed by the presence of second phase particles or solute atoms in the structure. The external temperature (test temperature) drives the kinetics of defect dynamics in the tin layer by affecting stress relaxation and atomic mobility-related mechanisms. For instance, a high temperature (relative to tin's recrystallization temperature) is expected to impede the continued growth along the protruding direction, resulting in short whiskers. It is also worth noting that tin's recrystallization temperature changes with the level of its purity. In other words, when adding elements into tin, tin's behavior in relation to the external temperature (test temperatures) will change.

The propensity of a tin deposit to grow whiskers strongly depends on its structure: grain size and the relative crystallographic orientation of grains in the deposit. The evidence of recrystallization and grain growth prior to whisker formation is presented for bright tin deposit—large irregular shape grains that are the precursors for whiskers. However, recrystallization is only a part of the tin whisker process.

Further key points include:

- If there is sufficient strain to drive nucleation, whisker grain nuclei may form
- If there is sufficient "stored" energy, whisker may grow
- To sustain growth, tin material has to be adequately supplied, and tin atoms need to be able to move to a whisker grain through passable paths
- Driving forces push the tin from the free surface of the whisker grain outward, resulting in protruding whiskers
- The appearance of whiskers in a range of shapes and lengths from rounded mound to long needles depends on relative nuclei sites, stored energy and temperature
- But as an aggregate, two points are clear:
  1) the driving forces are stress-related, and
  2) internal stresses (compressive or tensile) play an important role to both whisker formation and growth
- Various tests were performed under temperature cycling and electric field. The lack of harmonious testing results regarding the effects of temperature cycling and electric field on whisker growth suggests the intricate nature of the internal stresses engaged in the process.

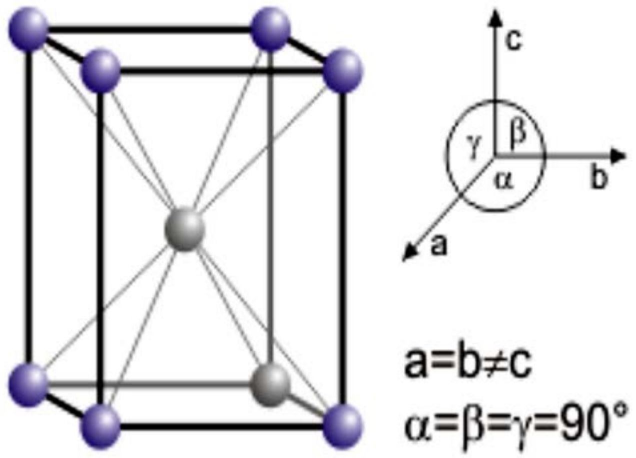


Figure 7: Tin whiskers—tin crystal structure.

It is safe to say that tin whiskering is more than a classical recrystallization process and it is more than a classical stress relief phenomenon. I would say that, for a given tin-based material, there is a threshold strain and there is a threshold temperature (in lieu of recrystallization temperature) to cause tin whiskering.

Concluding Remarks

Our effort is to alleviate the uncertainty, ultimately control tin whiskering propensity.

Each of the mitigating tactics has its limitations. Combined tactics offer a high level of confidence in preventing tin whisker-related reliability issues. And each of the causes and factors as discussed does not play out by itself. An illustration is the Ni layer approach that has been proven to be effective in most cases. Nonetheless, a photo in one NASA report[7] reveals that Ni layer did not categorically prevent tin whisker as shown in Figure 6.

Some of causes and factors as listed above are intricately interplayed and application-specific. This is the challenge imposed to the evaluation of tin whisker propensity based on a set of testing conditions. And this is also the very reason that tin whisker appears to be elusive.

Seeking an absolute prevention is hardly a practical task. Based on the scientific principles as well as the decades' field service performance, a tin-lead reference material containing lead in the range of 3% to 37% is indispensable. And this defines tin-whisker-resistance.

As to which preventive approach to take, it is the priority setting in the order of importance and effectiveness by assessing the design and specific application. For whisker-sensitive applications, with practical importance in mind, steps to be taken in descending priority steps are: step one is not to use pure tin; step two is to select an effective composition of tin-based alloy; steps three, four or five, if needed, are to be selected from the above list with the assessment based on the specific system.

There are a number of SAC alloy compositions and the number of the compositions is looming. A specific composition of an SAC should be specified (e.g., SAC105 has different mechanical behavior and physical phenomena from SAC305).

Lead-free solder comprises a wide array of alloy systems not to mention that each alloy system can be modified in numerous ways. The bottom line is that an alloy, SAC or other, does not represent the material world of lead-free unless a sufficient testing scheme comprising representative materials is designed and the representative tests are conducted to validate the "representation."

In whisker phenomenon, the physical metallurgy engaged in the process is complex and intricate—a compositional shift and /or an addition of extraneous elements to a base alloy system can change its whisker propensity enormously. Tin whisker propensity under a study should be concluded with a specific alloy composition—the clarity is the name of the game. **SMT**

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Upcoming Appearances

Dr. Hwang will present a lecture on "Tin Whiskers – What is Important to Know" at SMT International Conference/Exhibition, on September 28 in Chicago, IL.

Dr. Hwang, a pioneer and long-standing contributor to SMT manufacturing since its inception as well as to lead-free development and implementation, has helped improve production yield and solved challenging reliability issues. Among her many awards and honors, she is inducted into the WIT International Hall of Fame, elected to the National Academy of Engineering, and named an R&D-Stars-to-Watch. Having held senior executive positions with Lockheed Martin Corp., Sherwin Williams Co., SCM Corp, IEM Corp., she is currently CEO of H-Technologies Group providing business, technology and manufacturing solutions. She has served on U.S. Commerce Department's Export Council, various national panels/committees, and the board of Fortune 500 NYSE companies and civic and university boards. She is the author of 400+ publications and several textbooks, and an international speaker and author on trade, business, education, and social issues. Her formal education includes four academic degrees (Ph.D., M.S., M.A., and B.S.) as well as Harvard Business School Executive Program and Columbia University Corporate Governance Program. To read past columns, click here. For further information, go to: www.jenniehwang.com.