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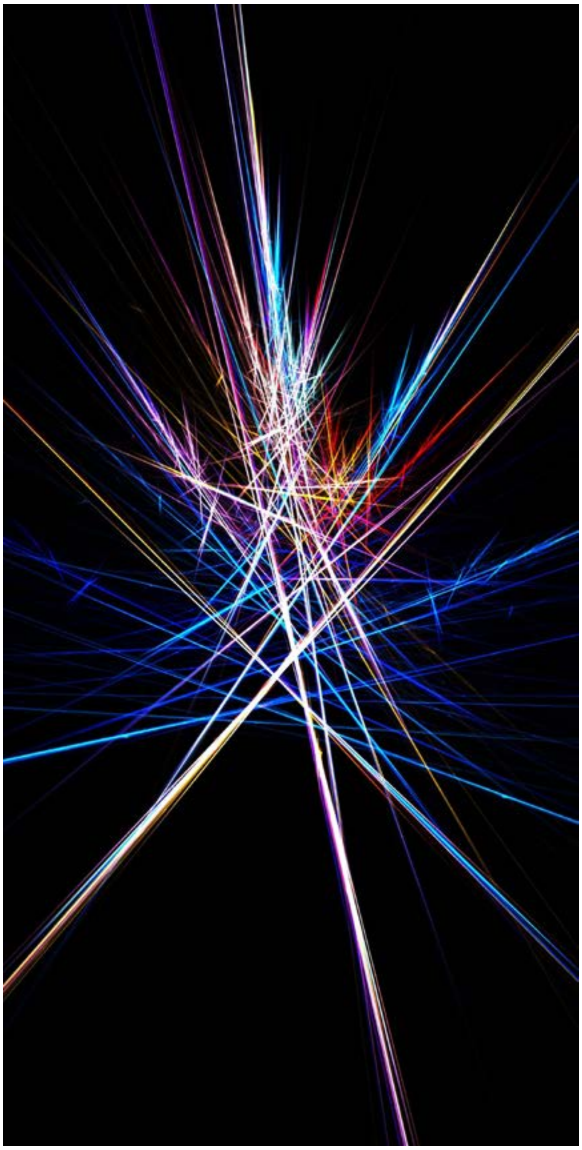
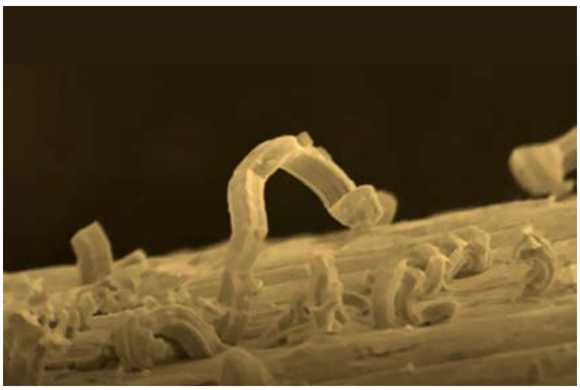
TIN WHISKERS

Since the EU passed the Restriction of Hazardous Substances directive in 2006, tin whiskers have become a serious threat to the assembly of PCBs. This month, our feature contributors Dr. Jennie Hwang, Andrzej Czerwinski, and Linda Woody tackle this prickly subject.





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ELECTRONIC INTERCONNECTIONS

Electronic Assembly with Solder: an Unblinking Look at "The Devil We Know"

by Joe Fjelstad
VERDANT ELECTRONICS

Solder is unquestionably highly practical technology for joining metals, and carries with it a long history. Its roots go back more than 2,000 years. Somewhere in the distant past, one of our more clever and observant ancestors chanced to create an alloy of tin and lead that melted at a low temperature. They or someone who learned of their discovery found that this unique combination of elements could be used to join pieces of metal together. This combination of chance observation and applied imagination has proven a key development in the technological history of mankind. Those in the electronics industry of today are very familiar with this ancient technology and today it is still the method of choice for making electronic assemblies of every sort. The only fly in the ointment is that the EU parliament, in a mad rush to try to look "green," took the emotional and scientifically ill-advised position that lead needed to be banned from electronic solders.

Sadly, there was never presented a credible piece of scientific evidence that any user had ever been harmed by tin-lead solder in electronic equipment. Nor could they prove their assertion that it would be a risk to ground water. That said, it is true that greed and complete mismanagement of electronic waste boarding on criminal behavior, has resulted in physical illness and environmental harm in areas of the world where

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uncontrolled recycling was being carried out by uneducated individuals. While all is not yet well in that regard, that "hole" in the system is being addressed by businesses, NGOs and governments around the world.

Not to be forgotten is the fact that the impact of the EU's decision has been significant and far-reaching and it has caused the industry to spend needlessly many tens of billions of dollars diverting the considerable talents of countless talented engineers and scientists around the world to make products that are unfortunately proving less reliable and arguably less environmentally friendly electronics than those built with tin lead solders.

The Devil We Know, Disrobed

While soldering (especially tin-lead soldering) holds many benefits in terms of offering a means of mass assembly of electronic components to printed circuit boards and is fundamentally simple, its application in the assembly and manufacture of electronic products of the present age is much more complex and fraught with opportunity for defects to be generated, but it is also the a demon we have elected to live with, for as the old saying suggests that "Better is the devil we know." The devil we know is at least familiar and the simple truth is that humans are creatures of habit and most of us abhor change. There is a lingering question in the current situation? Is dealing with the devil we know on a daily basis really worth the price we are paying?

Following is a recitation of some of the many types of solder and solder-related defects that test and inspection is tasked with finding before a product reaches market. Bear in mind as these defects are recounted and reviewed that the cost of defects rises as a product moves further from the manufacturing line.

a) Opens: Opens are discontinuities generated in the soldering process that can be manifest in assembly in a number of ways. For example, a bent or lifted lead on a QFP component, missing solder ball on a BGA, insufficient solder on an LGA or the warpage of the component during the high-temperature, lead-free reflow process can all result in an open circuit.

b) Shorts: Solder shorts are bridges of solder between one or more component leads on an assembly. As component lead pitch continues to drop, the incidence of short circuits increases. Presently, the threshold of pain for most assembly is experienced when the lead pitch drops below 0.5 mm.

c) Insufficient Solder: Insufficient solder is a condition where the amount of solder in a solder joint is less than desired or specified contractually through industry specifications or customer requirements.

d) Excessive Solder: Excessive solder is obviously the opposite of the condition of insufficiency and is again measured against agreements. It also introduces a wild card because it is not what reliability testing is based on.

e) Solder Cracking: Solder cracking is an obvious concern as it could result in a latent open circuit condition. Good during product test before shipping but then failing in the field.

f) Tin Whiskers: Tin whiskers are small metal projections emanating from a solder joint. They can grow up to 15 mm long and given the fine pitch of today's components, they are a significant concern. There are also challenging because they are typically a latent defect that shows up unpredictably. Past research indicated that the addition of lead to tin solder alloys would mitigate the formation of whiskers; however, with the ban on lead in electronic solders the incidence of whiskers is on the rise.

g) Poor Wetting/Dewetting: Good wetting is manifest by the presence of uniform coat of solder on both the leads of the component and terminations of the printed circuit to which they are joined. In areas of poor wetting or dewetting the solder thins appreciably in areas leaving only a thin silvery sheen.

h) Voids: Voids are defect which are often difficult to detect without use of special equipment such as an X-ray apparatus. The challenge with voids is that they represent potential weakness in the solder joint owing to their inconsistent nature. Voids can be found both in through-hole and surface mount components. In the case of surface mount components the voids are often extremely small and are sometimes referred to as champagne voids.

i) Blowholes: A term applied to a phenomenon where a small hole is observed in a solder joint. Typically, the defect is found to be the result of discontinuities in the plated through-hole wall, which may absorb flux and then explosively out gas during the soldering process.

j) Cold Solder Joints: Solder joints that did not form completely a good metallurgical bond. They are often the result of the joint receiving sufficient heat to cause complete melting and joining of the solder. Cold solder joints are often seen in cases where the component lead is connected to a large thermally conductive feature or element and insufficient heat is retained near the lead to assure a good solder joint. With lead-free solders, the phenomenon provides a greater challenge as the amount of heat which must be supplied is much greater than it might have been with a tin lead solder, thus potentially degrading device and assembly reliability.

k) Brittle Solder Joints: Solder joints wherein the alloy formed in the soldering process due to dissolution of elements within the finish or on the circuit board (e.g., gold), results in a solder joint that is less ductile than the solder used in the assembly process.

l) Head-on-Pillow: A new type of defect which was identified only with the introduction of lead-free soldering. It is an unsettling type of defect in that it is not easily detected but could result in an intermittent open in the operation of the assembly. The term was chosen because the phenomenon is reminiscent of an individual's head forming a depression on a pillow.

m) Graping: Another lead-free related defect wherein the small, often ball-like particles of solder in a solder paste do not reflow completely, leaving a surface that looks like the surface of a bunch of grapes. Like head-in-pillow, it is a defect that may not be easily detected.

n) Tombstoning: Tombstoning is a term that has been applied to the appearance of a defect related to discrete devices such as resistors and capacitors, wherein solder connections are not made simultaneously; the slight lag causes the first side to reflow to pull back and rotate up, resembling a grave marker (which is somewhat apropos given that the assembly will likely be dead if tombstones are present).

o) Component Cracking: Component cracking can have multiple causes, one being a situation where there is a significant mismatch in terms of coefficient of thermal expansion between the component and the printed circuit to which it is attached. It can also occur if the assembly is flexed in the area of the component, causing the device to crack.

> ***"Component cracking can have multiple causes, one being a situation where there is a significant mismatch in terms of coefficient of thermal expansion between the component and the printed circuit to which it is attached."***

p) Popcorning: Popcorning is a phenomenon manifest when moisture entrapped within a component outgases during assembly, causing a blister to form in the encapsulation material. With the advent of lead-free soldering and its higher temperatures, the incidence of popcorning rises and in fact moisture sensitivity levels of components are degraded to reflect the new reality.

q) Solder Balling: Solder balling is a condition which happens during the reflow of a solder paste on a surface mount assembly. It is a result of the high temperature of reflow causing rapid volatility station of the flux and spatter of the solder particles that are part of the flux. While a viable solder joint may be created even as solder balls are being formed, they represent a risk to the long term reliability of the assembly as potential shorting elements.

r) Misregistration: Components with fine pitch leads, if jostled before or during the assembly, may be misregistered relative to the land pattern, resulting in a nonfunctional product.

s) Insufficient Cleaning Under Devices: As mentioned previously, insufficient cleaning under surface mount devices can result in latent failure through the formation of high resistance shorts or the growth of dendrites.

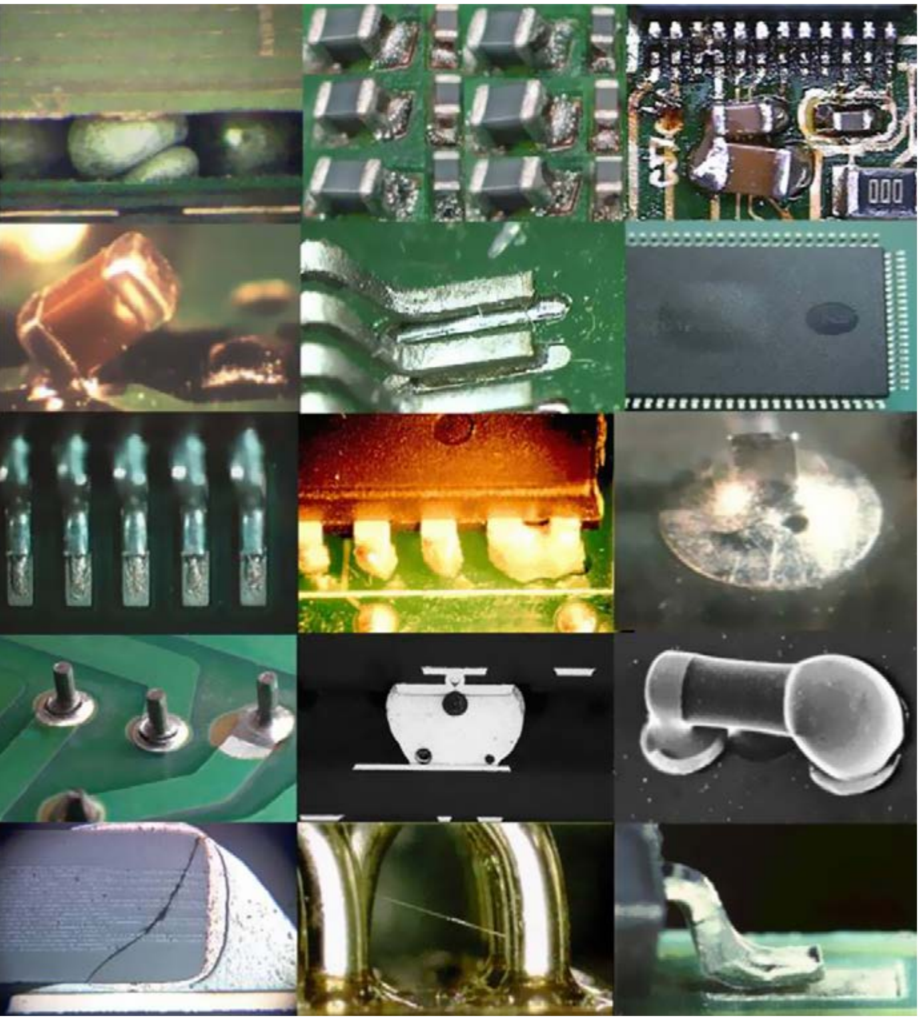


Figure 1: Representative images of some of the solder related defect found on printed circuit assemblies. Top row – left to right: head in pillow, graping, misregistration short and overheated flux. Second row, left to right: tombstoning, insufficient solder with open, popcorning. Third row, left to right: dewetting, blowhole, shorting between adjacent leads. Fourth row, left to right: cracked solder joints, voids, excessive solder. Bottom row, left to right: cracked component, tin whisker, open (lifted lead).

Clearly there is a great deal of nuance in the detection and identification of solder related defects; numerous books have been written over the last few decades that both characterize and suggest methods for eliminating or mitigating them (the devil is also "in the details" as another aphorism attests). It is not within the scope of this brief commentary to provide detail on all of the various types of solder related defects which can extend from the macro to the micro but for the benefit of the reader the following figure is offered providing representative examples of a number of the defects described above.

The "Devil's" Impact on the PCB

The importance of managing the soldering process is clear, but making a good solder joint is also just part of the story and there are a number of defects that can be generated within a printed circuit assembly because of the soldering process, including:

a) Corner Cracking: A crack that forms at the interface between the whole and the land that surrounds. It is normally the result of the Z-axis expansion of the PCB during the thermal excursions such as soldering.

b) Barrel Cracking: Another phenomenon associated with the soldering process; it is similar in some ways to a corner crack except that it is manifest near the center of the hole.

c) Post Separation: A separation of the plating in the through hole from an innerlayer connection

d) Hole-Wall Pull Away: Hole-wall pull away is manifest as a bulge in a plated through hole, which reduces its diameter.

e) Resin Recession: Roughly, the opposite of hole-wall pull away wherein a small gap is formed between the plated hole wall and a resin rich area of a plated through-hole

f) Delamination: A separation of the layers of a multilayer circuit. It is normally seen in cases where the glass transition temperature of the resins used in the multilayer structure is exceeded.

g) Pad Cratering: Another phenomenon unseen before the introduction of lead-free sol-

dering. It is manifest as a circumferential tear of the copper land to which a component, normally a BGA, is assembled.

h) Decomposition: Decomposition of a PCB is a relatively new phenomenon associated with higher temperatures used with lead-free soldering. In fact, a new term was added to the industry lexicon, T_d, which is the temperature of decomposition representing a loss of a specified percentage of the weight of the printed circuit.

Clearly, printed circuit technology, like soldering technology, is fraught with its own vulnerabilities due to the complexities of processing. The demands on PCB technology foisted upon the industry by the imposition of lead-free soldering requirements have placed a heavy burden on the printed circuit manufacturing industry. The need for higher glass transition temperatures to assure a measure of survival through the elevated temperatures of lead-free soldering has required the printed circuit industry to qualify new materials. Simultaneously, there has been a demand placed upon the industry to remove halogenated flame retardants from its materials. This double-barreled challenge is one that the industry had not faced before. Moreover, the industry has been challenged to provide circuits with ever-finer features which operate at ever-increasing frequencies.

To their credit, printed circuit industry technologist, engineers and scientists have struggled admirably to address these challenges, including the challenge of finding solutions to defect modalities that were unknown to the industry just a few years ago. Unfortunately, a number of the defects described are related to soldering and its effects. The earlier problems have been exacerbated by the increased temperature required for lead-free soldering. Figure 2 offers cross-sections of representative printed circuit defects resulting from thermal excursions.

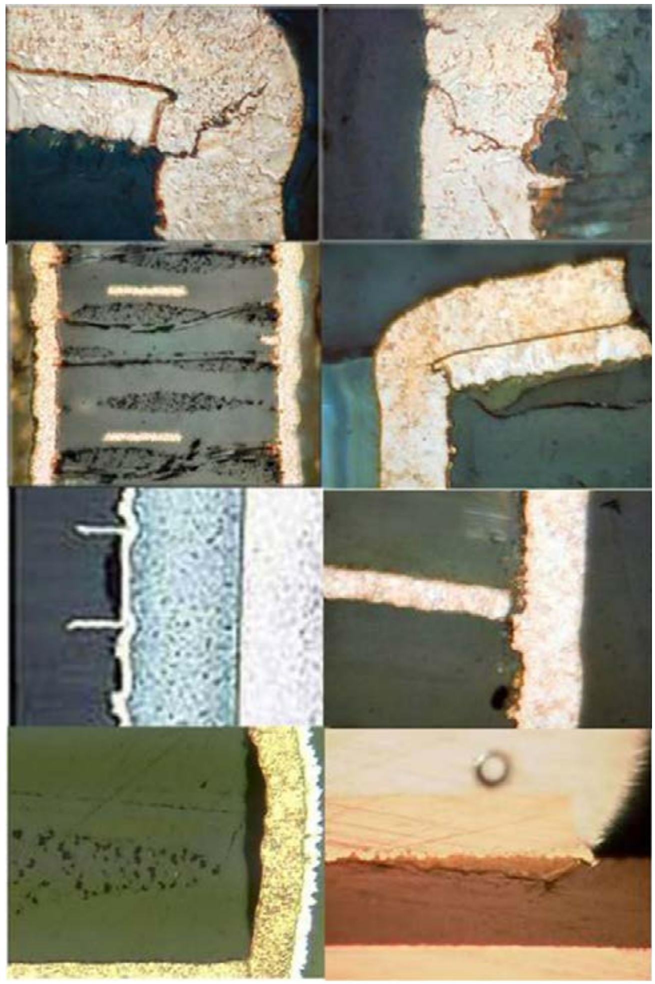


Figure 2: Cross-sectional micrographs of printed circuit defects caused by soldering are provided above. Clockwise from the upper left-hand corner: corner crack, barrel crack , pad lifting, post separation, pad cratering ,hole wall pull away, resin recession and delamination.

Solderless Assembly for Electronics (SAFE) Technology: A Simpler Approach?

Given all the challenges and risks associated with soldering, every thoughtful and prudent manufacturing engineer must constantly be seeking a way or ways to make assembly processing more robust. If one looks for inspiration on how they might end their dealing with the devil, they can find it in the Bible, where it is written: "If thine eye offend thee, pluck it out, and cast it from thee." Perhaps this is a bit extreme, but this seems to be where the industry is stuck today in dealing with the devil. Solder is by analogy an offending element of manufacturing and source of many if not most manufacturing problems. The industry will continue to have to deal with that devil as long as we persist in its use.

One can do their own research to test this assertion if they choose. They need look no further than the titles of papers in publications. Presently, this and other industry/academic journals and proceedings on electronic manufacturing are rife with articles, papers, commentaries and advertisements offering new materials, processes and equipment both for manufacture and inspection to try and beat lead-free solder into submission. Unfortunately, solder appears a wily and crafty adversary that always seems to offer another challenge to each new solution proposed. This situation begs the question: "Is there any alternative?" The answer, in the opinion of this author, is "Yes." The answer is to assemble electronics without solder.

The potential benefits of eliminating solder is significant in many areas of current concern or high interest in electronic manufacturing, including: cost , reliability, performance, environmental impact, design security, a means of addressing some elements of counterfeiting, sustainability, a means of sidestepping conflict metals concerns and others.

So how can it be done? It is really quite simple: Build assemblies in reverse and instead of placing and joining components on circuit boards with solder, build up circuits on "component boards" using copper plating, thereby bypassing the soldering process completely along with all of its many extra processing steps, ongoing challenges, and problems. The potential economic, environmental and reliability benefits are substantial as will be shown. The concept of SAFE assembly and its practicality will be examined in more detail in a future paper. **SMT**

Verdant Electronics Founder and President Joseph (Joe) Fjelstad is a four-decade veteran of the electronics industry and an international authority and innovator in the field of electronic interconnection and packaging technologies. Fjelstad has more than 250 U.S. and international patents issued or pending and is the author of Flexible Circuit Technology.

Tin Whiskers: Capsulization

by Dr. Jennie S. Hwang
H-TECHNOLOGIES GROUP

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 above-mentioned.

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

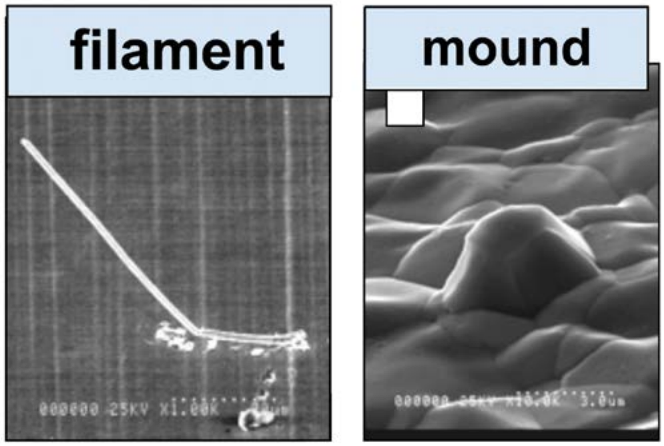


Figure 1: Tin whiskers appearance, from mound to filament.

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.

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

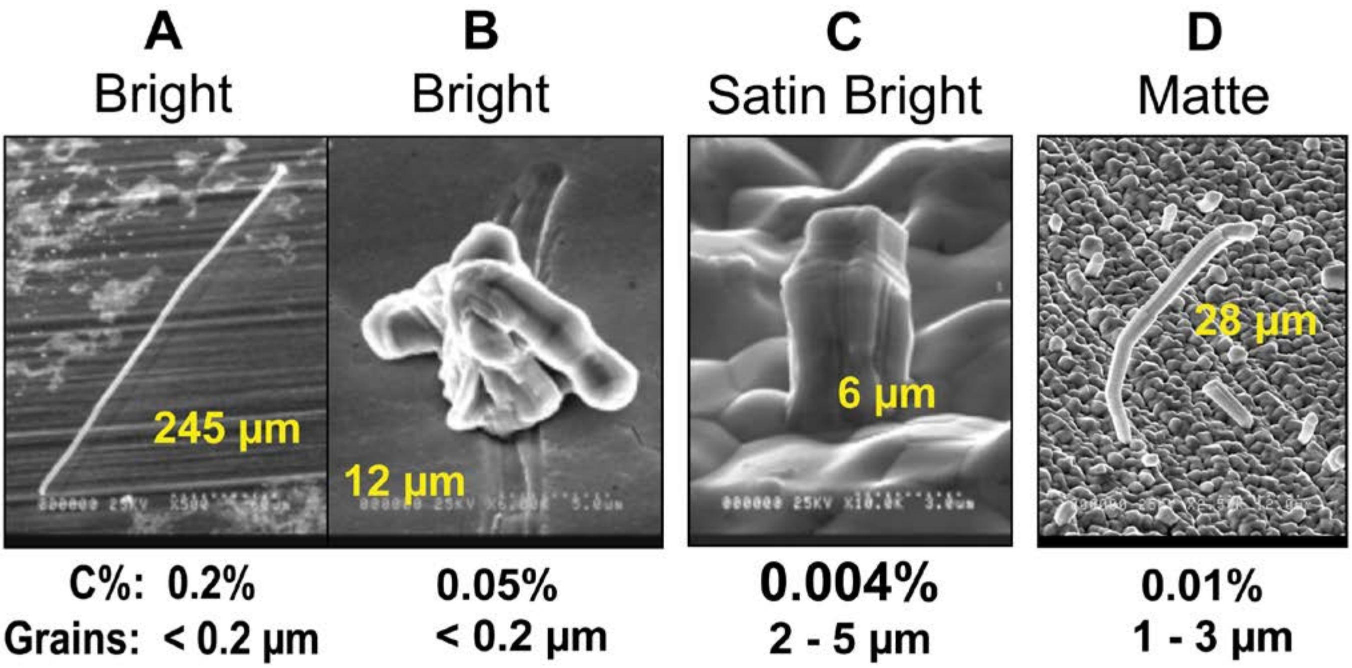


Figure 2: Tin whiskers—organic inclusions and grain size (four months aged at 50°C).

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,

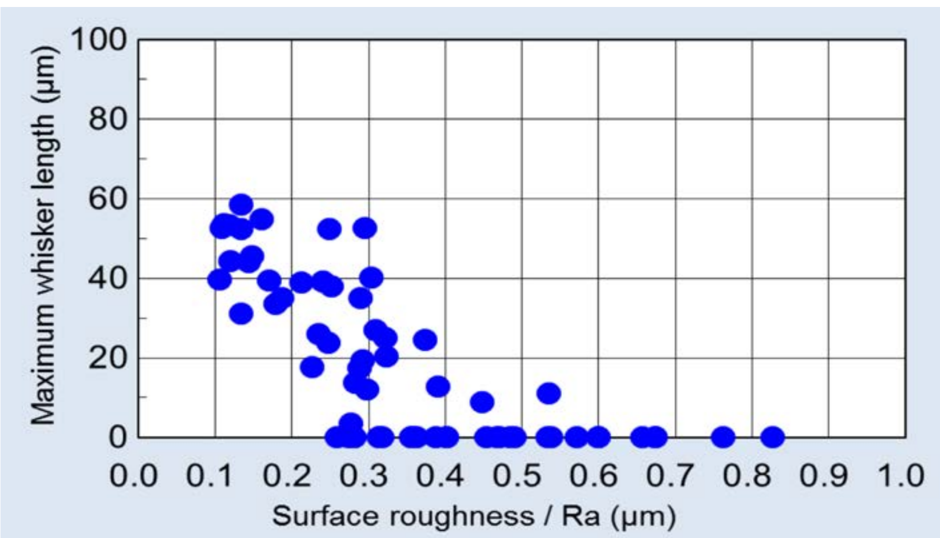


Figure 3: Tin whiskers—role of surface morphology (chemical micro-roughening to produce a set of surface roughness with specific Ra values).

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.

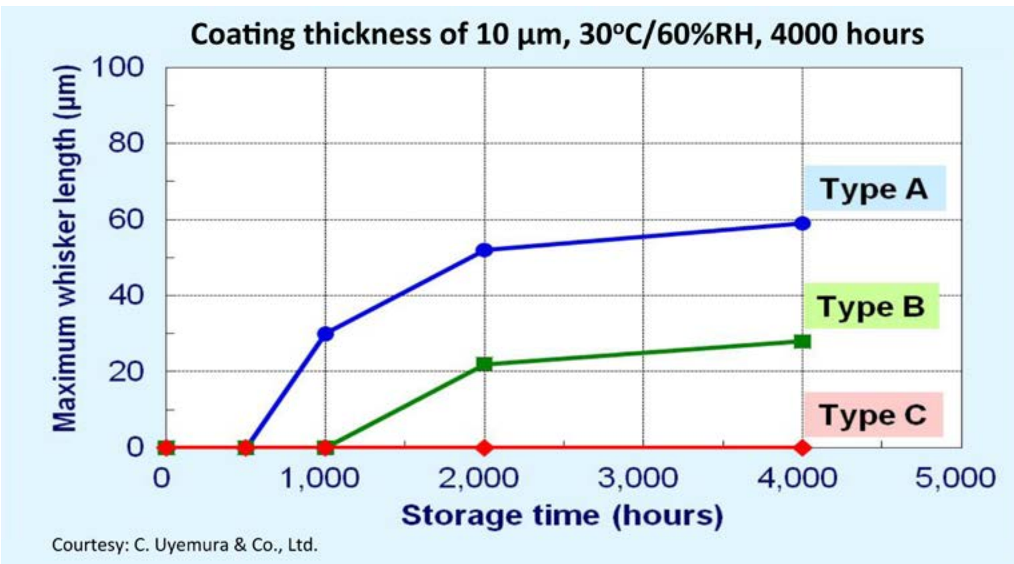
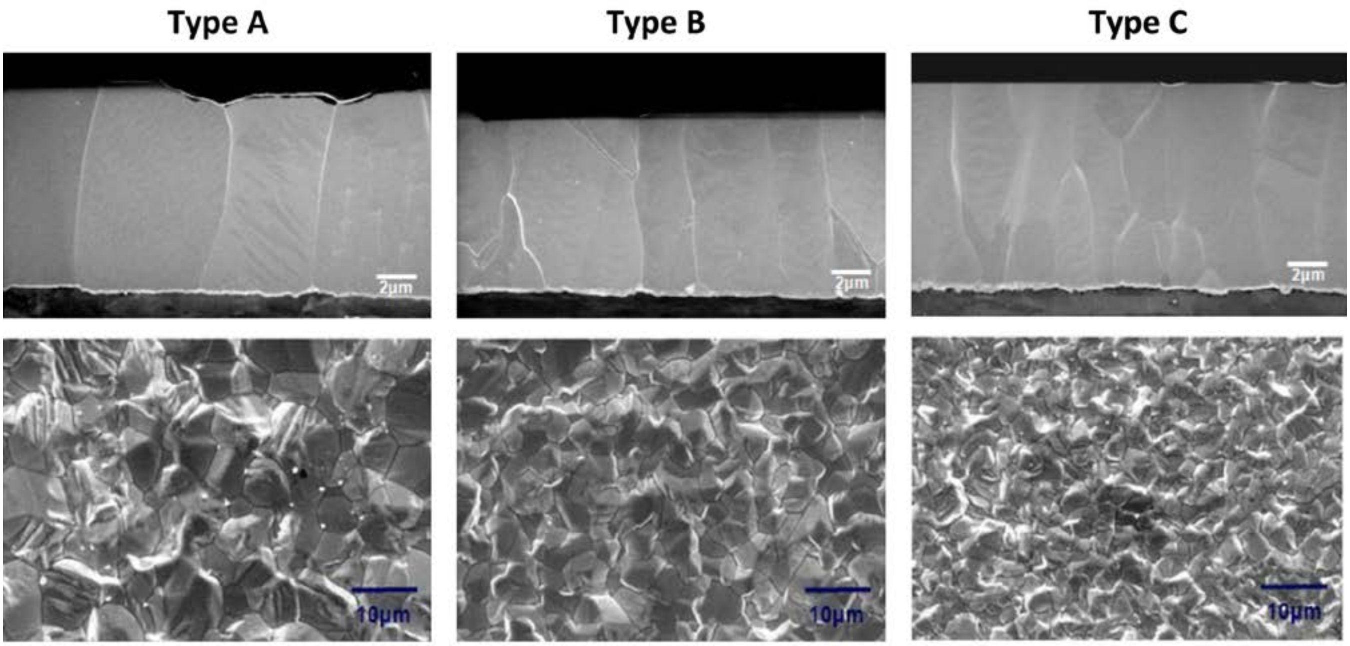
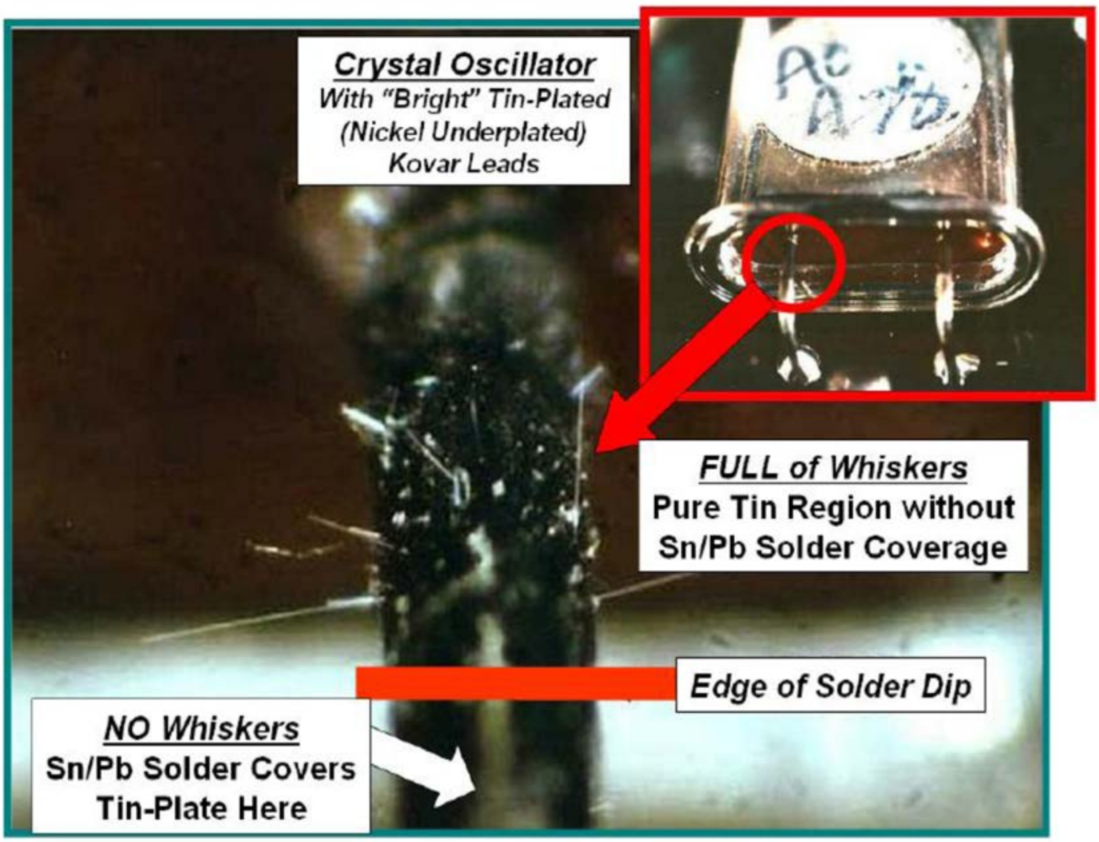


Figure 4: Tin whiskers—effect of coating crystal structure.



Courtesy: C. Uyemura & Co., Ltd.

Figure 5: Tin whiskers—coating crystal structure.



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 oc-

cur 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.

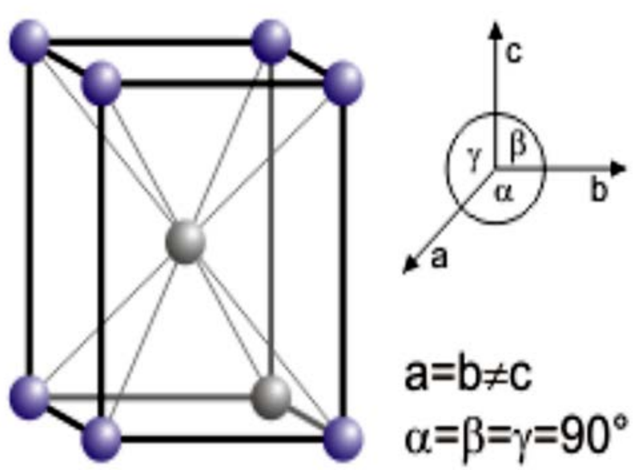


Figure 7: Tin whiskers—tin crystal structure.

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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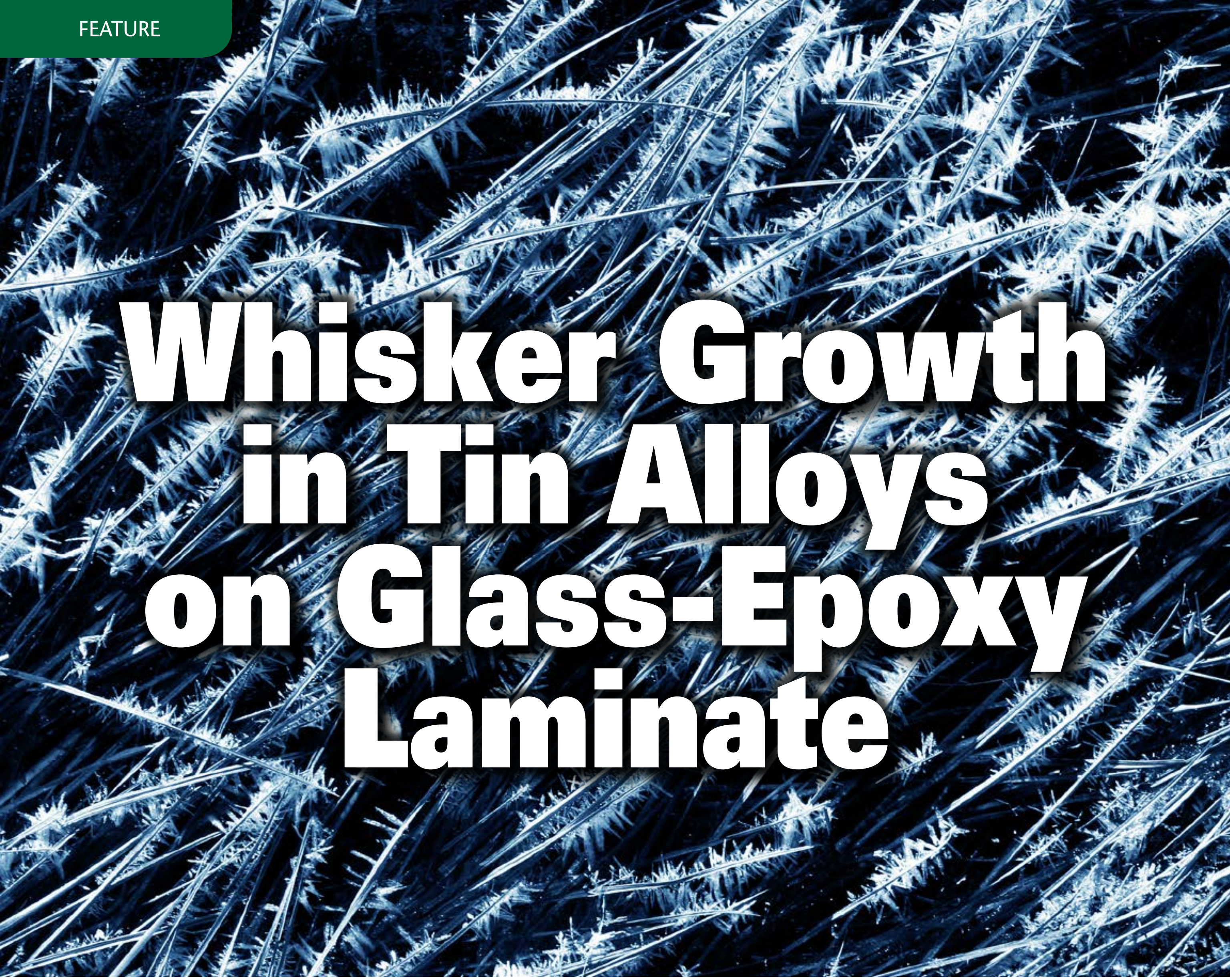
Upcoming Appearances

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.



Whisker Growth in Tin Alloys on Glass-Epoxy Laminate

by A. Czerwinski, A. Skwarek, M. Płuska, J. Ratajczak, K. Witek
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Abstract

Tin-rich solders are widely applied in the electronic industry in the majority of modern PCBs. Because the use of lead-tin solders has been banned in the European Union since 2006, the problem of the bridging of adjacent conductors due to tin whisker growth (limited before by the addition of Pb) has been reborn. In this study, tin alloys soldered on glass-epoxy laminate (typically used for PCBs) are considered. Scanning ion microscopy with focused ion beam (FIB) system and energy-dispersive X-ray spectroscopy (EDXS) were used to determine correlations between spatial non-uniformities of the glass-epoxy laminate, the distribution of intermetallic compounds and whisker growth.

Introduction

Tin whiskers are crystals growing from tin or tin-alloy surface that are a threat to the reliability of electronic circuits because of short circuits (due to the bridging of adjacent conductors), increased electromagnetic radiation or device littering [1,2]. The phenomenon can occur in tin-rich solders, but the addition of lead to the tin alloy inhibits whisker growth. In the twentieth century, the most popular solder was Pb37Sn63 eutectics. However, since July 2006, when the Restriction of Hazardous Substances (RoHS) Directive was adopted by the European Union, the amount of Pb in solders has been limited to 0.1 wt.%. The application of tin-rich lead-free solders in the PCB assembly process has reintro-

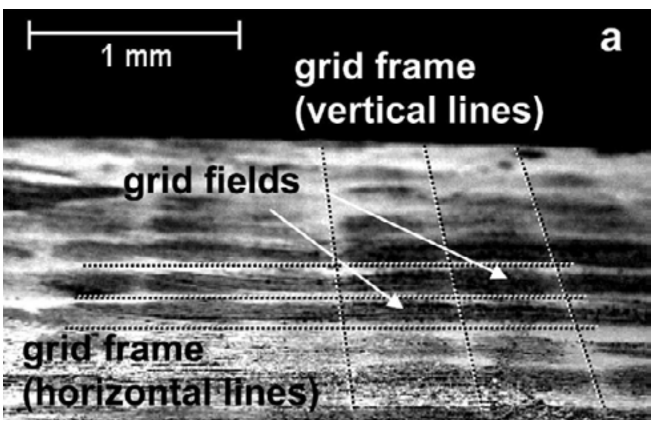
duced the problem of tin whisker growth which had been limited before by the addition of Pb. Whiskers are responsible for many system failures in the military, medical and telecommunication industries.

There is no single, commonly accepted model of whisker growth in the literature [2]. However, most theories involve the role of compressive stress [2-5], which may result from chemical, mechanical and thermal factors, with the whisker growth as a phenomenon of stress relief. The growth is affected by such factors as temperature, residual stress, mechanical force, the formation of intermetallic compounds (IMCs), broken oxide layer, electric field, etc. The higher the compressive stress, the greater the volume of Sn contained in whiskers [6].

In typical PCBs with a copper layer above a laminate substrate, the compressive stress generated as a result of volume expansion during the formation of IMCs (a Cu-Sn alloy formed at the Sn/Cu interface), is generally regarded as the driving force for Sn whisker growth. Whisker formation during thermal stress is also induced to a great extent by compressive stress resulting from the thermal expansion coefficient (CTE) mismatch of different layers. It has also been observed that when a tin-alloy layer is deposited on copper and there is compressive stress induced by IMCs created at the interface between tin and copper, the compressive stress near the surface is lower for thicker films, which therefore are more resistant for tin whisker formation [7,8]. Although full agreement has not yet been reached, it is suggested that when tin plating is over 5 μm [9] (or 8 μm [10]) thick then the layer is more resistant to the whisker growth. Thicknesses below 0.5 μm and above 20 μm retard growth even more [9], although these very thin or thick plates may not be feasible in practice.

This paper concerns the whisker growth on the surface of tin-rich, lead-free alloys soldered on a Cu layer above a non-conductive glass-epoxy laminate (FR-4) (i.e., with epoxy resin and woven fiberglass reinforcement), which is the most widely used PCB substrate material [11]. The glass-epoxy laminate is a mixture of two materials resin and glass fiber, with the resin filling the empty spaces between glass fibers. It was shown previously in [12] that the structure of the glass-epoxy laminate-surface has a fabric-like spatial non-uniformity caused by the regular structure of woven glass fibers and resin regions [12]. Precise analysis of the glass-epoxy surface (before the deposition of the solder) showed that in a general planar view, a grid is apparent. The same grid pattern was visible on the surface of a tin alloy soldered over a glass-epoxy laminate after standard reliability tests of temperature cycling conditions (Figure 1).

The structure of the laminate is responsible for forming the grid pattern visible on the sol-



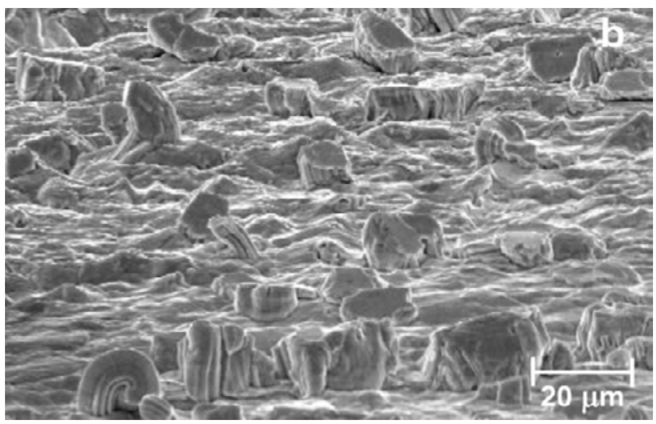


Figure 1: (a) An SEM image of an alloy surface soldered on glass-epoxy laminate (with a Cu layer) with a visible grid of rectangular grid-field regions (with hillocks and whiskers) and surrounding them grid-frame regions (i.e., flat areas practically without surface roughness). Image was taken after tilting the sample to attain better visibility of the grid. (b) Whiskers and hillocks visible within the region of grid field.

der surface. Local compressive stress in the solder layer due to large differences in the coefficient of thermal expansion (CTE) of the resin and glass fiber promotes whisker growth in the area of the alloy soldered on the Cu layer over the glass fiber (Figure 1) (i.e., in regions of grid fields of the visible grid pattern [12]). The coefficient of thermal expansion is much higher for the resin (e.g., about 63 ppm/°C), than for the glass fiber (about 5 ppm/°C) [11], while for tin and copper it is equal to 23 ppm/°C and 16.5 ppm/°C, respectively. This effect does not occur for an alloy soldered on Cu over a paper-phenol laminate, for example. The lines of the grid frame correspond to the area of the solder placed over the resin while the grid fields between the grid frames correspond to the area of the solder placed over the glass fiber in a cross-section [12].

"The lines of the grid frame correspond to the area of the solder placed over the resin while the grid fields between the grid frames correspond to the area of the solder placed over the glass fiber in a cross-section."

Experiment

The studied samples were PCB glass-epoxy laminate covered by a Cu foil (at least 17 µm thick) with a layer of tin or other, commercially available tin rich solder alloys: Sn100C ($Sn_{99.3}Cu_{0.7}Ni$), Sn99Cu1, $Sn_{97}Cu_3$, $Sn_{99.5}Ag_3Cu_{0.5}$, $Sn_{99.3}Cu_{0.7}AgNiGe$, and $Sn_{99}Ag_{0.3}Cu_{0.7}NiGe$. The alloys were applied by hand soldering with the application of a water flux. The soldering temperature was dependent on the alloy composition.

The samples were tested in a VÖTSCH chamber for 1500 shocks within a cyclic temperature range of -45°C to +85°C, with each cycle lasting 20 min and the transition time of the lift between hot and cold zones equal to 5 s. These conditions are recommended by iNEMI (International Electronics Manufacturing Initiative) and JEDEC (Joint Electronic Device Engineering Council) as inducing whisker growth in most Sn and Sn-alloy layers [13].

The FEI Helios NanoLab 600 DualBeam FIB system was applied to the milling (cross-sectioning) of samples with a precise gallium ion beam and also for scanning ion microscopy imaging (i.e., induced by the ion beam and detected by the secondary-electron detector) for the range of energies up to 30 keV. The cross-sections were thoroughly cleaned in FIB to remove contaminations introduced during the FIB cross-sectioning process [14, 15]. EDXS with a Philips XL30 SEM and EDAX spectrometer (with 130 eV spectral resolution) was used, with an energy range from 5–15 keV applied in the considered case.

Results and Discussion

Scanning ion microscopy imaging and EDXS measurements were performed at various points on the mentioned grid to determine the correlations between the spatial non-uniformities of the structure of glass-epoxy laminate, of IMC distribution in the solder and of whisker growth after standard reliability tests. The grid on the solder is formed by grid fields (rectangular regions with hillocks and whiskers) surrounded by the grid frame (flat regions without surface roughness).

The measurements were first performed when the samples were observed in a planar view, with the sample surface placed perpendicular to the electron beam. Results obtained from grid fields (with hillocks and whiskers) showed a significant Cu content, much higher than that from grid frames where this content was negligible.

Afterwards, FIB was used for milling samples with a gallium ion beam. These cross-sections were performed at several adjacent points spaced along a line from the grid frame to the grid field, with the aim of comparing neighboring points (instead of comparing random points in these two regions, because additional factors may be relevant in remote locations).

Images of cross-sectioned layers were taken by use of electron and ion microscopy. The scanning ion microscopy performed in FIB system, where detected secondary electrons are generated by the incident gallium ions, allowed for better image contrast than that observed in images obtained from standard secondary-electron (SE)

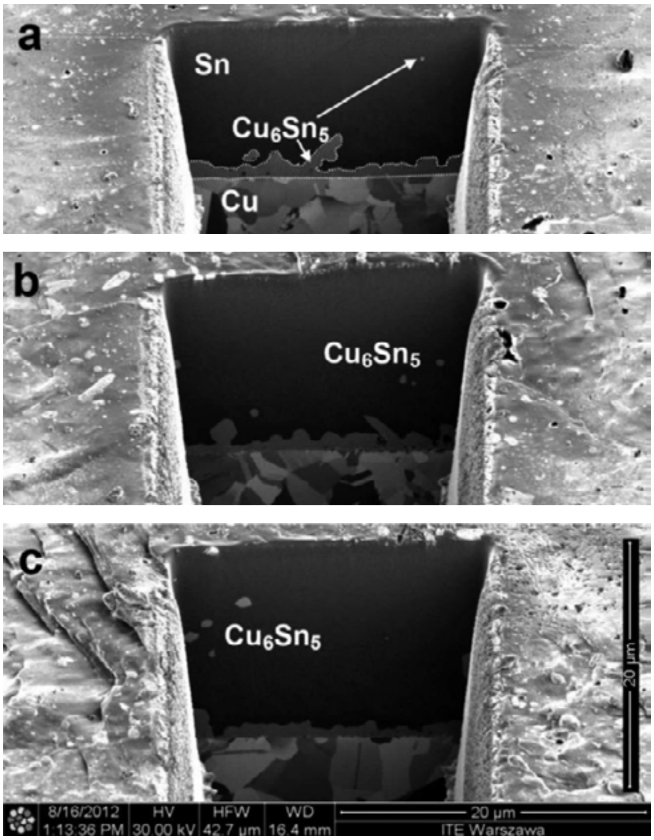


Figure 2: Scanning ion microscopy image of cross-sections milled by FIB in three consecutive adjacent places along a line from the grid-frame to the grid-field region: (a, b) in the grid-frame region; (c) at the boundary between the grid-frame and the grid-field regions. From the bottom to top, the copper film, the interface IMC layer (with IMC protrusions extending upwards) and the solder layer (with small separate Cu_6Sn_5 precipitates inside) becoming thicker towards the grid-field region, are visible in these cross-sections.

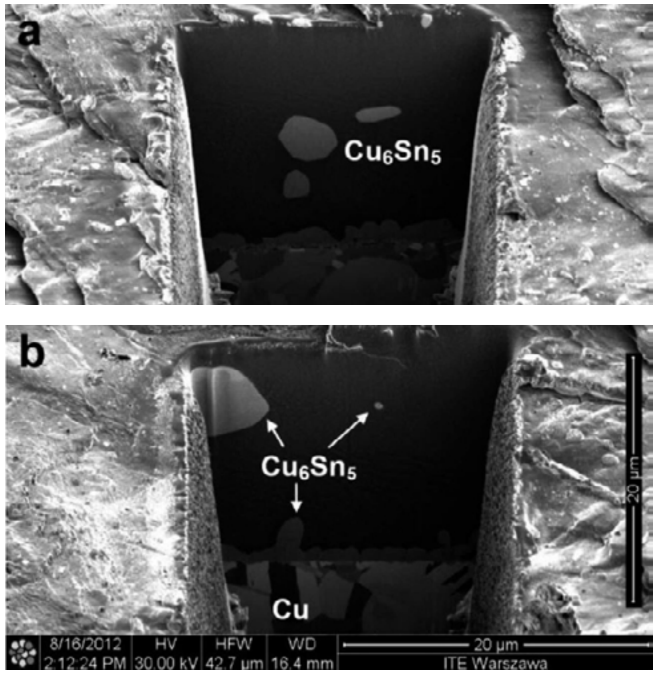


Figure 3: Scanning ion microscopy image of cross-sections milled by FIB in the grid field region in the two consecutive adjacent places along a line from the grid-frame to the grid-field region (situated next to the three places shown in Figure 2). Going from the bottom to the top the copper film, the interface IMC layer and the solder layer (with large separate Cu_6Sn_5 precipitates inside) are visible in these cross-sections. Due to tilting of the sample the vertical marker is different from the horizontal one.

or backscattered-electron (BSE) modes of SEM. Various tin-alloy, copper and IMC grains look quite different in these FIB images (Figures 2, 3), due to significantly different ion channeling inside various grains even in the case of the same material (e.g., tin alloy [16]).

Small dotted lines drawn along boundaries of IMC layer (at the alloy/Cu interface) enhance its visibility in the Figure 2a. Due to tilting of the sample the vertical marker is different from the horizontal one.

Cross-section images show three metallic layers above the laminate: a Cu layer at the bottom, a tin-alloy layer on the top and a thin IMC layer between them. The studies revealed a distinct difference between distinguished regions of grid frames and grid fields with respect to the quantity, size and location of IMC precipitates within the solder layer (Figures 2 and 3). Although in the region of grid frames even long Cu_6Sn_5 protrusions extended into the solder layer from the IMC layer (i.e., situated at the interface between the layers of tin-alloy and copper), but only small IMC precipitates (with a sub-micrometer diameter) were observable inside the solder layer(i.e., without a direct contact with the IMC layer), as shown in Figures 2a,b.

In contrast, in the region of grid fields much bigger IMC precipitates (with diameters even in the range 5-8 µm) were observed inside the solder layer, without a direct contact with the IMC layer and close to the solder top surface (Figures 3a,b). In many cases densely distributed round-shaped Cu_6Sn_5 precipitates with diameters from one to several micrometers even reached the top surface of the tin alloy and these were observable at close distances from each other (Figure 4). The occurrence of IMC precipitates on solder surfaces has been observed previously [17].

Numerous previous observations have shown and discussed IMC protrusions extending from the IMC layer into the solder layer as well as have shown IMC precipitates located within the solder layer and positioned along grain boundaries [18, 19]. However, in our investigations (as well as observations in some other studies [20]) Cu_6Sn_5 precipitates were found not only along grain boundaries but also inside the solder grains, i.e., without a visible contact with grain boundaries (Figures 2, 3 and 5). Separate Cu_6Sn_5 precipitates were also observed even inside some whisker crystals (Figure 5), confirming that during their upward migration IMCs can penetrate into various grains. It can also be seen in this figure that the density of IMC precipitates in the solder increases closer to the whisker.

Generally, during the soldering operation, material from the metal sublayer dissolves and mixes with the solder, allowing the formation of IMCs. In alloys consisting of Sn and Cu, two different phases of IMCs may be present: Cu_6Sn_5 and Cu_3Sn. Especially the formation of a Cu_6Sn_5 phase (because of its large-volume expansion in comparison with the pure tin) is a strong factor promoting whisker growth in the neighboring alloy [3]. Our EDXS measurements revealed a content of about 39 wt.% Cu in the IMC layer at the interface between copper and tin-alloy layers, i.e. measurably equal to the Cu content in the Cu_6Sn_5 layer. The same content of about 39 wt.% Cu was found for all measured IMC precipitates observed within the tin-alloy layer, confirming that they also constituted a Cu_6Sn_5 phase. In contrast, the content of Cu in another possible Cu-Sn IMC phase (i.e., Cu_3Sn) would

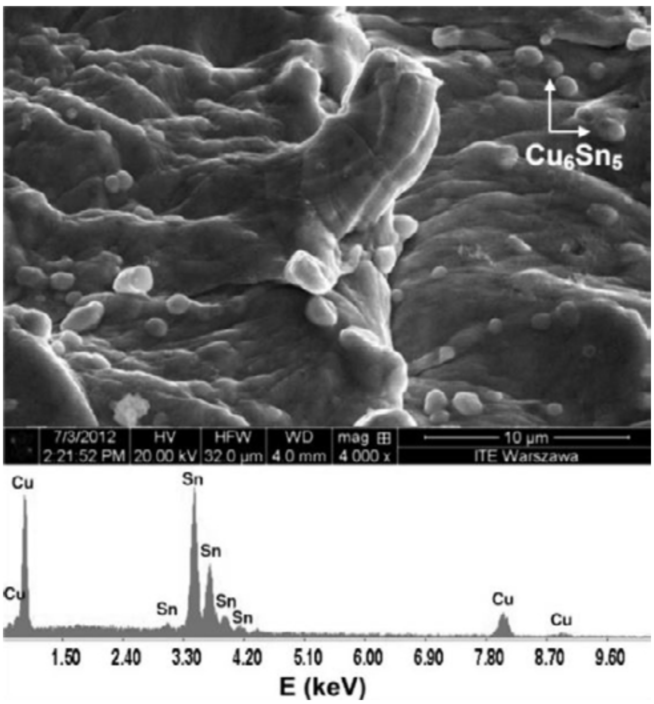


Figure 4: SEM image of a single whisker. Densely distributed round-shaped Cu_6Sn_5 precipitates at the top surface of the tin alloy at the grid field are visible close to the whisker apparent in the center of the image. EDXS spectrum (obtained at electron energy 15 keV) of an example precipitate is shown below.

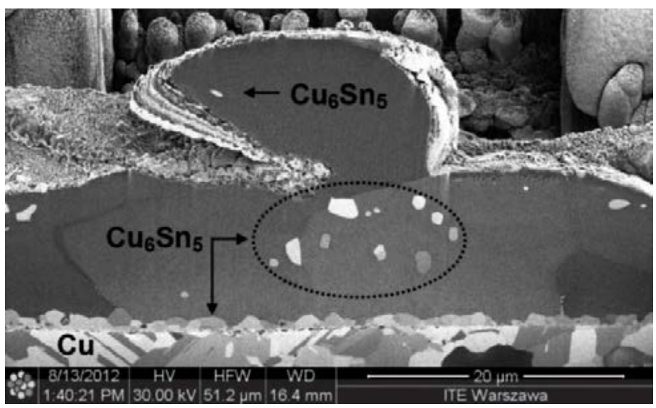


Figure 5: Scanning ion microscopy image of a cross-section with a whisker grown in the grid-frame region. An increased density of Cu_6Sn_5 precipitates in the tin-alloy solder close to the whisker base and a small separate Cu_6Sn_5 precipitate inside the whisker are seen.

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be equal to above 60 wt.% Cu, much higher than revealed in our measurements.

In contrast, no distinguishable difference in the shape of the interface IMC layer was observed between the two regions (of the grid frame and of grid fields, see Figures 2 and 3). This means that the spatial non-uniformity caused by the regular structure of glass fibers and resin regions in the top layer of a glass-epoxy laminate also promotes spatial non-uniformity of the IMC-precipitate distribution within the solder layer, often close to its top surface. This effect seems to constitute an additional factor for the apparent non-uniformity of whisker growth.

Thick solder layers (significantly more than 10 μm) were applied in samples to ensure their resistance to whisker growth. Cross-sections performed in regions adjacent to grid frames and grid fields show that the thickness of tin alloy in the frame regions is significantly lower than in the field regions, e.g., equals about 13 μm at the grid frame (Figure 2a) while about 18 μm in the adjacent regions of grid fields (Figures 3a,b). The calculation of alloy thickness takes into account that the studied samples were tilted during observations in the microscope chamber. Thus markers shown in Figures 2, 3 and 5 represent horizontal dimensions, while the vertical dimensions are underestimated and therefore their multiplication by the tilt angle secant is required (i.e., by 1.24, because the tilt angle equals 36° there).

Whisker growth depends on many factors with an impact of one factor being distinguishable only when other important factors are fixed. Although a thinner (if not very thin) solder is considered to be more prone to whisker growth [7-10], the mentioned additional factors related to the compressive stress have forced an absence of whiskers in grid frame regions (with thinner solder), and their presence in regions of grid fields (with thicker solder).

Much higher thermal expansion coefficient of the resin than of the glass fiber causes the resin to expand and shrink more than the glass fiber during tests performed with a cyclic temperature range of -45°C to +85°C. A nonuniform expansion of the top area of the glass-epoxy laminate occurs in its longisection, as well as in its cross-section. It may be expected that alongside differences in compressive stress in adjacent regions, the layers in various regions will be differently affected mechanically, shifted and pushed up during temperature cycles.

"Whisker growth depends on many factors with an impact of one factor being distinguishable only when other important factors are fixed."

The observed non-uniform spatial distribution of IMC precipitates seems to occur due to differences in mechanical interactions and compressive stress in various regions, while the presence of IMCs is a driving force for whisker growth. Therefore, it may be expected that CTE differences in various regions of PCBs with tin-alloy on glass-epoxy laminate facilitate spatially non-uniform whisker growth in two ways, directly by the implemented compressive stress and indirectly by the generation of non-uniform IMC distribution.

Summary

Whisker growth on the surface of tin alloys soldered above a glass-epoxy laminate was studied (i.e., for the most widely used PCB substrate material). The structure of the glass-epoxy laminate surface has a spatial non-uniformity caused by the regular structure of glass fibers and resin regions in the top layer of the laminate. Therefore, the local compressive stress in the solder layer due to differences in the thermal expansion of the resin and glass fiber promotes whisker growth in the area of the alloy soldered on the Cu layer over the glass fiber.

Scanning ion microscopy using the FIB system and EDXS performed after standard reliability tests determined a strong correlation between the structure of glass-epoxy laminate, the spatial distribution of IMCs and whisker growth. In the region of grid frames only small IMC precipitates were observable inside the solder layer (i.e., without a direct contact with the IMC layer situated at the interface between the tin-alloy and Cu layers). In contrast, in the region of grid fields much bigger IMC precipitates were observed inside the solder layer, without a contact with the IMC layer and close to the solder top surface. Densely distributed round-shaped Cu_6Sn_5 precipitates with diameters from one to several micrometers also reached the top surface of solder in many places.

It can be concluded that CTE differences of various PCB regions with tin alloys on glass-epoxy laminate facilitate spatially non-uniform whisker growth directly by the non-uniform compressive stress and indirectly by the generation of a non-uniform spatial distribution of IMCs. **SMT**

Acknowledgements

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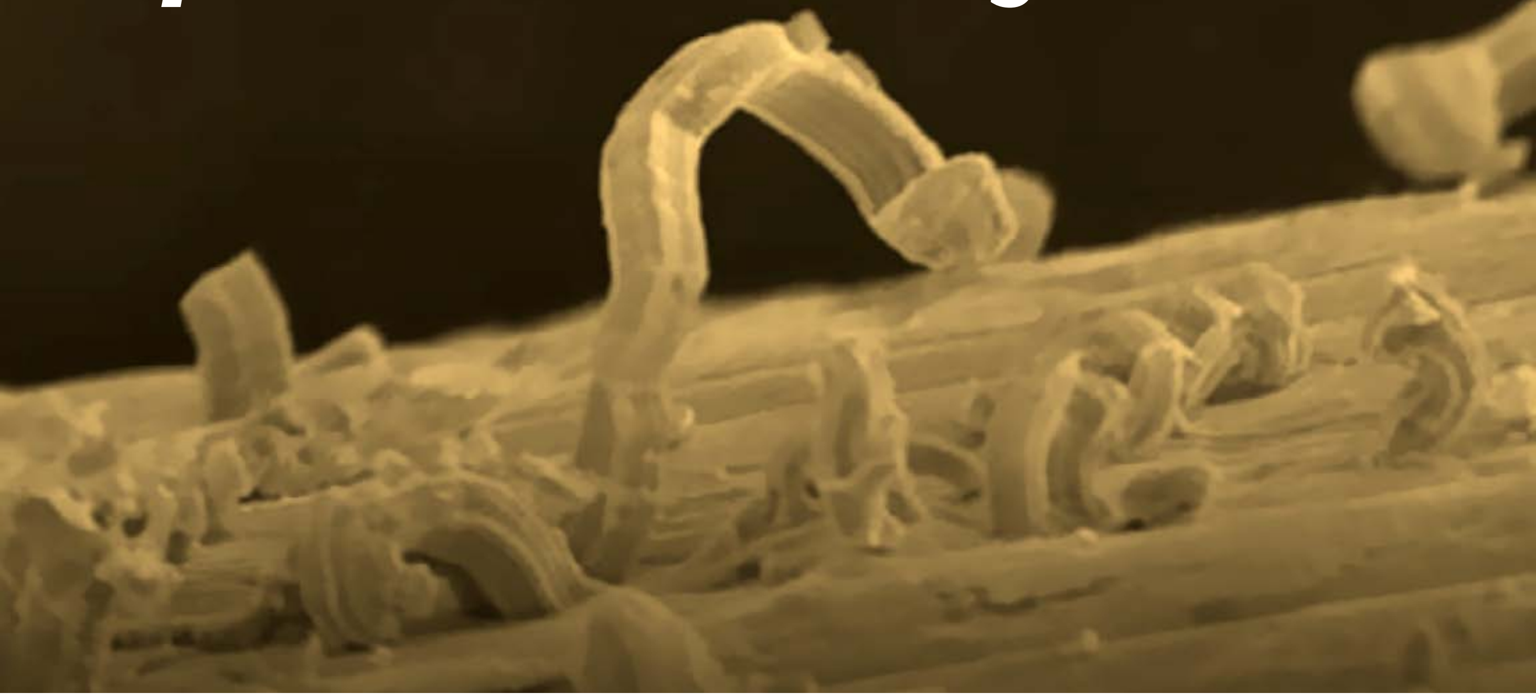
FEATURE

Tin Whisker Risk Management by Conformal Coating



by Linda Woody and William Fox
LOCKHEED MARTIN MISSILES AND FIRE CONTROL

Abstract

The objective of this study is to evaluate conformal coatings for mitigation of tin whisker growth. The conformal coatings chosen for the experiment are acrylic, polyurethane and parylene. The coatings were applied in thicknesses ranging from 0.5 to 3.0 mils on 198 bright tin plated coupons with a base metal of either Copper C110 or Alloy 42. Prior to coating, light scratches were applied to a portion of the coupons, and a second fraction of the coupons were bent at 45° angles to provide sources of stress thought to be a possible initiating factor in tin whisker growth. The coupons have been subjected to an environment of 50°C with 50% relative humidity for 9.5 years. Throughout the trial period, the samples were inspected by both optical and scanning electron microscopy for tin whisker formation and penetration out of the coatings by tin whiskers. Tin whiskers were observed on each coupon included in the test, with stressed regions of the bent samples demonstrating significantly higher tin whisker densities. In addition, the Alloy 42 base metal samples showed greater tin whisker densities than the Copper C110 base metal samples. There were no observable instances of tin whisker penetration out of the coatings or tenting of the conformal coat materials for any of the non-stressed test coupons. The stressed coupons demonstrated tin whisker protrusion of the 1.0 and 2.0 mil thick acrylic coating and the 1.0 mil polyurethane coating for the Alloy 42 base metal samples. The greater thickness coatings did not demonstrate tenting or tin whisker protrusion. Also included in this paper are tin whisker inspection results of tin-plated braiding and wire that was exposed to an environment of 50°C with 50% relative humidity for over five years.

Introduction

A tin whisker is a spontaneous growth of a tin crystal from tin-finished surfaces. The crystal often grows in a needle-like form, and due to the electrical conductivity of the anomaly,

there is a resulting risk of current leakage and shorting due to bridging of adjacent conductors. There have been multiple studies into the mechanisms for whisker growth and both environmental and mechanical factors that may promote whisker growth[1-5].

Similarly there have been multiple studies on methods for mitigating tin whisker growth[6,7]. Mathew et al. reviewed research into mitigation strategies such as conformal coating, electroplating techniques, surface treatments, alloying tin, use of various under-plates and annealing of tin[6].

The conformal coating mitigation strategy has shown multiple results using various coating materials and environmental storage conditions. NASA studies[8-10] indicated that bright tin plated brass coupons, conformal coated with a uralane-based material, was able to prevent tin whisker protrusion following nine years of ambient storage when the coating thickness was at least 2.0 mils. If the coating was thinner, there were observations of tin whisker protrusions.

Woodrow and Ledbury released two papers[11,12] examining tin whisker growth through multiple conformal coating materials. Both studies used bright tin plated brass test coupons. For the first study, when the test coupons were subjected to an environmental chamber set to 50°C with 50% relative humidity (RH), tin whisker penetration was noted after approximately one year for coatings of 1.5 mils and less, but not for coatings of at least 3.9 mils. For the second study, the conformal coatings examined were urethane-acrylic hybrid, silicone, acrylic and parylene. The test coupons were subjected to an environmental chamber set to 25°C with 97% RH. All of the test coupons exhibited tin whisker penetration of the conformal coatings, even on samples with up to 6.0 mils of coating.

The University of Maryland's Center for Advanced Life Cycle Engineering (CALCE) has studied the interfacial strength of conformal coatings in comparison to the whisker buckling force[13] initially presented by Kadesch and Leidecker[8]. Preliminary testing indicated that conformal coatings of 25 microns (approximately 1.0 mil) or less with a modulus of 100MPa or less are at risk of tin whisker penetration. Nakagawa et al. similarly identified harder coatings with high adhesion strengths as the most likely materials to prevent tin whisker protrusion[14].

Han et al. review the effectiveness of conformal coatings as a tin whisker mitigator on actual circuit cards and determined that coating coverage is an essential factor[15]. As the coating thinned along the edges of component leads, the potential for tin whiskers to protrude through the coating, regardless of the coating type increased dramatically. This was confirmed by the NPL's Hunt and Wickham who designed a test vehicle to determine the propensity of whiskers to grow through coatings and contact a neighboring plate[16].

"Reviewing the multiple studies on the use of conformal coatings as a mitigation technique for tin whiskers indicates that tin whiskers can grow through a coating. One of the leading factors for the risk of a protrusion through a coating is the thickness."

Reviewing the multiple studies on the use of conformal coatings as a mitigation technique for tin whiskers indicates that tin whiskers can grow through a coating. One of the leading factors for the risk of a protrusion through a coating is the thickness. Coating thicknesses below 2.0 mils appear to present a greater risk of tin whisker penetration, although extreme environmental conditions coupled with the type of tin plating could promote tin whisker growth through any type of coating at relatively large coating thicknesses.

This company conformal coats 99% of all circuit boards using one of three different conformal coating materials: acrylic, polyurethane and parylene. This study examined the effects of tin whisker growth on the three coatings applied to test coupons at varying thicknesses.

Acrylic conformal coatings are perhaps the most popular of all conformal coating materials due to their ease of application, removal and forgiving nature[17]. Acrylics dry rapidly, reaching optimum physical properties in minutes, are fungus resistant and provide long pot life. Additionally, acrylics give off little or no heat during cure eliminating potential damage to heat-sensitive components. They do not shrink during cure and have good humidity resistance and exhibit low glass transition temperatures.

Polyurethane coatings are available as either single or two-component formulations[14]. Both formulations provide excellent humidity resistance and far greater chemical resistance than acrylic coatings. Single component polyurethanes, while easy to apply, enjoy long pot life but sometimes require very lengthy cure cycles to achieve full or optimum cure. Two component formulations can reach optimum cure properties in as little as one to three hours with the assistance of heat. However, when compared to single component formulations, two-component formulas can have a relatively short pot life sometimes making them difficult to work with. Since polyurethanes are polymerized and cross-linked in place, they have excellent resistance to chemicals, moisture and solvents. They are available in tough, abrasion-resistant varieties and also in low modulus varieties for extreme temperature ranges. Polyurethanes have good adhesion to most materials and provide for a robust coating process. The material is difficult to remove following cure except by thermal or mechanical means.

The parylene coating is chemically inert and moisture resistant[14]. Very thin, uniform layers can be applied to the surface with no pinholes or voids. Parylene coating has a high dielectric strength. Due to the nature of the deposition process used to apply the coating, there are no volatiles generated. Parlylene coatings are extremely low weight and yet have the highest modulus of the three coatings being examined. The coating process must be performed in batch mode, using specialized coating equipment. Rework is difficult, and a microabrasion process is usually required to remove the coating.

The spray process used at the company for application of the acrylic and polyurethane coatings is automated with a rotating spray head. The motion of the head is designed to cover a given width from all angles. Masking is required to keep coating out of areas that should not be coated.

Parylene is applied at room temperature with deposition equipment that controls the coating rate and ultimate thickness. Polymer deposition takes place at the molecular level in three stages. The raw material dimer is vaporized under vacuum and heated to a dimeric gas. The gas is then pyrolized to cleave the dimer to its monomeric form. In the room temperature deposition chamber, the monomer gas deposits as a transparent polymer film.

In addition to tin whisker growth on component leads and coatings, the risk of tin whisker growth on braiding and wires is also of concern. Hillman et al. indicated a low risk for tin coated copper wire, braid and cable following exposure of samples to 85°C and 85% relative humidity[18].

Scope and Objective

This study was designed to examine the effects of tin whisker growth on the three coatings, applied to test coupons at varying thicknesses. In addition, the tin whisker growth on braiding, stranded wire and solid single strand wire with pure tin coating was also monitored to determine the risk of use in high-reliability products.

Examination of Conformal Coating as a Mitigating Material for Tin Whisker Growth

Test coupons consisting of two types of base material (Copper C110 alloy and Alloy 42) were electrodeposited with a layer of "bright tin" plating. Copper C110 and Alloy 42 are common base metals utilized for component leads. After plating and prior to conformal coating a quantity of the plated coupons were scratched to simulate those found during handling and shipping conditions, and another quantity of plated coupons were bent (without scratches) to induce tensile and compressive stresses on the plating. All of the test coupons were then conformal coated on approximately half of the surface with the other half remaining uncoated. The coupons were masked, coated, and then demasked to ensure the coating thickness was uniform and there was no thinning at the edges. The test coupons were placed in an environmentally controlled temperature / humidity chamber to promote the growth of the tin whiskers.

At specific time intervals, a sampling of test coupons were removed from the temperature / humidity chamber and evaluated for tin whisker growth on the plated and uncoated surfaces versus the plated and conformal coated surfaces. Data samples were collected and examined under high magnification, photomicrographs, or scanning electron micrographs. Energy dispersive spectroscopy (EDS) analysis also provided metallurgy to confirm anomalies as tin whiskers. All data collected was documented, logged and charted to show whisker growth and other variations.

The test had three primary objectives:

1. Grow tin whiskers on the bright tin plated test coupons.
2. Provide positive evidence that conformal coating, over a bright tin plated coupon protects against tin whiskers through growth reduction, abatement or containment.
3. Evaluate the different conformal coating materials and thicknesses to evaluate which materials and coating thicknesses provide the best protection against tin whisker growth.

Examination of Tin Whisker Growth Risk for Tin-Coated Braiding, Stranded Wire and Solid Single Strand Wire

Three samples each of pure tin coated braiding, stranded wire and solid single strand wire were taken directly from stock reels manufactured in 2008. The samples were inspected for the presence of tin whiskers using optical microscopy and scanning electron microscopy prior to exposure to an environmentally controlled temperature/humidity chamber to promote the growth of the tin whiskers. Following five years of exposure, the samples were removed from the temperature/humidity chamber and evaluated again for the presence of tin whiskers.

The primary objective of the testing was to determine if the typical pure tin coating present on braiding and wire would grow tin whiskers of the size capable of causing electrical failure to an assembly.

Procedure and Materials

Examination of Conformal Coating as a Mitigating Material for Tin Whisker Growth

A diagrammed outline of the test coupon preparation procedure is shown in Figure 1. The test coupons measured 1in x 4in x 0.032in. The bright tin coating was applied to the test coupons by electrodeposition according to ASTM B545. The thickness of the tin coating was 215-225µin. The test coupons were supplied and tin plated by Alexandria Metal Finishers. There were a total of 99 coupons with the Copper C110 base metal and 99 coupons with the Alloy 42 base metal.

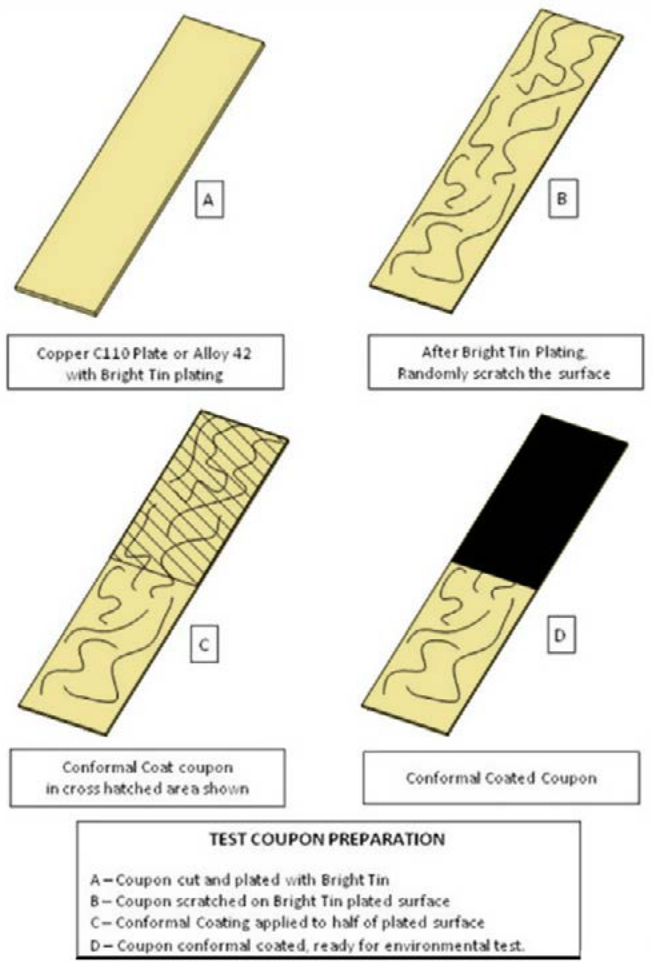


Figure 1: Test coupon preparation procedure.

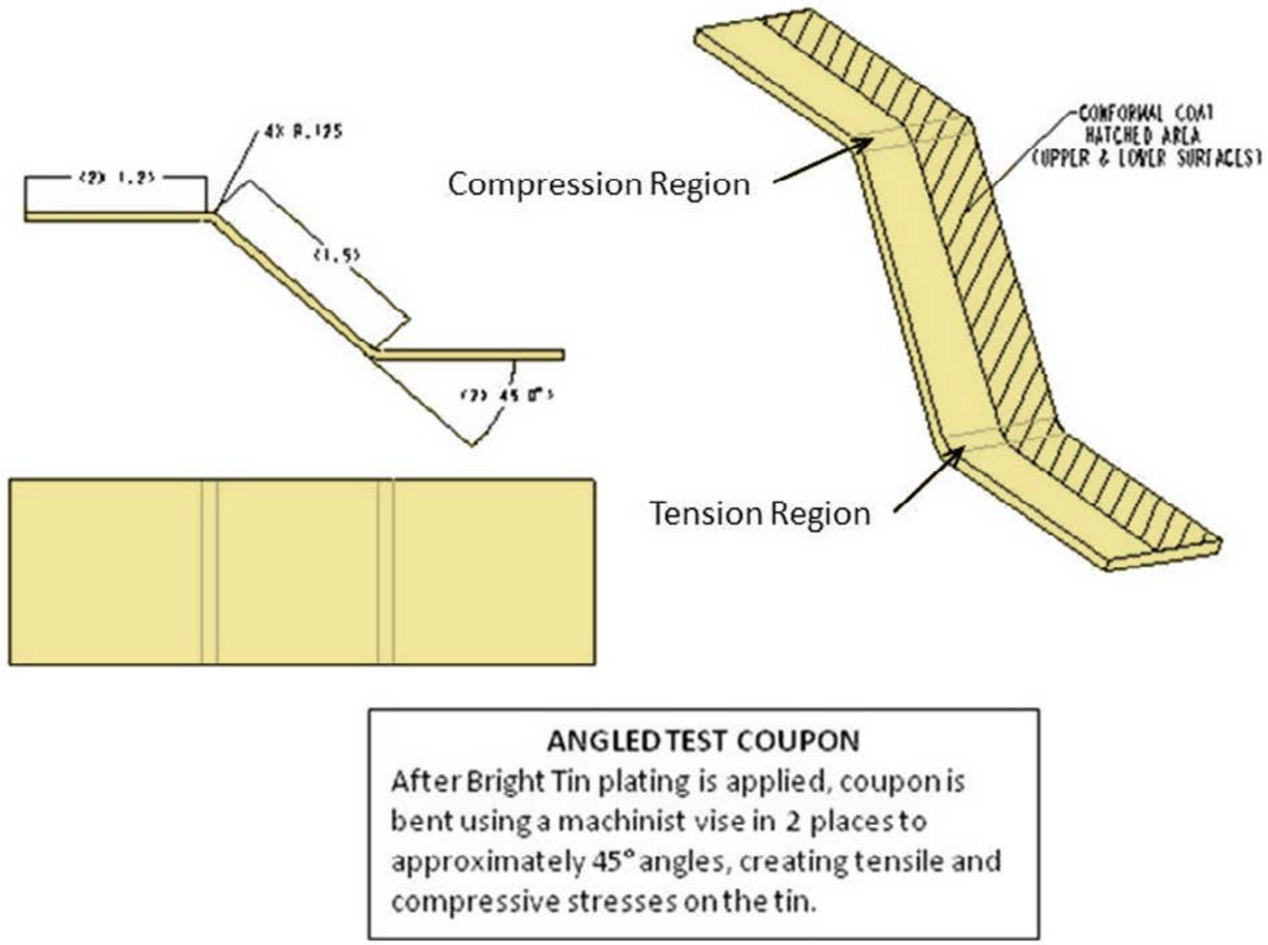


Figure 2: Drawing of bent test coupons. (Note: For the bent test coupons, the regions of compression and tension in the tin plating, caused through relaxation of the material following the bending process are identified in the schematic.)

Following the plating process, 69 Copper C110 base metal coupons and 69 Alloy 42 base metal coupons were scratched along the surface. Brown paper wrapping material was cut in sheet sizes approximately 8.5in x 11in, wrinkled by "balling and crushing" and then unraveled and flattened. Each coupon was separately wrapped (one sheet/coupon), then individually laid on a hard surface (i.e., tabletop) and shuffled around several times on each of the flat sides thereby randomly creating light scratches on the tin surface. These scratches were intended to simulate those found on the surface of component leads as a result of shipping and handling. The typical light scratch created by this method was photo documented.

Also following the plating process, 30 copper C110 base metal coupons and 30 Alloy 42 base metal coupons had a 45° bend placed in 2 places as shown in Figure 2 using a machine vise with appropriate protection applied to the jaws of the vise (i.e., Teflon tape or equivalent). This bend was intended to put the tin plating under stress. Necessary precautions were taken to protect the transfer of metal to the tin plating during the bending process. These coupons do not have scratches in the tin plated surfaces.

The conformal coatings used in the testing were acrylic per MIL-C-46058, Type AR, polyurethane per MIL-C-46058, Type UR, and parylene per MIL-C-46058, type XY. Table 1 includes mechanical properties of the coatings

Property	Test Method	Conformal Coating		
		Acrylic Type AR	Polyurethane Type UR	Parylene Type XY
Young's Modulus (psi)	ASTM D882	11,600	13,000	400,000
Elongation to Break (%)	ASTM D882		100-1000	200
Water Absorption (% after 24 hours)	ASTM D570	0.3	0.02-1.50	<0.1
Hardness	ASTM D785	M68-M105	10A-25D	R80
Dielectric Strength (V/mil)	ASTM D149	3,500	3,500	5,600

Table 1: Properties of confomal coatings used in testing. (Note: Properties from material technical data sheets.)

used in the testing. The application thickness of the coatings was 1.0, 2.0 or 3.0 mils for the acrylic and polyurethane coating and 0.5 mils for the parylene coating.

Prior to the coating process, the samples were cleaned using the existing in-line cleaner and then baked at 85°C for two hours. The appropriate areas of the coupons were masked using tape. The acrylic and polyurethane coatings were applied using a spray coat process and the parylene coating was applied using a vapor deposition process. All test coupons were coated by the company. The samples were labeled according to Table 2.

Following the conformal coating of the test coupons, and a visual inspection to insure continuity of the coating as well as a measurement of the coating thickness on approximately ten samples to insure that the proper coating thicknesses were applied, the samples were placed in an environmental chamber. The environmental chamber was capable of maintaining a temperature of 50° ± 10°C and a relative humidity of 50% ± 15%. The oven was equipped with a fail-safe device to ensure against overheating. The internal working envelope of the environmental chamber was 16in x 16in x

Coupon Base Material	Conformal Coating	Coating Thickness	Number of Coupons
Samples below were scratched along the surface prior to coating			
Copper C110 (scratched)	None – Bare	NA	5
	Acrylic	1.0	8
		2.0	8
		3.0	8
	Polyurethane	1.0	10
		2.0	10
		3.0	10
	Parylene	0.5	10
			Total Coupons: 69
Alloy 42 (scratched)	None – Bare	NA	5
	Acrylic	1.0	8
		2.0	8
		3.0	8
	Polyurethane	1.0	10
		2.0	10
		3.0	10
	Parylene	0.5	10
			Total Coupons: 69
Samples below angled 45° to stress the bright tin plating			
Copper C110 (bent)	Acrylic	1.0	5
		2.0	5
		3.0	5
	Polyurethane	1.0	5
		2.0	5
		3.0	5
Alloy 42 (bent)	Acrylic	1.0	5
		2.0	5
		3.0	5
	Polyurethane	1.0	5
		2.0	5
		3.0	5
Total Coupons: 60			

Test coupon size prior to plating: 1in x 4in x 0.032 in

Plating: Electrodeposited bright tin (per ASTM B545); thickness 215-222µin 1.0mil = 0.001in = 25.4µm

Table 2: Test coupon matrix.

12in. The temperature and humidity was continually monitored by an electronic recording device. The date of the initial insertion of the coupons into the environmental chamber was June 15, 2004.

On one occasion during the last quarter of each year, a sample of test coupons was removed from the environmental chamber and inspected. The inspection consisted first of optical microscopy, using the indirect light procedures described on the 'NASA Tin Whisker Homepage' website [19]. Anomalies in the integrity of the conformal coating were noted, and any areas with suspect tin whisker growth were noted and inspected further using scanning electron microscopy. SEM was also used on the areas of the test coupons without conformal coating to determine the length and density of tin whiskers.

Examination of Tin Whisker Growth Risk for Tin-Coated Braiding, Stranded Wire and Solid Single Strand Wire

Three samples each of braiding, stranded wire and solid single strand wire were removed directly from stock reels. The braiding selected had a braid length of 4in, an average braid width of 0.172in, an average braid height of 0.029in and a strand quantity of 30. The stranded wire selected conformed to the M22759/34-24-9 specification. The insulation was stripped on each sample to expose approximately 3in of wire. The solid single strand wire selected conformed to the A-A-59551, Type S, 20AWG tin-coated specification. All of the samples examined were manufactured in 2008.

Prior to environmental exposure, the samples were inspected by optical microscopy and scanning electron microscopy for the presence of tin whiskers. The samples were placed in an environmental chamber set to 50° ± 10°C and a relative humidity of 50% ± 15% in September 2008. In September 2013, all of the samples were removed from the environmental chamber and again inspected by optical microscopy and scanning electron microscopy for the presence of tin whiskers.

Results and Discussion

Examination of Conformal Coating as a Mitigating Material for Tin Whisker Growth

A detailed review of the annual inspection results for the initial 5.5 years of environmental exposure was reported previously[20].

Original inspection of the test coupons following application of the tin plating indicated no observable anomalies in plating integrity (Figure 3). Cross-sections of ten samples confirmed the plating thickness to be between 215 and 225µin. The thickness of the applied conformal coating was confirmed from several previous processing tests run to evaluate processing parameters for required coating thickness. Inspection of the conformal coating integrity indicated no significant anomalies. The coat-

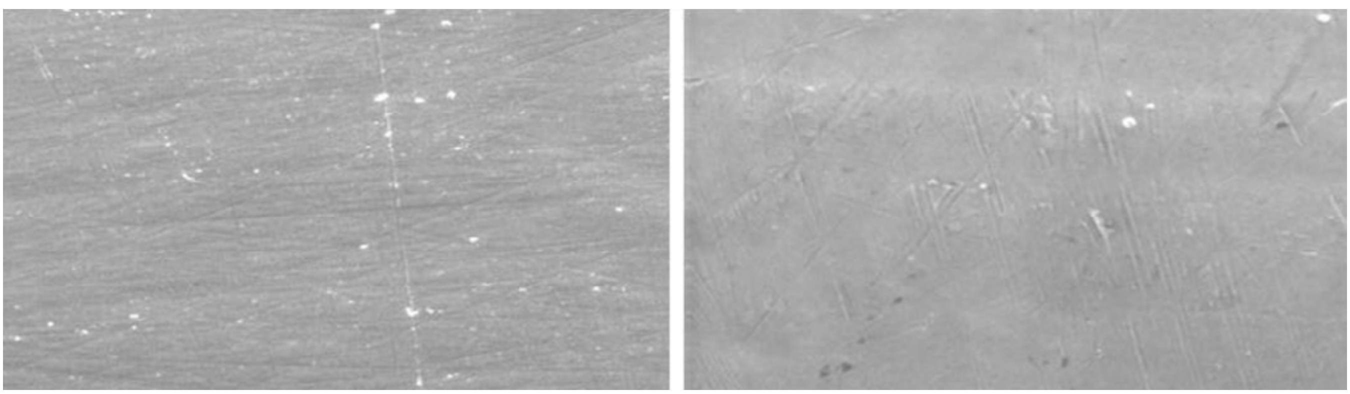


Figure 3: Scanning electron micrographs (800X magnification) demonstrating the condition of the surface of the tin plating prior to conformal coating for both the Copper C110 base metal (left) and Alloy 42 base metal (right).

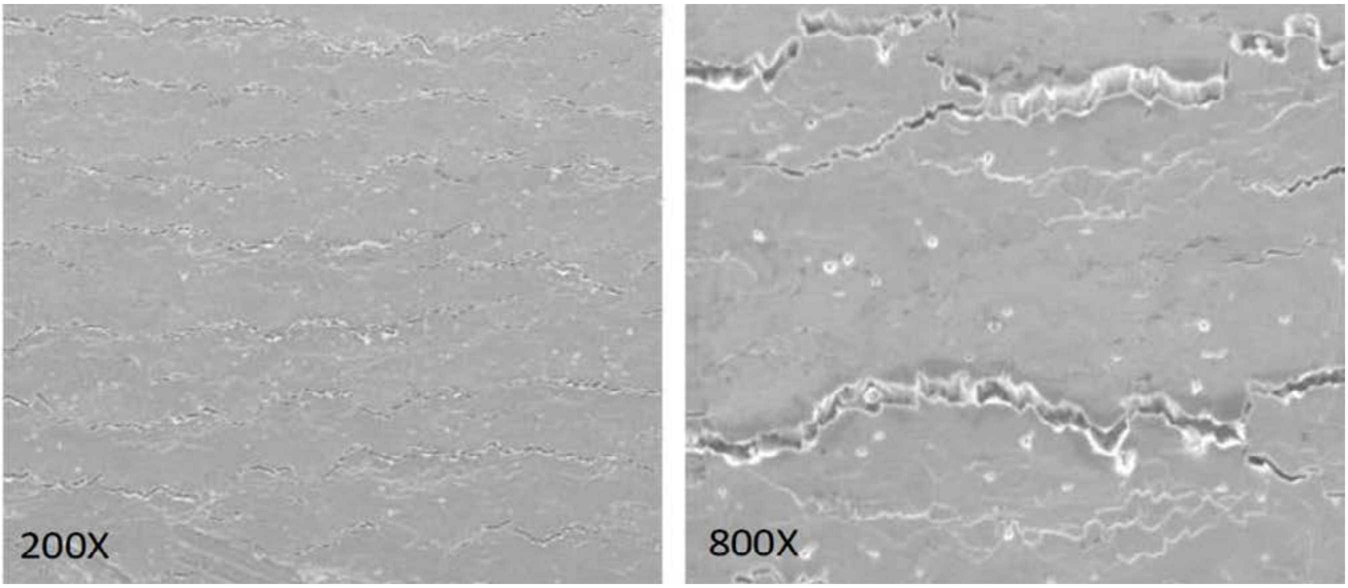


Figure 4: Scanning electron micrographs of the tin plating following the bending process on the Copper C110 base metal.

Sample	Whisker Density (# / mm2)									
	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Copper C110	0	2	5	13	19	26	31	34	36	39
Alloy 42	0	4	11	21	33	47	53	57	60	62
Copper C110 Bent (Compression)	0	3	9	20	29	42	72	101	121	128
Alloy 42 Bent (Compression)	4	38	71	131	212	291	320	336	352	367
Copper C110 Bent (Tension)	0	2	7	16	22	31	40	48	57	59
Alloy 42 Bent (Tension)	3	18	41	74	94	130	161	182	201	213

Table 3: Average tin whisker densities on uncoated regions throughout environmental exposure.

ing thickness at the line of demarcation for the flat samples tended to be slightly less than that for the remainder of the sample but not significantly.

Figure 4 includes scanning electron micrographs of the tin plating on a Copper C110 base metal coupon at the location of the bend prior to conformal coating. There are observable stress cracks in the tin plating caused by the bending process. The tin plating on the Alloy 42 base metal appeared similar.

Inspection Results for Coupons without Conformal Coating

Table 3 includes whisker density values for the uncoated samples for both the Copper C110 base metal and the Alloy 42 base metal on the control samples and on the bent samples for both regions in tension and compression. As of the fourth quarter of 2013 sampling, the whisker density on the Alloy 42 base metal control sample (62 whiskers/mm^2) was greater than that of the whisker density on the Copper C110 base metal control sample (39 whiskers/mm^2). The largest tin whiskers and odd-shaped eruptions observable on the control samples approached 5.0 mils, indicating that whiskers were present with minimum lengths dimensionally capable of extending through the conformal coating thicknesses applied to the test coupons. The effect of the light scratches applied to the surface of the control samples was negligible with no observable pattern of whiskers accumulating along the scratches.

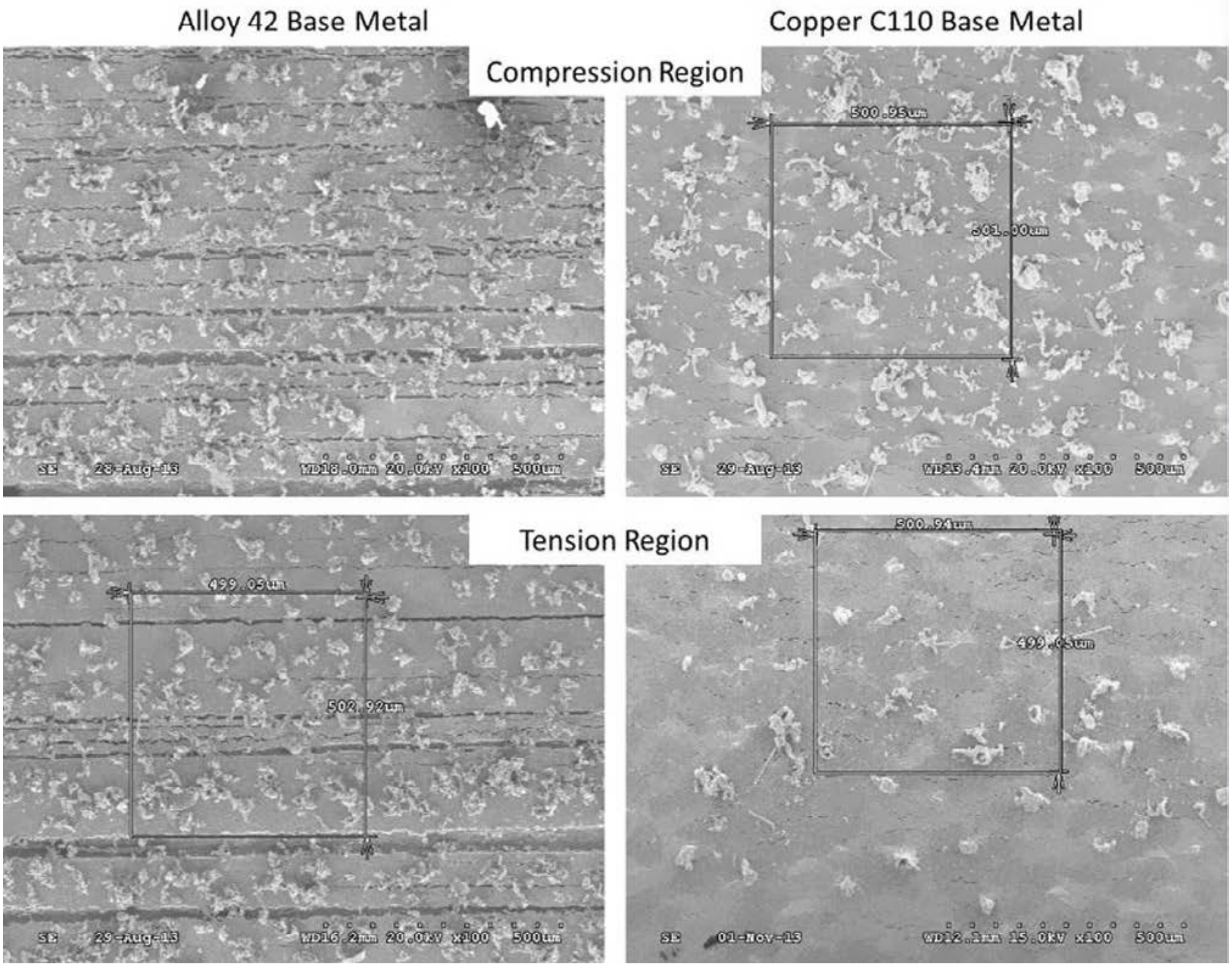


Figure 5: Scanning electron micrographs (100X magnification) demonstrating the density of tin whiskers on the uncoated areas in the compression regions the bent coupons (top two micrographs) and the regions of tension for the bent coupons (bottom two micrographs).

As of the fourth quarter 2013 sampling, the whisker densities in the stressed regions were considerably higher than that for the control samples (Figure 5). The regions in compression exhibited greater whisker densities than the regions in tension for both the Copper C110 and Alloy 42 base metal coupons. The whiskers tended to grow along stress cracks in the tin plating caused by the bending process. The Alloy 42 coupons had significantly greater tin whisker density in both regions of compression (367 whiskers/mm^2) and tension (213 whiskers/mm^2) than that of the bent Copper C110 base metal coupons (128 whiskers/mm^2 in regions of compression and 59 whiskers/mm^2 in regions of tension). The length of tin whiskers growing along the surface of the samples from both base metals approached 8.0 mils (Figure 6).

The observations of the conformal coated test coupons as of the fourth quarter of 2013 are summarized in Table 4.

Inspection Results for Straight, Scratched Coupons with Conformal Coating

There were no observed tin whisker protrusions through any of the conformal coating

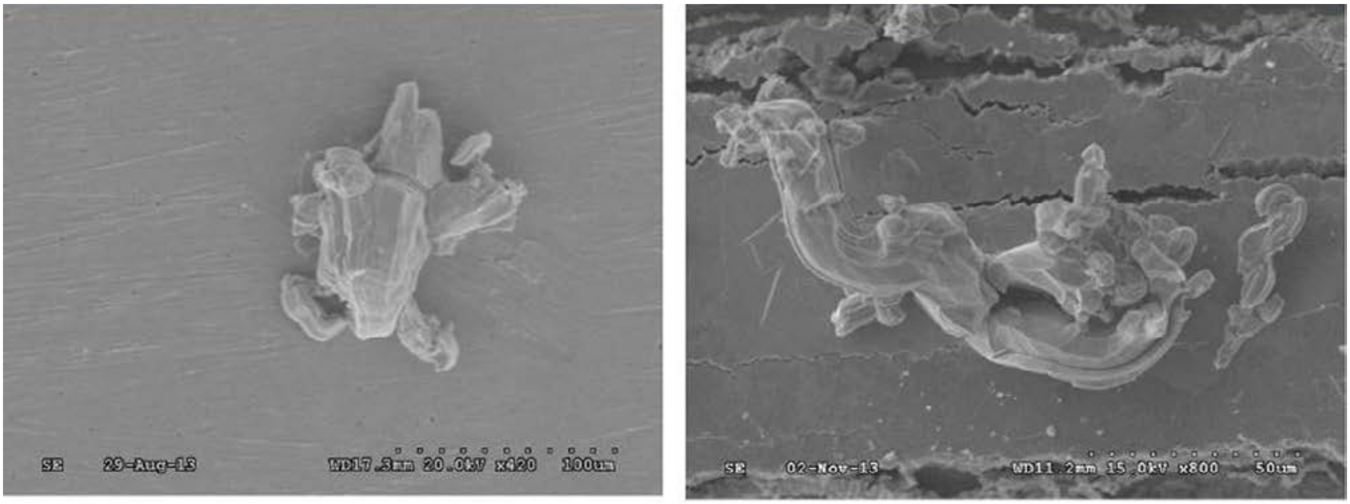


Figure 6: Scanning electron micrographs detailing the appearance of tin whiskers growing on uncoated regions of the bright tin-plated coupons.

materials used on the coupons that were not bent for both base metals (Table 4). In addition, there was no indication of tenting of the conformal coat where a tin whisker may push the coating away from the tin plating. There were tin whiskers or odd-shaped eruptions observed beneath the conformal coating for samples of both base metals and all coating types; however the observed tin whiskers did not cause any disturbance to the conformal coating. The presence of conformal coating over the tin whiskers was confirmed by EDS. Figure 7 includes a scanning electron micrograph detailing the interface of the parylene coating to the uncoated region of one coupon. Tin whiskers are observed growing on the uncoated region of the coupon; however the parylene coating appears undisturbed.

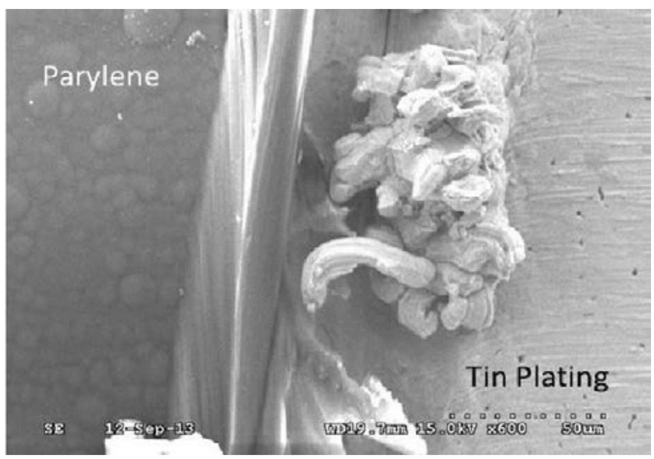


Figure 7: Scanning electron micrograph (600X magnification) detailing the appearance tin whiskers growing on an uncoated region of a coupon adjacent to the parylene coating.

Coupon Base Material	Conformal Coating	Coating Thickness (mils)	Observations
Samples below were scratched along the surface prior to coating			
		1.0	No tenting or tin whisker protrusions
	Acrylic	2.0	No tenting or tin whisker protrusions
		3.0	No tenting or tin whisker protrusions
Copper C110		1.0	No tenting or tin whisker protrusions
	Polyurethane	2.0	No tenting or tin whisker protrusions
		3.0	No tenting or tin whisker protrusions
	Parylene	0.5	No tenting or tin whisker protrusions
		1.0	No tenting or tin whisker protrusions
	Acrylic	2.0	No tenting or tin whisker protrusions
		3.0	No tenting or tin whisker protrusions
Alloy 42		1.0	No tenting or tin whisker protrusions
	Polyurethane	2.0	No tenting or tin whisker protrusions
		3.0	No tenting or tin whisker protrusions
	Parylene	0.5	No tenting or tin whisker protrusions
Samples below angled 45° to stress the bright tin plating			
Copper C110	Acrylic	1.0	Tenting in compression regions initially observed following 5.5 years of exposure; no protrusions.
		2.0	Tenting in compression regions initially observed following 9.5 years of exposure; no protrusions
		3.0	No tenting or tin whisker protrusions
		1.0	No tenting or tin whisker protrusions
	Polyurethane	2.0	No tenting or tin whisker protrusions
		3.0	No tenting or tin whisker protrusions
Alloy 42	Acrylic	1.0	Tin whisker protrusions in compression and tension regions initially observed following 5.5 years of exposure.
		2.0	Tin whisker protrusions in compression regions initially observed following 9.5 years of exposure. Tenting in compression regions initially observed following 9.5 years of exposure; no protrusions.
		3.0	No tenting or tin whisker protrusions
	Polyurethane	1.0	Tin whisker protrusions in compression regions initially observed following 5.5 years of exposure.
		2.0	Tenting in compression regions only initially observed following 9.5 years of exposure.
		3.0	No tenting or tin whisker protrusions

Table 4: Tin whisker observations at end of experiment.

Inspection Results for Bent Coupons with Conformal Coating

There was observable tenting but no tin whisker protrusion of the 1.0 mil and 2.0 mil thick acrylic conformal coating on the regions in compression for the Copper C110 base metal samples during the sampling in the fourth quarter of 2013. There was no indication of tenting or tin whisker protrusion for the 3.0 mil acrylic conformal coating or any of the thicknesses of

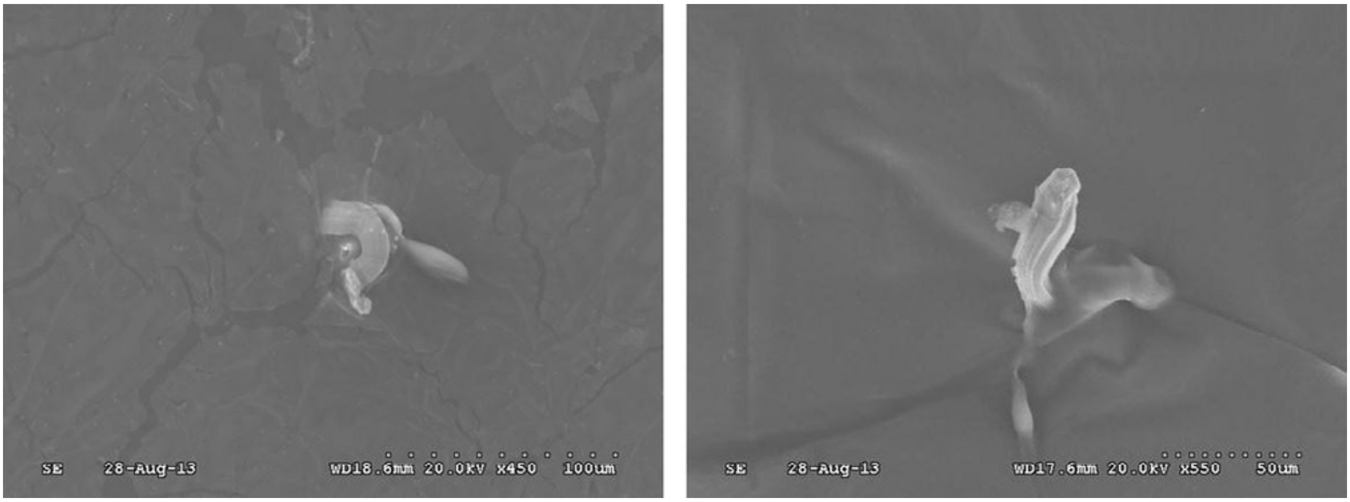


Figure 8: Scanning electron micrographs detailing the appearance of tin whiskers protruding through 2.0 mil thick acrylic coating in the compression region of a bent Alloy 42 base metal coupon.

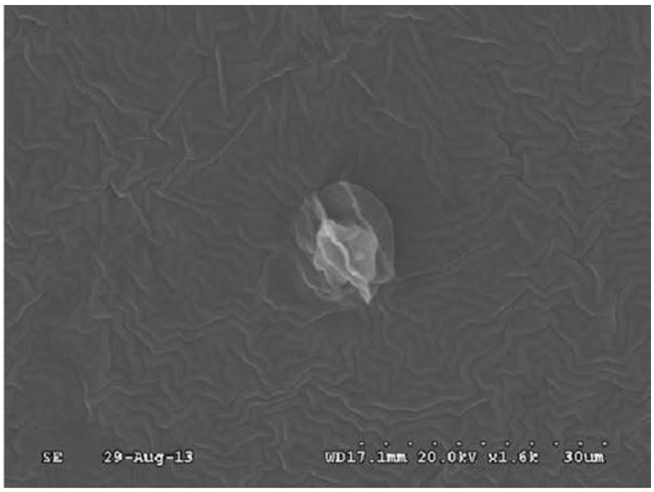


Figure 9: Scanning electron micrograph characteristic of tenting of the 2.0 mil thick polyurethane coating in a region of compression on a bent Alloy 42 base metal coupon.

polyurethane conformal coating. The regions in tension similarly showed no evidence of tenting or tin whisker penetration for any of the coated areas of the Copper C110 base metal samples.

For the bent Alloy 42 base metal samples, there was tin whisker protrusion of both the 1.0 mil thick acrylic and polyurethane conformal coatings in both the regions of compression and tension as reported previously. The Alloy 42 base metal samples with acrylic conformal coating of 2.0 mil thickness exhibited tin whisker protrusion in the compression region (Figure 8), and the Alloy 42 base metal samples with polyurethane coating of 2.0 mil thickness exhibited tenting of the coating in the compression region (Figure 9). The 3.0 mil thick acrylic and polyurethane coatings showed no indication of tenting or tin whisker protrusion in either the tension or compression regions.

Examination of Tin Whisker Growth Risk for Tin-Coated Braiding, Stranded Wire and Solid Single Strand Wire

Following exposure of the samples to a temperature of 50°C and a relative humidity of 50% for five years, the tin coated braiding and the stranded wire exhibited no observable tin whisker growth. For the solid single strand wire, there was a significant concentration of tin whiskers along the surface of all three samples (Figure 10). The longest whiskers present on the surface of the wire measured up to 40µm in length (Figure 11).

Conclusions

The Alloy 42 base metal test coupons exhibited higher tin whisker densities in uncoated regions than that of the Copper C110 base metal test coupons. The stressing of the test coupons by applying a 45° bend in two locations caused a significant increase in tin whisker density for

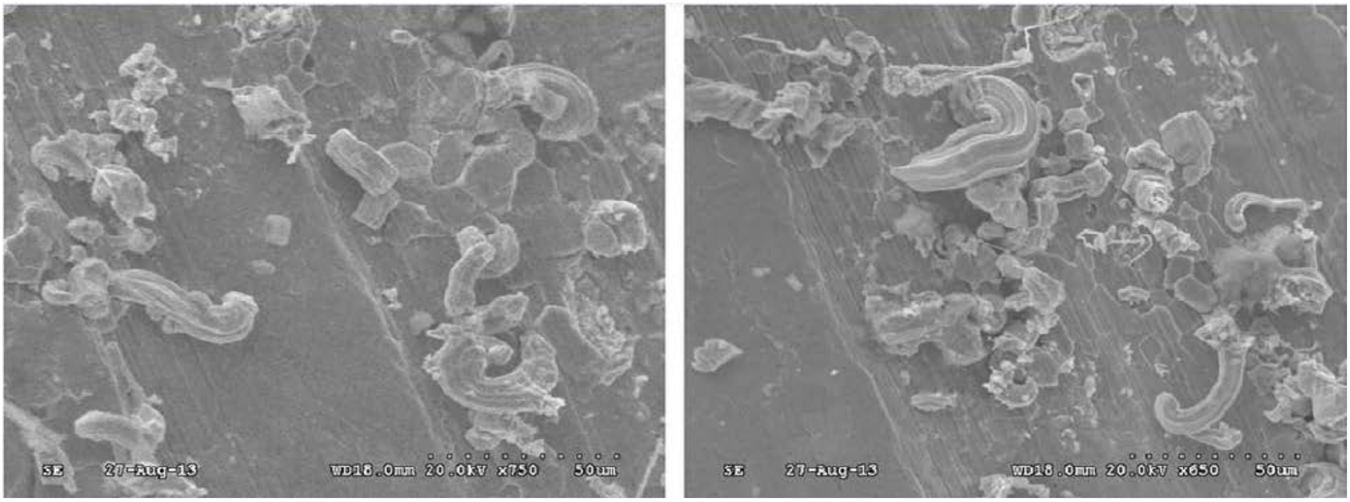


Figure 10: Scanning electron micrographs detailing the concentration of tin whiskers on the surface of tin coated solid singled strand wire following five years of exposure to 50°C / 50% relative humidity.

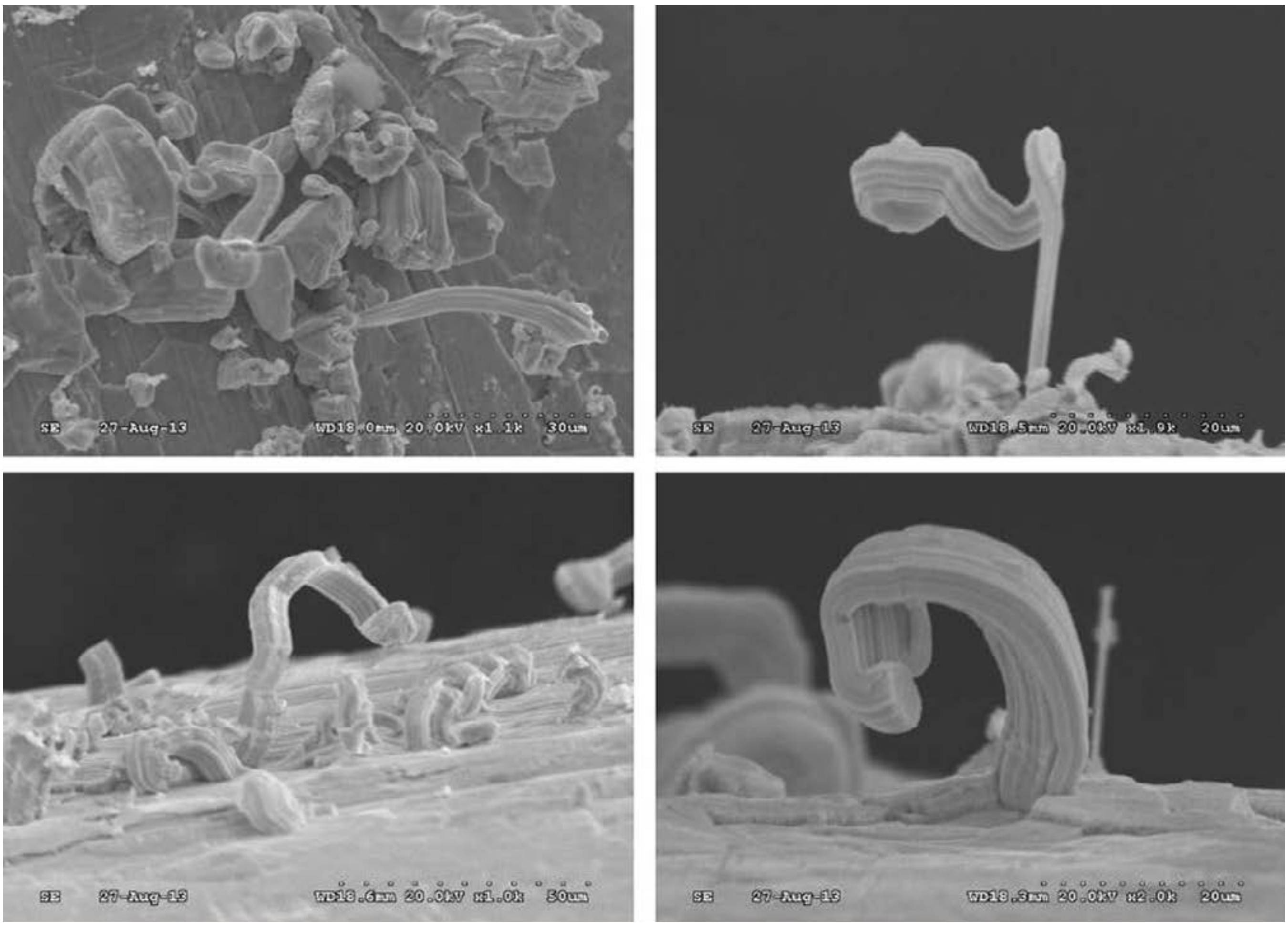


Figure 11: Scanning electron micrographs detailing the characteristic appearance of tin whiskers on the surface of tin coated solid singled strand wire following five years of exposure to 50°C / 50% relative humidity.

both regions of tension and compression. The effect of the bending was noticeably more significant for the Alloy 42 base metal test coupons and the regions of compression had higher whisker density than the regions of tension. The negative effect of Alloy 42 base metal on the propensity of electrodeposited bright tin coatings to whisker has been shown in previous research. In addition, the effect of stressing tin plating resulting in increased tin whisker density has also been previously reported.

The conformal coatings used in this experiment mitigated tin whisker protrusions for the test coupons that were not stressed. Parylene coating at a thickness of 0.5 mils and both acrylic and polyurethane coatings with a minimum thickness of 1.0 mils did not exhibit any tenting following the 9.5 years of environmental exposure to 50°C and 50% RH.

Tenting was observable on the 1.0 and 2.0 mil thick acrylic coating in regions of compression for the bent Copper C110 base metal samples; however there were no indications of tin whisker protrusions. There was no disruption of the polyurethane coating of any thickness for the bent Copper C110 base metal samples.

For the Alloy 42 base metal samples, in addition to the tin whisker protrusion in the tension and compression regions for the 1.0 mil thick acrylic coating reported after 5.5 years, there was tin whisker protrusion of the 2.0 mil thick acrylic coating in the compression regions observed initially after 9.5 years. The 2.0 mil thick acrylic coating also exhibited tenting due to tin whisker growth in the tension regions. While there was observable tin whisker protrusions through the 1.0 mil thick polyurethane coating in regions of tension and compression for the bent Alloy 42 base metal samples, there was no observable tin whisker protrusions through the 2.0 mil thick polyurethane coating. The 2.0 mil thick polyurethane coating did exhibit tenting only in the compression regions, initially observed after 9.5 years. The improved tin whisker mitigation with thicker conformal coating is in agreement with the CALCE study stating that coatings of 1.0 mils and thickness and low modulus are at risk for tin whisker penetration.

The conformal coating materials used in this testing mitigated the growth of tin whiskers through the coating for this specific electrodeposited tin plating and this specific environmental exposure when there were no additional stresses applied to the coupons. It should be noted that the tin plating selected and applied during this experiment were intentionally designed to promote the growth of tin whiskers and would not normally be considered as an acceptable plating for component leads of real hardware. Parylene, which has a significantly higher modulus demonstrated in this experiment the ability to mitigate tin whiskers at a thickness of 0.5 mils; however there were no stressed (bent) samples for parylene. The bent samples indicate that stressed regions of tin plating will have a greater tendency to whisker. Additional testing on real world component leads mounted to circuit cards is warranted to determine minimum requirements for each coating type.

For the tin coated braiding and stranded wire subjected to temperature and humidity exposure, there was no observable tin whisker growth on the surface following five years of exposure. The lack of observed tin whiskers may be due to the minimal thickness of the tin coating and the lack of stressed regions within the strands. In addition, the thin tin coating may have been consumed by the tin-copper intermetallic layer relatively quickly following manufacturing, resulting in the reduced risk of tin whisker formation. The braiding and stranded wire products should be considered acceptable for use in high-reliability assemblies without having to add mitigation steps to reduce the risk of tin whisker growth.

The tin coated single strand wire did exhibit a high concentration of tin whisker growth with whiskers measured up to 40µ in length. This does comply with the JESD201 maximum tin whisker length for Class 2 hardware; however the presence of tin whiskers is not allowable for JESD201 Class 3 hardware. While the JESD201 specification is not accepted industry-wide, the observed presence of tin whiskers on the tin coated single strand wire indicates that further analysis may be required to insure that the potential growth of tin whiskers on the product is accounted for in design and building of hardware. **SMT**

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William Fox is the lead materials engineer for the Lockheed Martin Ocala Advanced Services Laboratory focusing on failure analysis and process and materials development. He has authored or co-authored nine technical papers including papers on mixed-metal alloy soldering processes and properties and tin whisker mitigation and analysis.

Mil/Aero007 News Highlights

Flextronics Nets Contract from Aviage Systems

Flextronics has been selected by Aviage Systems to manufacture Integrated Modular Avionics (IMA) cabinet units to support commercial aircraft programs in China.

Delta Boosts Military Capability with Partnership

Delta Group Electronics Inc. and Mesa Secure Acquisitions LLC have signed a Joint Marketing Agreement whereby they will combine their collective knowledge and expertise to provide product design, engineering support, and EMS services to U.S. government and industrial customers with communication systems products.

NATEL EMS Lands Contract for NASA's Space Station

The company has been awarded a multimillion dollar contract from Aerojet Rocketdyne to assemble replacement lithium ion battery orbital replacement units (ORUs) for NASA's International Space Station, announced President and CEO Sudesh Arora. NATEL EMS has previously worked on control electronics for the Space Shuttle arm and other similar projects through contracts with NASA.

PEI-Genesis Achieves AS9100C:2009 Certification

PEI-Genesis Inc., one of the world's fastest assemblers of precision connectors and power supplies, has reached the achievement of AS9100C:2009 certification for its corporate headquarters and South Bend, Indiana production facility.

NATEL Boosts Military Services with RF Filters Contract

NATEL is breaking new ground in its services to the U.S. military with a five-year contract to manufacture sophisticated radio frequency (RF) filters for U.S. Navy and Army communications systems.

Aerospace & Military APU Market to Hit CAGR of 3.92%

APU use the same fuel as the aircraft's engines and generally account for about 2% of the total fuel consumption on a given mission. The global aerospace and military APU market is estimated to be $1,527.89 million in 2014 and is projected to register a CAGR of 3.92% to reach $1,851.69 million by 2019.

Analysis of Global Air & Missile Defense Radar

This report provides an in-depth analysis of the air and missile defense radar market from the year (2014–2020). It includes information about the current trends in the market with respect to platforms, technology, region, country, and the current market scenario.

Report: SATCOM Terminals & Commercial off the Shelf

Research and Markets has announced the addition of the "Military Communications Market— Worldwide Forecasts & Analysis (2014-2019)" report to their offerings.

Review: UAV/UAS Market & Future Business Trends

The report that analyzes UAV/UAS industry demand prospects, key markets, top investment regions, and major challenges also examines trends that currently affect the industry is now available.

SIA Lauds DoD Rule Reducing Counterfeit Semicon

The Semiconductor Industry Association (SIA), representing U.S. leadership in semiconductor manufacturing and design, has applauded a newly finalized DoD rule that reduces the risk of counterfeit semiconductor products being used by our military by implementing needed safeguards in the procurement of semiconductors and other electronic parts.

DFARS Flow Downs and Trusted Suppliers

by Todd Kramer
SECURE COMPONENTS LLC

On May 6, 2014, the Department of Defense issued Defense Federal Acquisition Regulation Supplement: Detection and Avoidance of Counterfeit Electronic Parts (DFARS Case 2012–D055); Final Rule. The purpose of this rule is to clarify the sections of the National Defense Authorization Act (NDAA) for 2012 and 2013, which deal with counterfeit parts. This supplement sought insight from industry that would allow the clarification of several key terms such as "trusted supplier" and "counterfeit part." Additionally, this supplement addresses both the applicability of these clarifications and the role that existing industry standards play in assessing the trusted status of suppliers.

One of the main components of the DFARS is the clarification of two key definitions: "counterfeit part" and "trusted supplier." These two terms are both major components of NDAA Section 818, which among other things, requires the use of trusted suppliers in order to mitigate the proliferation of counterfeits. There was a very large industry response to requests for comment, which were put forward on these subjects. Ultimately, several key responses were given by the DoD to industry recommendations regarding the definition of "counterfeit part," as follows:

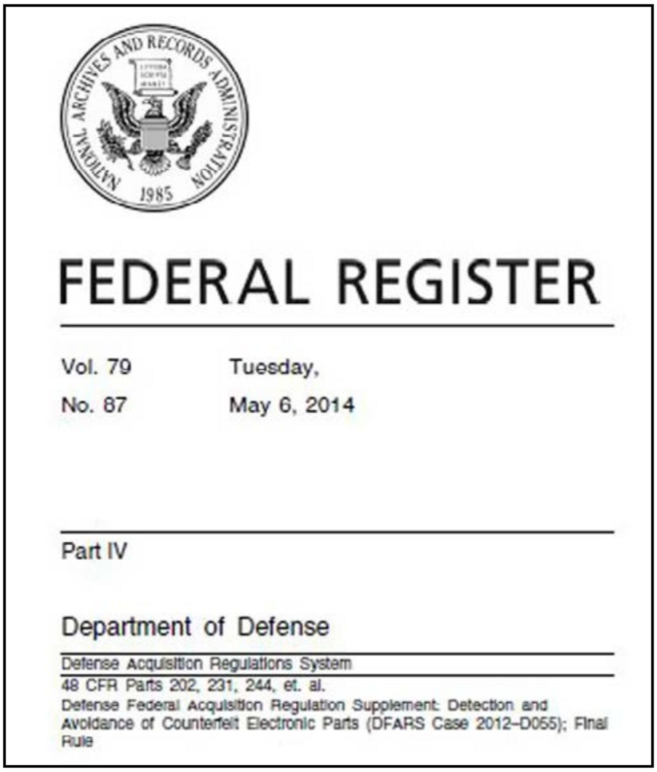
- Due to concerns regarding the broad nature of the term "counterfeit part," the term was determined to apply specifically to electronic components
- An element of intent was added to the term "counterfeit part" by including the term "misrepresented"
- All terms in the original definition referring to a part's "substitute" were replaced with the term "unlawful substitute"

Figure 1: Defense Federal Acquisition Regulation Supplement: Detection and Avoidance of Counterfeit Electronic Parts.

The ultimate effect of these three changes is the fact that in order for a part to be considered counterfeit under DFARS, it must be substituted for a legitimate part with the intent of deceit. This eliminates the possibility that parts might be considered counterfeit as a result of manufacturing defects or improper handling.

The definition of the term "trusted supplier" is likely of even larger importance than what determines a counterfeit component. This is due to the fact that the idea of who is considered a trusted supplier is not only essential to DFARS, but also one of the main concepts put forth by NDAA Section 818: the use of "trusted suppliers" in the defense industry is now required by law.

DFARS FLOW DOWNS AND TRUSTED SUPPLIERS *continues*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Part IV

Department of Defense

Defense Acquisition Regulations System
48 CFR Parts 202, 231, 244, et. al.
Defense Federal Acquisition Regulation Supplement: Detection and Avoidance of Counterfeit Electronic Parts (DFARS Case 2012–D055); Final Rule

Figure 2: Recent update on DFARS by the DoD.

The most important take away from the DFARS regarding the term "trusted supplier" is as follows:

DoD is concerned that defining and using the term "trusted supplier," or a variation of it, would create confusion due to the use of this term in other, current DoD and industry initiatives. Accordingly, the systems criteria in DFARS are revised to express what is intended by "trusted supplier" without directly using the term, e.g., 252.246–7007(c)(5) uses the phrase "suppliers that meet applicable counterfeit detection and avoidance system criteria."

Ultimately, while the DoD is still noncommittal on what is, clearly, a key tenet of its own requirement that prime defense contractors use "trusted suppliers," it does at least present an update to this definition that requires the implementation of a counterfeit avoidance plan for parts that are not purchased from an OEM or authorized distributor.

The DoD adds no additional clarity with its stance on the use of current industry standards to determine the suitability of suppliers. While according to the Supplement, the majority of respondents "urged" the DoD to adopt "industry standards such as AS5553A," noting that AS5553A has already been adopted for internal use by both DoD and NASA. According to the Supplement:

Other respondents focused on the "secondary market," i.e., distributors and brokers, stating that these types of sources are necessary. These respondents recommended that covered contractors should be encouraged, if not required, to impose known industry standards, such as AS5553A, AS6081, or AS6171 on their secondary market sources and small business suppliers.

Despite the urging of the private sector, the DoD remains noncommittal on the application of industry standards to DFARS. Despite its own official adoption of the AS6081 counterfeit mitigation standard, among others, the DoD responded to respondents with the following:

"… industry standards on counterfeit parts currently vary and continue to evolve. For this reason, the DoD has not mandated the use of specific industry standards but left their use to the contractor, and the DoD has not adopted the still-changing definitions in industry standards."

The ultimate critical piece of information from the DFARS is that the DoD requires the implementation of some type of counterfeit avoidance program, even if it is unwilling to specify a standard to which suppliers should be held.

What is telling, however, is the DoD's official stance on the flow down of these requirements to firms beyond the cash accounting standards (CAS)-covered firms that are called out in the original text of the DFARS. When faced with concerns that smaller firms and subcontractors would not be covered by the quality and counterfeit mitigation standards set forth in DFARS, the DoD had this to say:

"However, all levels of the supply chain have the potential for introducing counterfeit or suspect-counterfeit electronic items into the end items contracted for under a CAS-covered prime contract. The

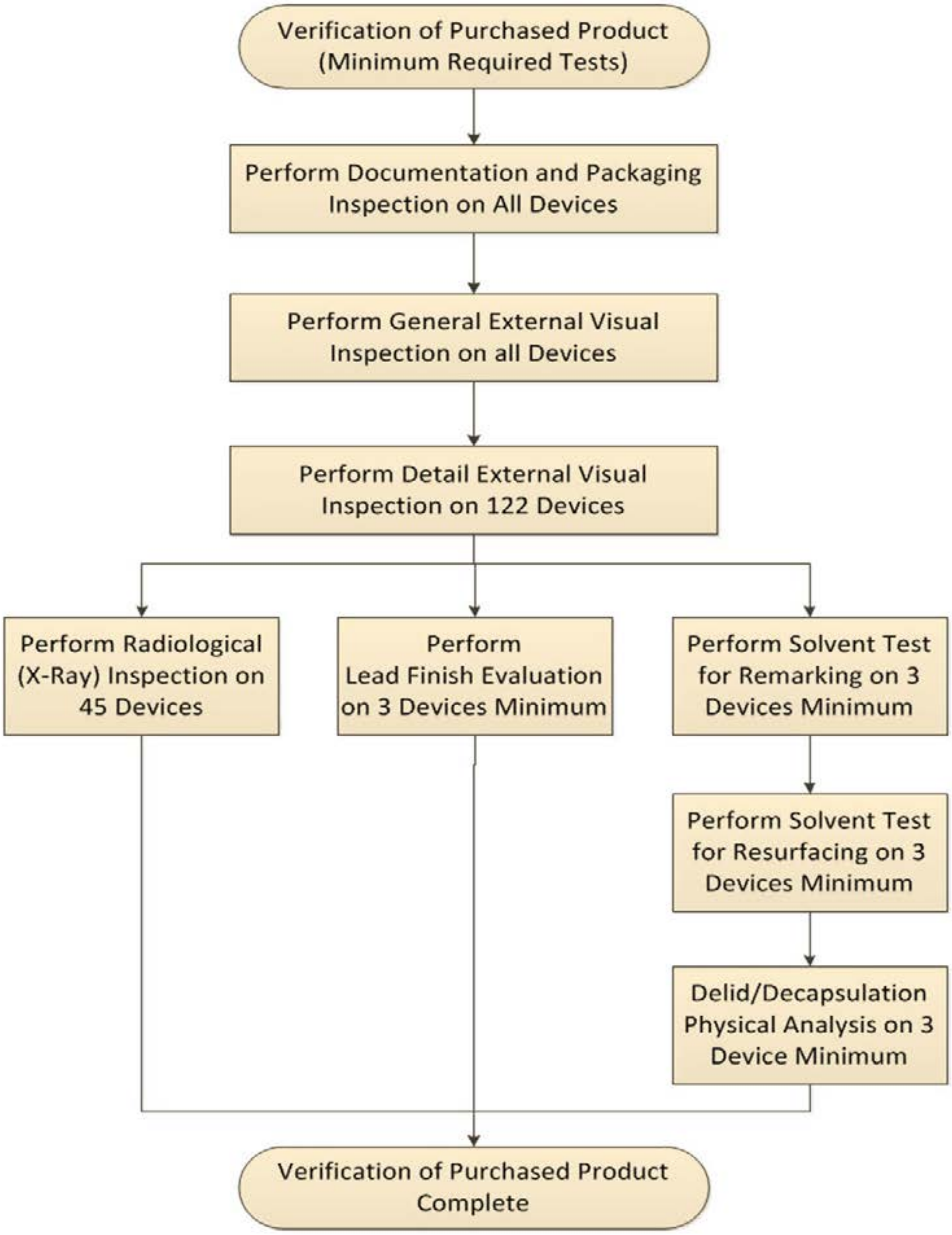


Figure 3: Authenticating purchased product flow down.

prime contractor cannot bear all responsibility for preventing the introduction of counterfeit parts. By flowing down the prohibitions against counterfeit and suspect counterfeit electronic items and the requirements for systems to detect such parts to all subcontractors that provide electronic parts or assemblies containing electronic parts (without regard to CAS-coverage of the subcontractor), there will be checks instituted at multiple levels within the supply chain, reducing the opportunities for counterfeit parts to slip through into end items."

What does this mean for businesses that supply components to prime defense contractors and other CAS-covered firms?

Ultimately, as requirements are flowed down from larger firms who wish to reduce their own liability, smaller firms will be required to adapt to the new market conditions in the defense sector. This will ultimately take the form of an industry-wide push towards certification, as larger firms attempt to mitigate liability and smaller suppliers fight to keep the business of the primes and other large firms.

The main points of the DFARS that should be considered are as follows:

- Firms that already maintain a certification to the most recent standards such as AS5553A and AS6081 should both maintain these levels of counterfeit mitigation and encourage other firms to do so
- Those suppliers which are compliant, but not certified to up-to-date standards should strongly consider certification in order to keep pace with the flow down of DFARS, as well as for the limiting of liability
- Firms which do not maintain a counterfeit avoidance program should immediately develop a program that is, at the very least, compliant with current standards, and should rapidly pursue certification to these standards. This is both for the good of the firm and for the good of the ultimate customer, the Warfighter.

These points should be considered by all firms who wish to remain in the defense supply chain—hopefully the application of these standards will lead to the eventual eradication of the current counterfeit epidemic. **SMT**

Todd Kramer is CEO of Secure Components LLC, an AS6081 & AS9120 certified independent distributor of electronic and mechanical components to the aerospace, defense, and high-reliability industries. To contact Kramer or to read past columns, click here.

SMTonline Market News Highlights

The Conference Board Sees Strong, Steady Job Growth

The underlying hiring trend, especially in professional services, is encouraging, with more good news expected through the summer and into the fall. More jobs means more pay checks, lifting sentiment and resulting in still more consumer buying.

Industrial Robotics Market to See Steady 6.4% CAGR

In United States alone the sale of industrial robotics for manufacturing use grew by 44% during 2011, indicating that the industrial robotics market is a correlant to the overall revitalization of the production base in the U.S. and a an important component of the general economic performance of the country.

Energy Capacity of Energy Storage Applications: CAGR of 71%

According to a recent report from Navigant Research, the annual energy capacity of advanced batteries for utility-scale energy storage applications will grow from 412 megawatt-hours (MWh) in 2014 to more than 51,200 MWh in 2023, at a compound annual growth rate of 71%.

Automotive Electronics Market at $77B by 2020

The automotive under-the-hood ECU electronics market is estimated to have been worth $44.8 billion in 2013 and is forecast to grow to $77 billion in 2020, a CAGR of 8%. Semicast forecasts global light vehicle production volumes to grow over this period from 82 million to 106 million. However, more than 40% of the increase in global light vehicle production is forecast for China alone.

3D Printing: The Making of a $7B Market

The market has huge potential, but is still embryonic in terms of development, with main players taking their first steps by 3D printing conductive and insulating materials into a single object. 3D printed electronics, including 3D printed transistors, will not be fully realised within 10 years, but some emerging medical applications will be commercialised well before 2025.

IoT Market to Reach $1,423 Billion by 2020

The value of Internet of Things (IoT) market was worth $1029.5 billion in 2013, and is expected to reach $1,423.09 billion by 2020, at an estimated CAGR of 4.08% from 2014–2020.

Graphene Markets to Top $390 Million in 2024

New research by IDTechEx in the report "Graphene Markets, Technologies and Opportunities 2014–2024" shows that graphene markets will grow from around $20 million in 2014 to more than $390 million in 2024, at the material level.

Printing Technologies Extend to PE Components

Printed electronics uses graphic arts techniques such as screen printing or inkjet, to print electronic and photonic devices by using conducting or dielectric inks that results in the development of active or passive devices such as resistors or thin film transistors (TFT).

Positive Outlook Develops for Global Economy

Paul A. Laudicina, founder of the FDI Confidence Index, notes, "Despite racking volatility and economic uncertainty on a global scale, the findings from the 2014 FDICI suggest that a corner is being turned. Corporations sitting on massive cash reserves are increasingly confident they can parlay these into productive investments with attractive returns."

EMS Market Driven by Demand for Testing Services

The testing services provided by EMS providers are dependent on the solutions required by OEMs and the vertical to which they cater. The outsourcing of testing services to EMS providers will increase due to innovation in consumer electronics products. The market is driven by strong demand for such services from the telecommunication and consumer electronics industries.

THE SHORT SCOOP

More Stencil Questions (and the Answers!)

by Rachel Miller-Short

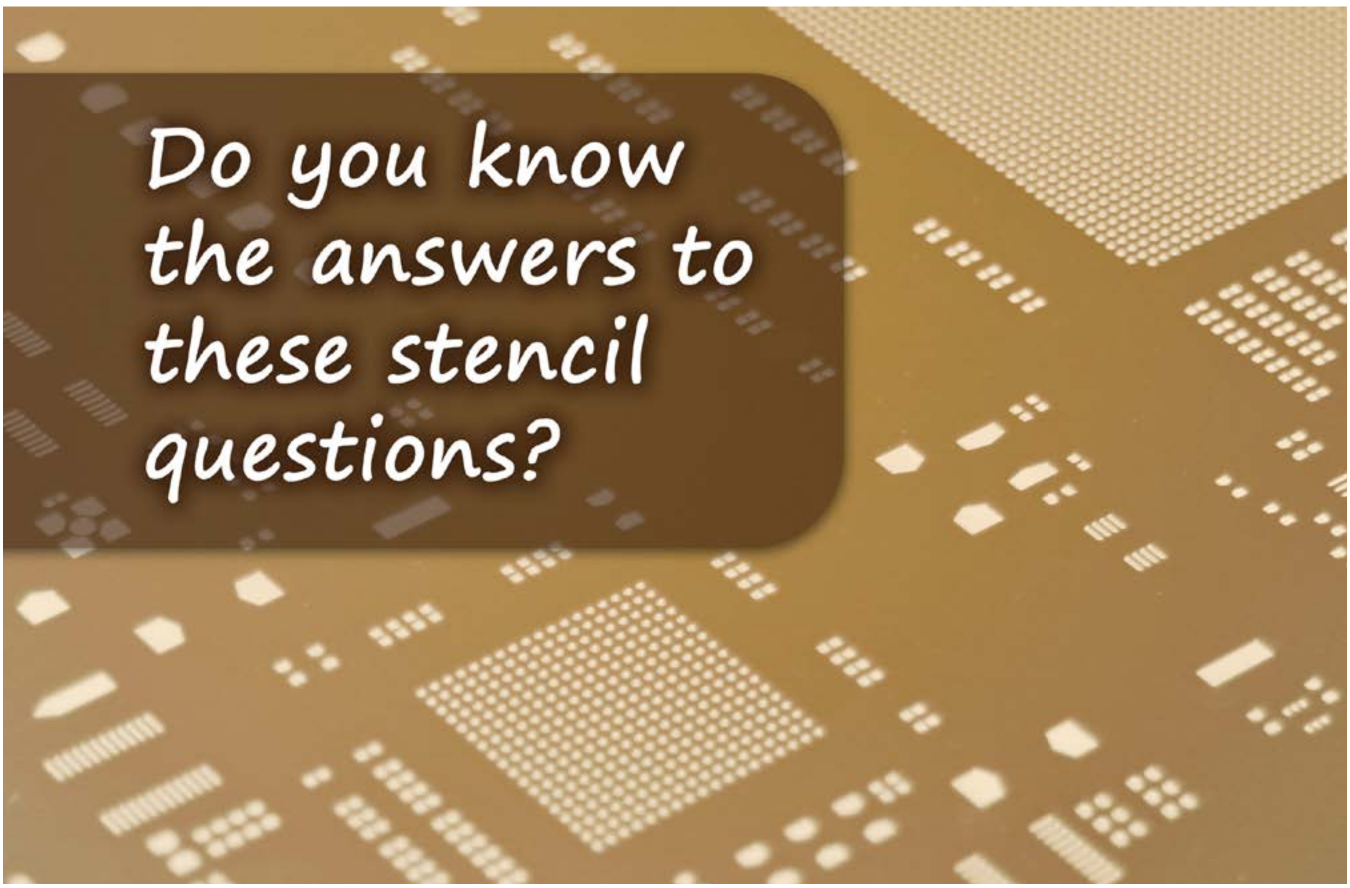
My March Short Scoop column, 10 Common Stencil Questions, brought in a slew of new questions from customers. Do you know the answers?

1. What are my fiducial choices and how do they differ?

Yes, stencils require fiducial markings to make sure the stencils are aligned correctly to properly print the pattern, as most people know. What they might not know is that there are actually several types of fiducials, and when you select a stencil, you must choose one of them.

The fiducial choices available today depend on the stencil manufacturer you use and/or your own requests, but truthfully, there really are only two predominate types. One is half-etched and filled, which have an etched pocket in the stencil at the fiducial location that is then filled with a black epoxy. Ultimately, these offer one of the strongest contrasts for the visual printer cameras, but they are an older technology and often, the epoxy falls out at the least opportune time.

The other predominate type is a laser tattooed fiducial, which is a relatively newer technology. These are applied by a laser (usually the same one that cuts the apertures for a laser stencil). In this technology, the laser truly burns the



fiducial to the stencil. The benefits are that it lasts forever and the epoxy doesn't fall out. Laser tattooed fiducials provide the tightest location tolerance of any fiducial and most companies are moving toward this technology. It is imperative to note, however, that the darkness of the laser fiducials have varying contrasts from one stencil to another. This is usually due to the material type, the pattern density of the stencil, laser type, and several other factors. I mention this because some printers struggle with the contrast that is less than what they might have had previously in the half-etched and filled fiducials.

2. What CAD information and files are needed to make my stencil and how will I receive my check plots?

These are very important questions so that manufacturers know what to expect and don't waste time or effort preparing something that isn't usable by the stencil manufacturer. Additionally, they don't have to go back to a format that is different from what is usually done. We use IGI and Valor, which are software systems that can custom design each stencil. The types of files we need include:

- Import file types: Gerber (274x), ODB++, dxf/dwg and gdsII
- Export file types: Gerber (274x), ODB++, dxf/dwg, gdsII and pdf
- Types of files needed to create a stencil: Gerber (274x), ODB++, dxf/dwg, gdsII and pdf

It's always best to ask this question at the initial meeting with your stencil manufacturer to make sure your systems are compatible.

3. What types of quality inspection are performed on my stencils and when are they done?

QC checks can vary quite drastically from one stencil vendor to another. High-quality stencil manufacturers usually have QC checks starting from the very beginning when a new order comes in, which ensures that the order is processed correctly, the CAD files are interpreted and modified correctly, and customer requirements are clearly understood. In addition, a completed stencil usually goes through a QC process to ensure that all of the apertures are present. This entails a scan of the stencil to compare it to the Gerber file, thus making sure that all necessary apertures are present. Especially with electroformed or step stencil technologies, the stencil thickness needs to be verified to see that the targeted thickness or thicknesses have been achieved.

Final QC checks usually include verification of aperture size, either on certain selected apertures or apertures in certain defined geographies of the stencil, image run-out, fiducial count and darkness, surface roughness, frame type and flatness, and any additional QC checks that the manufacturer or customer deems necessary. Some customers require a Certificate of Compliance to accompany purchased stencils. Usually included in a Certificate of Compliance are specifications such as thickness, certain aperture size measurements, and run-out.

Figure 1: DuraGlide squeegee blades yield near perfect solder brick deposits over tens of thousands of print cycles.

4. What is an average blade life and how often should I change them?

We seem to get a lot of blade questions. Blades are a key component to the print process.

Through many conversations with customers and time on SMT lines, it has become apparent to me that blades are not getting the attention they should be. The right blade, when paired with a stencil in an application, can make the difference between a successful print and a print that needs substantial rework.

That said, in general, standard OEM blades are sufficient for most print applications as long as they are changed and inspected for defects regularly. As a rule of thumb, an SMT line running 1.5–2 shifts, 5–6 days a week, with a couple of different blades or blade size changes during the course of a week, should have the blades changed every 3–4 months. At that point, the blades will have produced enough prints to dull the blade edge, which has probably been nicked or dinged a couple of times already, but not severely enough to cause them to be replaced. Most OEM blades cost under $55 a set, and some companies can even arrange an automatic replacement program. The negative impact on your process and product that results from not changing the blades regularly certainly costs more than $55.

In a future column, I will explore questions regarding the possible causes of poor printing results. **SMT**

Rachel Miller-Short is global VP of sales at Photo Stencil LLC. To contact the author, or to read past columns, click here.

Video Interview

DEK Deals with Automotive Device Miniaturization

by Real Time with...
IPC APEX EXPO 2014

DEK's Clive Ashmore and Editor Kelly Dack explore the ways DEK handles automotive customers' challenges with device miniaturization, and why the lessons learned in the mobilephone segment don't necessarily translate into the automotive world.

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SMTonline Supplier/New Product News Highlights

GOEPEL's GATE Extends Partnership in China

GOEPEL electronic extends its strategic partnership program GOEPEL Associated Technical Experts (GATE) in the Asian market by adding the Chinese company SiFo as a new member.

CircuitWorks Overcoat Pen Released by Intertronics

Intertronics' recent launch of the CircuitWorks Overcoat Pen is expected to make coating of PCBs especially convenient during manufacture, rework, and prototyping, by enabling the replacement of permanent solder resist or mask over repaired areas, or where it is damaged or missing.

Electrolube Coating Earns SMT China VISION Award

Electrolube, the leading manufacturer of specialist chemicals for the electronics, automotive, and industrial manufacturing industries, announced that its UVCL UV cure conformal coating has won the 8th SMT China Vision Award in the Conformal Coatings category.

Essemtec Strengthens Partnership with ACI Technologies

The company has renewed its partnership with ACI Technologies Inc. (ACI) and will provide ACI with a complete SMT line. In return, Essemtec will use ACI's facility for demos, seminars, training, and more.

Nordson Expands in Colorado; To Build New Facility

"We continue to see outstanding global growth opportunities for innovative components, devices and custom OEM solutions related to precision fluid management and delivery of biomaterials," said George Porter, vice president and general manager for medical product lines.

New Paste Retainer Design from Transisiton Automation

Transition Automation Inc. has unveiled a new paste retainers design which improves the management of solder paste within the printing area. The new product, SPR, helps eliminate leakage of solder paste out of the print area by way of a floating spring supported paste retainer attached to the end of the squeegee holder.

Manncorp Enhances Dip Soldering; Debuts New Models

Auto-Dip models feature programmable preheat and dip-height settings and include an adjustable, finger-type PCB holder that firmly grips the edges of the board throughout the soldering cycle. This flexible design is especially useful for heavy component-laden assemblies and can also accept customized pallets of very small, irregularly-shaped PCBs.

Universal Science B.V. Invests in Essemtec Machines

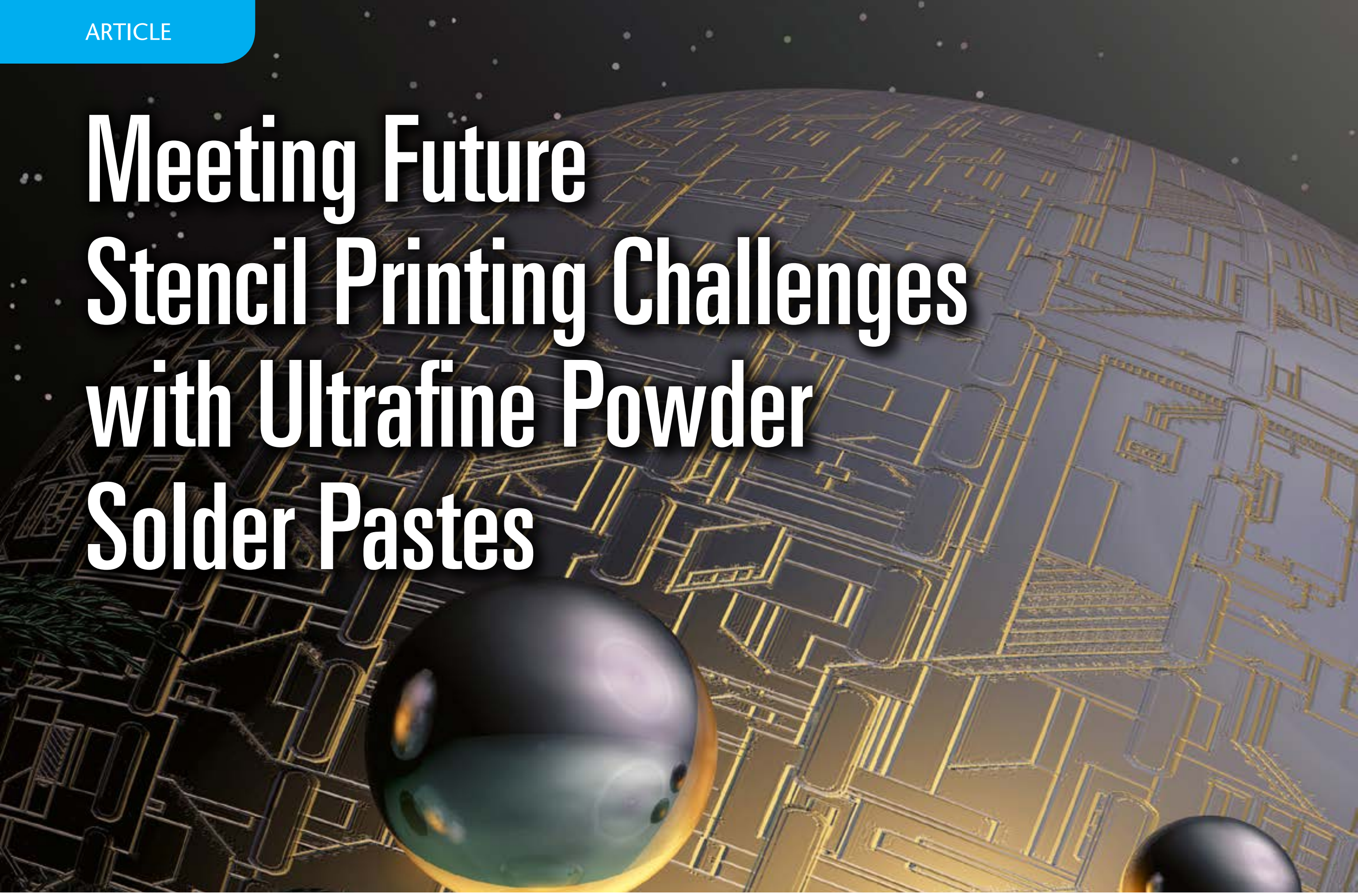
Universal Science, the international market leader in thermal management in electronics assemblies and LED lighting, has further expanded its SMT production line with the investment in an Essemtec Tucano Plus screenprinter.

Speedline Launches New Electrovert Electra

The new Electrovert Electra by Speedline Technologies is the next generation in wave soldering systems, offering new features and enhanced performance that make it the most state-of-the-art wave soldering system to be launched into the marketplace to date, according to Geoff Klein, Electrovert general manager.

Panasonic Selects Repstronics as Sales Rep in Mexico

"Repstronics' team of experienced, bilingual engineers, as well as their dedicated Technical Center in Guadalajara, are a great resource for helping manufacturers in Mexico find the right electronics assembly and software solutions for their challenges," said Mark Ragard, general manager, Electronics Assembly Sales.



Meeting Future Stencil Printing Challenges with Ultrafine Powder Solder Pastes

by Edward Briggs
INDIUM CORPORATION

As originally published in the 2014 International Conference on Soldering and Reliability Proceedings.

Abstract

The explosive growth of personal electronic devices, such as mobile phones, tablets, and personal music devices, has driven the need for smaller and smaller active and passive electrical components. Not long ago, 0201 passives were seen as the ultimate in miniaturization, but now we have 01005 passives with rumors of even smaller sizes not far behind. For active components, array packages with 0.4 mm pitch are virtually a requirement for enabling the many features in modern portable electronic devices. To meet the challenge of stencil printing smaller stencil apertures, there is an increased interest in using finer particle-sized solder pastes to improve transfer efficiency. The smaller particle size results in a large surface area-to-volume ratio that challenges the solder paste's flux to effectively perform its fluxing and oxidation protection action. The potential resulting surface oxidation can lead to voiding, graping, head-in-pillow, and other defects.

The combination of higher lead-free process temperatures, smaller print deposits, and temperature restraints on electrical components has created several challenges. Two in particular are obtaining consistent volume in the printed solder paste deposit and minimizing the oxidation of the solder powder in the small deposit during reflow. Solder pastes comprised of finer particle solder powders may help with stencil printing, but the increased surface oxide associated with finer powders may also reduce the reflow process window. The focus of this paper is to provide a statistical comparison of the transfer efficiency of different solder powder particle sizes, specifically types 3, 4, 5, and 6, and to visually observe post-reflow results in both optimal and harsh conditions.

Introduction

Back to the basics, or the fundamentals, is a term often heard in relation to sports teams when they lose sight of the basic foundations

2014 Event Schedule

July 15 & 22
Webtorial: Failure Analysis: Lessons Learned in Manufacturing
Instructor: Martin Anselm, Ph.D., Universal Instruments Corp.

July 17
Ohio Expo and Tech Forum
Doubletree Hotel, Independence, OH

July 17
Guadalajara Expo and Tech Forum
Real Inn, Ciudad Juarez, Mexico

August 12
Philadelphia Expo and Tech Forum
Crowne Plaza Philadelphia, Cherry Hill, NJ

August 14
West Penn Expo and Tech Forum
Doubletree Monroeville, Monroeville, PA

August 19 & 26
Webtorial: SMT for Movers, Shakers, and Rainmakers
Instructor: Ray Prasad, Ray Prasad Consultancy Group

September 9
Capital Expo and Tech Forum
Johns Hopkins University, Laurel, MD

September 10
Webinar: Power and High Temperature Electronics Manufacturing
Instructors: Dr. Chris Hunt, NPL
Bob Willis, NPL Defect Database Coordinator

September 11 & 18
Webtorial: Evaluating the Performance of Conformal Coatings
Instructor: Doug Pauls, Rockwell Collins

September 18
Empire Expo and Tech Forum
Radisson Hotel, Rochester, NY

September 18 - 19
Medical Electronics Symposium
Organized by SMTA, iNEMI & MEPTEC
Marylhurst University, Portland, OR

September 28 - October 2
SMTA International Conference & Exhibition
Co-located with IPC Fall Standards Development Committee Meetings
Donald Stephens Convention Center, Rosemont, IL

October 14
Austin (CTEA) Expo and Tech Forum
Norris Conference Center, Austin, TX

October 15
Long Island Expo and Tech Forum
Islandia Marriott, Long Island, NY

October 16 & 23
Webtorial: Improving Mechanical, Electrical and Thermal Reliability of Electronic Assemblies
Instructor: Tim Jensen, Indium Corporation

October 21
Connecticut Expo and Tech Forum
Waterbury Marriott, Waterbury, CT

October 23
Intermountain Expo and Tech Forum
University of Utah, Salt Lake City, UT

November 6
LA/Orange County Expo and Tech Forum
Grand Event Center, Long Beach, CA

November 11-13
International Wafer-Level Packaging Conference (IWLPC)
DoubleTree by Hilton Hotel, San Jose, CA

November 18-20
High-Reliability Cleaning and Conformal Coating Conference
Organized by SMTA & IPC
Chicago Marriott Schaumberg, Schaumburg, IL

November 19
Arizona Expo and Tech Forum
Phoenix Marriott, Tempe, AZ

December 4
Space Coast Expo & Tech Forum
Park Inn by Radisson, Kissimmee, FL

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of playing the game. In the SMT process, this may not necessarily be due to losing sight of the basic fundamentals, but because the game itself continues to evolve. As the trend towards miniaturization continues, a process that was successful in the past may suddenly present unacceptable results due to the decreasing size of the stencil apertures required to print ultrafine solder paste deposits. In an earlier paper titled "Process Guidelines to Ensure Optimal SMT Electronics Assembly" (Edward Briggs and Ron Lasky SMTAI Toronto, May 2012), I discussed solder paste storage and handling; process setup, including the importance of gasketing and registration; solder paste attributes; reflow processes; newer SMT technologies; and the data collection methods for characterizing the stencil printing process to meet this evolution. The focus of this paper is to single out one of those considerations—powder particle size (powder types) and its effect on the stencil printing process. In order to focus on particle sizes, many variables as possible were eliminated and the data analyzed using solder paste inspection equipment. A physical observation will also be made of the reflowed results. Finer powder particles mean an increase in surface oxide and can create challenges for reflow.

Stencil Printing and Area Ratio and Transfer Efficiency

In regard to stencil printing success, the two most critical parameters are the area ratio (AR) and transfer efficiency. Area ratio is the area of the stencil aperture opening divided by the area of the aperture side walls. Figure 1 shows an area ratio schematic for a circular aperture. Simplifying the calculation shows that the area ratio (AR) is the diameter (D) of the circle divided by 4 times the stencil thickness (t): AR = D/4t. The result is the same for square apertures, with the diameter (D) now equal to a side of the square. For the AR of a rectangular aperture, the formula is a little more complicated: ab/2(a+b)t, where a and b are the sides of the rectangle.

It is widely accepted in the industry that the AR (area ratio) must be 0.66 or greater to be successful in the stencil printing process. Historically, experience has shown that if AR < 0.66, the transfer efficiency will be low and inconsistent. Transfer efficiency is defined as the volume of the actual solder paste deposited divided by the calculated volume. Measuring the effect of AR on fine feature printing will be an important part of our experiment.

The Experimental Design

The focus of this printing experiment was to differentiate transfer efficiency and consistency between powder types. Therefore, in an effort to diminish the number of variables, the same stencil, squeegee blades and printer parameters were utilized (Figure 2).

A 4 mil thick laser cut stencil, 250 mm squeegee with edge guards, foilless clamps, and landscape vacuum support blocks were used on the stencil printer. Figure 2 depicts the printer

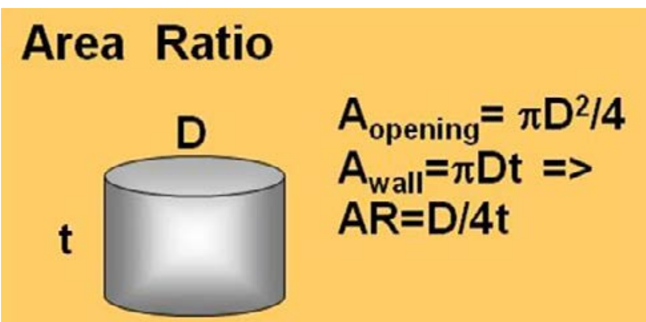


Figure 1: Definition of the area ratio for a circular stencil.

Figure 2: Printer settings.

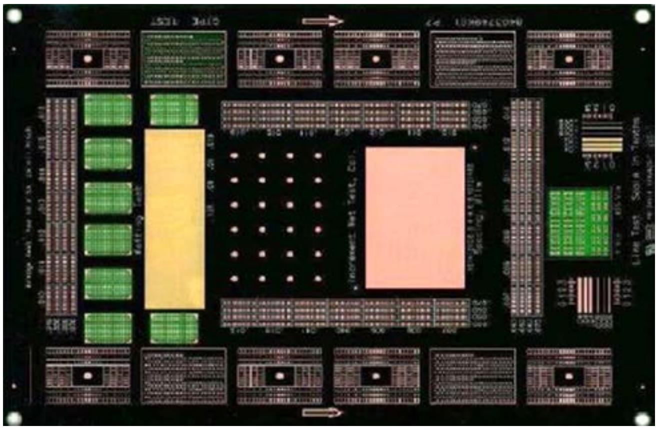


Figure 3: Test vehicle.

settings utilized for the experiment. Each solder paste was printed at 50 mm/s with a blade pressure of 4.4kg, 5 mm/s separation speed, and separation distance of 2 mm. The underside stencil-wipe method was used only during the one-hour pause W/D/V (wet/dry/vacuum).

A test vehicle (Figure 3) was selected with focus on 6, 7, 8, 9, 10, 12 mil circles and squares, as well as 0201 pads in both solder mask defined (SMD) and non-solder mask defined (NSMD) pads. Four powder types were evaluated: types 3, 4, 5, and 6 in no-clean and water soluble flux formulations. Response to pause was measured by continuous printing 20 times, pausing for 1 hour, and printing 6 more times. A wet/dry/vacuum stencil wipe was incorporated immediately after printing the first 20 PWBs. A Koh Young KY-3020T laser scanning system was used to measure the volume of the stencil printed deposits. In all, 1,386,500 data points (solder paste deposits) were collected.

Figure 4 shows the component identification and the area ratio associated with it.

Printing Results

Gauge Variability Chart for Volume (%)

Figure 5 represents a broad view of the resultant test data. The y axis of the upper graph indicates the transfer efficiency in volume %, with 100% being the target. The bottom graph indicates the standard deviation of the process; a smaller standard deviation indicates a more consistent process. Included in the test were a number of 0201 and 12 mil chip scale package

Component ID	Description	Area Ratio
C12_SMD	Circle 12mil Solder mask defined	0.7500
C12_NSMD	Circle 12mil Copper defined	0.7500
S12_SMD	Square 12mil Solder mask defined	0.7500
S12_NSMD	Square 12mil Copper defined	0.7500
C10_SMD	Circle 10mil Solder mask defined	0.6250
C10_NSMD	Circle 10mil Copper defined	0.6250
S10_SMD	Square 10mil Solder mask defined	0.6250
S10_NSMD	Square 10mil Copper defined	0.6250
C9_SMD	Circle 9mil Solder mask defined	0.5625
C9_NSMD	Circle 9mil Copper defined	0.5625
S9_SMD	Square 9mil Solder mask defined	0.5625
S9_NSMD	Square 9mil Copper defined	0.5625
C8_SMD	Circle 8mil Solder mask defined	0.5000
C8_NSMD	Circle 8mil Copper defined	0.5000
S8_SMD	Square 8mil Solder mask defined	0.5000
S8_NSMD	Square 8mil Copper defined	0.5000
C7_SMD	Circle 7mil Solder mask defined	0.4375
C7_NSMD	Circle 7mil Copper defined	0.4375
S7_SMD	Square 7mil Solder mask defined	0.4375
S7_NSMD	Square 7mil Copper defined	0.4375
C6_SMD	Circle 6mil Solder mask defined	0.3750
C6_NSMD	Circle 6mil Copper defined	0.3750
S6_SMD	Square 6mil Solder mask defined	0.3750
S6_NSMD	Square 6mil Copper defined	0.3750

Figure 4: Pad labels, description, and associated area ratios.

(CSP) test pads that are not depicted. The solder paste deposits on these pads were well-printed regardless of powder and flux type and were therefore excluded from further investigation. The data in Figure 5 reveals that the smallest test aperture (6 mil) did not print well for all powder types or flux vehicles. The area ratio is quite small (0.375) for the 6 mil aperture and the results were inconsistent.

Variability Gauge Component ID=S07_SMD Variability Chart for Volume(%)

A dramatic improvement occured with 7 mil apertures that deserved further investigation, notably between the water soluble and no-clean flux formulations. Figure 6 shows the improvement in more detail by expanding the view of the 7 mil aperture and breaking out the data before and after the 1-hour pause. Note that a standard deviation <10%, with the exception of a few outliers which exhibits a controlled process, was achieved specifically with the Indium8.9 no-clean flux chemistry. The area ratio for the

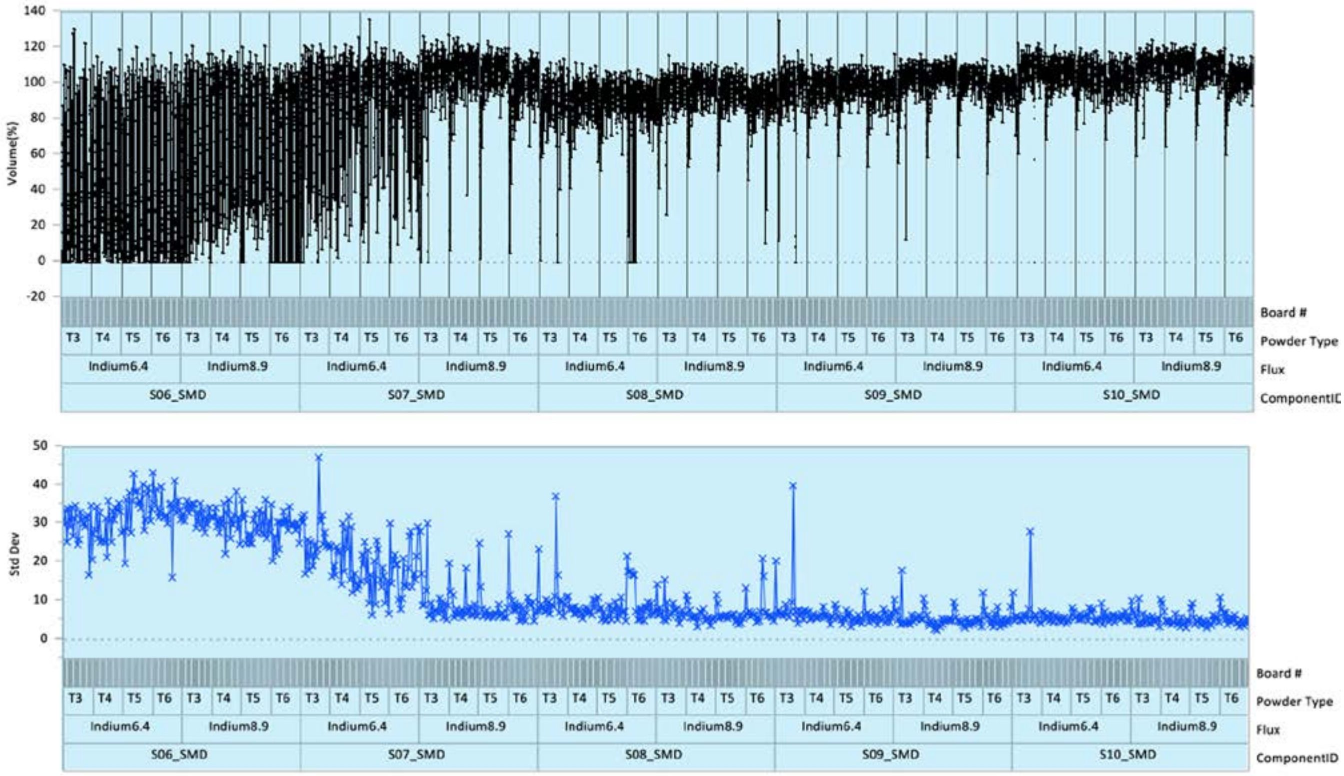


Figure 5: A broad view of test results.

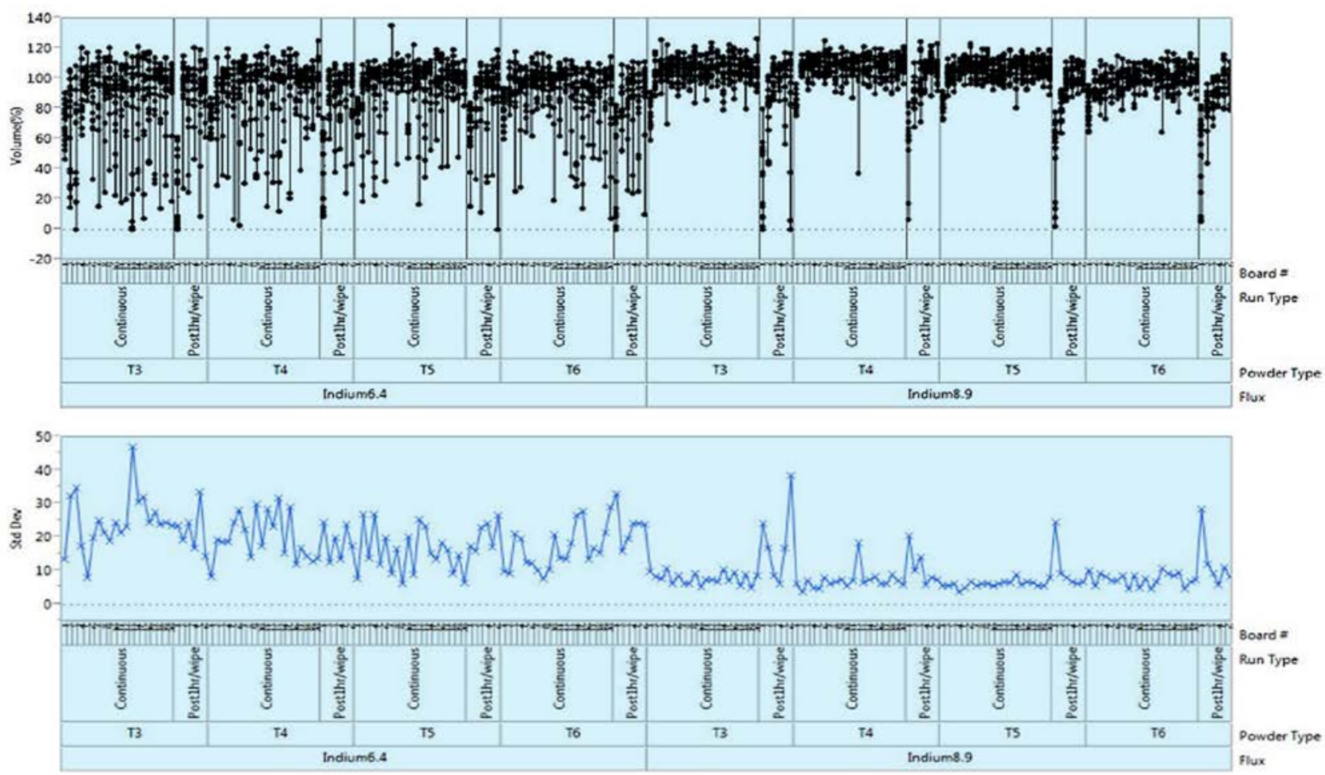


Figure 6: Example results of 7 mil square solder mask define pad.

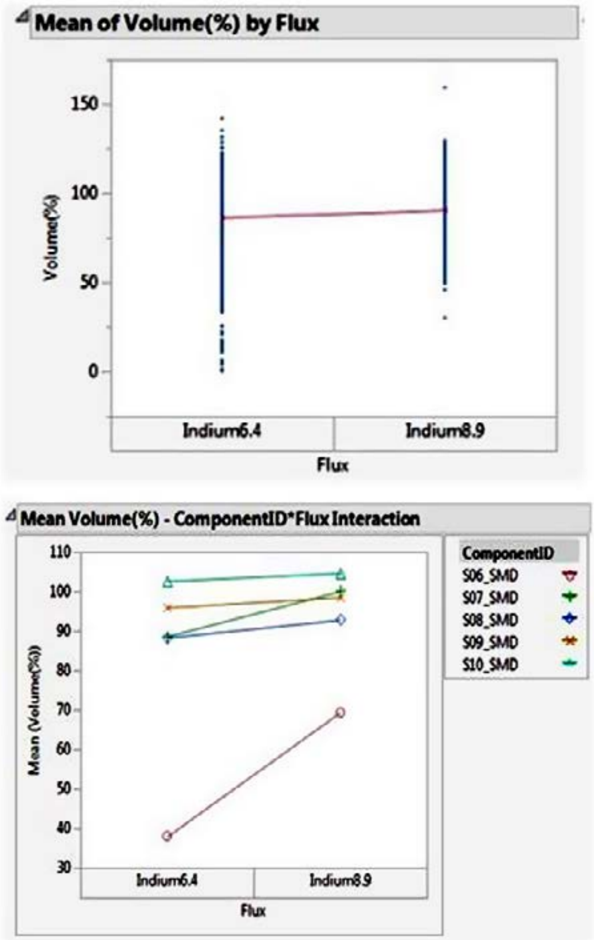


Figure 7: Mean of volume percent by flux and flux/aperture interaction.

7 mil aperture is 0.4375. The transfer efficiency was near the target (100%) and improved as the powder type moved toward type 6. Type 5 exhibited the best results; a narrow distribution in volume percent and low standard deviation except after first pause. It is important to note that the significant drop in transfer efficiency after the 1-hour pause is not consistent with previous experiments; this is attributed to a very low humidity (<10%) and had a dramatic effect on the first print after sitting on the stencil for one hour, for all solder pastes tested.

Looking at the first chart in Figure 7, it can be seen that the mean transfer efficiency favors the no-clean flux. The water soluble flux in the Indium6.4 solder paste was more erratic, giving more insufficient, as well as excessive, solder paste deposits. The second chart reveals that most of this inconsistency occurs with the 6 mil aperture. This result is consistent with previous experience. The rosin/resin bases found in most no-clean fluxes increase the material's tacky properties (adhesive and cohesive attractions) of the solder pastes. When releasing from the stencil aperture, adhesion of the solder paste to the PCB pad helps pull the paste from the stencil aperture as the PCB is lowered from the stencil. This is especially true for the smaller pads, as there is very little surface area for the paste deposit to cling to. The cohesive forces or attraction of the flux-coated powder particles to one another are also increased. These cohesive forces help the paste release from the stencil walls and retain shape of the stencil aperture after printing.

Variability Gauge
Variability Chart for Volume (%)

Figure 8 shows stencil printing results for square vs. circular apertures. The results for 7 and 8mil square apertures are designated S07 and S08 respectively, and those for 7, 8, and 9 mil circular apertures are C07, C08, and C09 respectively. The 7 mil square aperture exhibits acceptable results with less than10% standard deviation and good volume percent aperture filling. There were, however, a couple of outliers after the one-hour pause. The 7 mil circular aperture exhibits erratic behavior as shown by its high standard deviation. The 8 mil circular is comparable to the 7 mil square with much smaller standard deviation and good volume percent aperture filling. Consistent with past experience for the same area ratio, the square aperture with radius corners produced deposits with more volume of solder paste—21% more in this test.

Variability Gauge
Variability Chart for Volume (%)

Perhaps one of the more dramatic changes in transfer efficiency and standard deviation is noted for the same aperture size and shape, but with pads that differ in solder mask. Solder mask defined pads exhibit far better results than the non-solder mask defined or copper defined. This result is also consistent with pri-

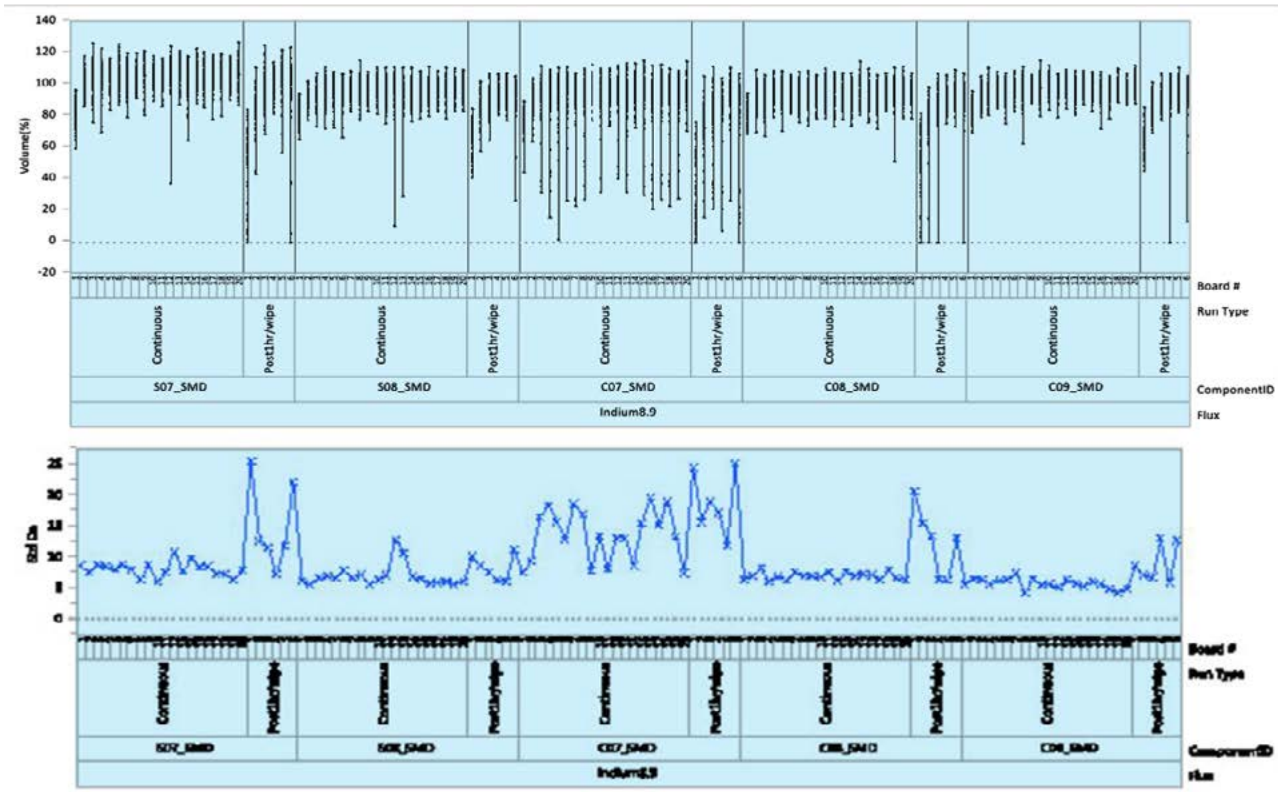


Figure 8: Circles vs. squares.

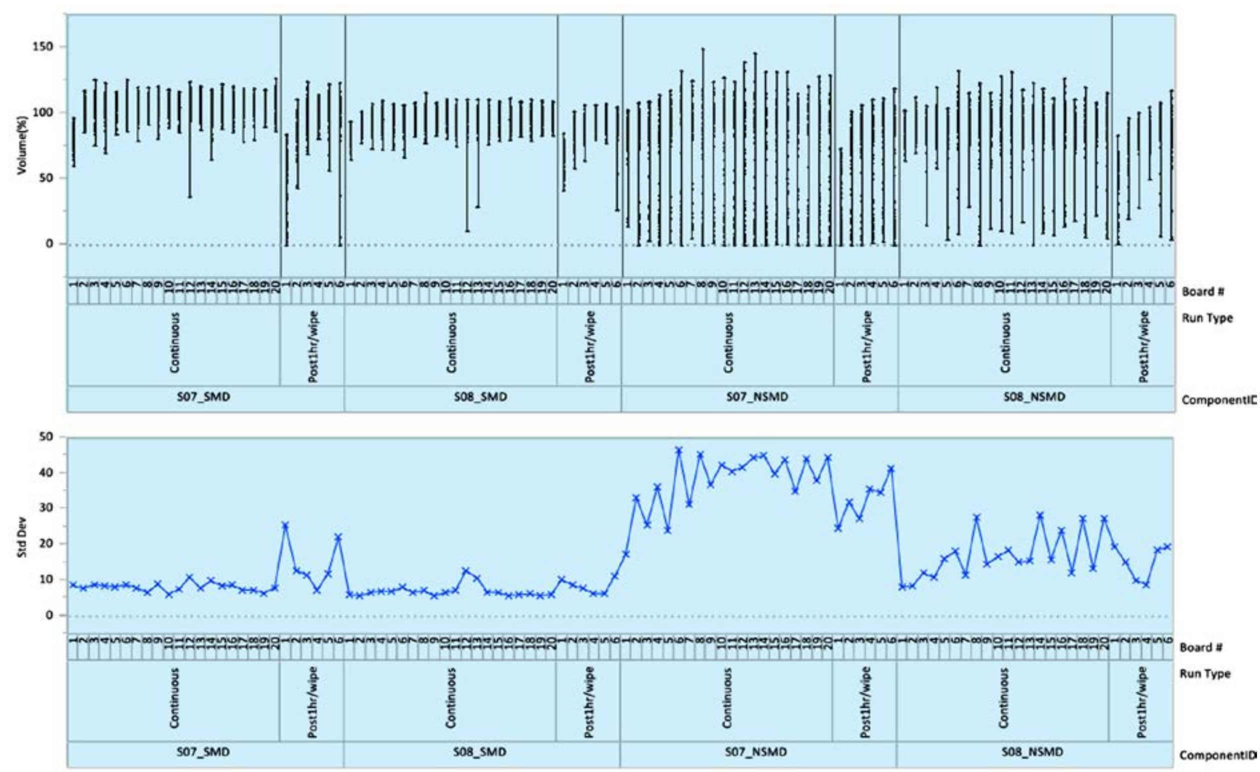


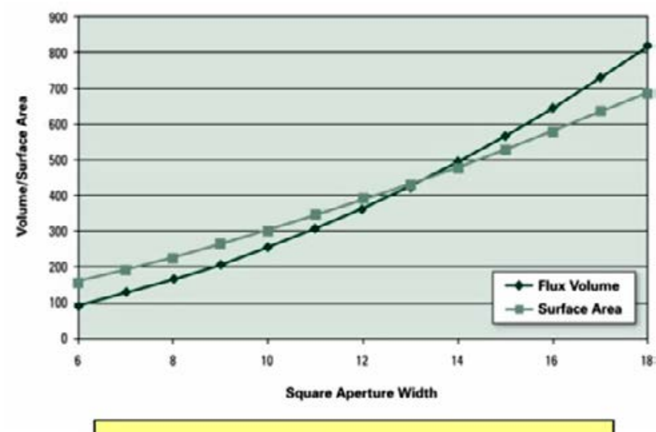
Figure 9: Solder mask defined vs. non-solder mask defined (copper defined) pads.

or experience and attributed to an increase in surface area for the solder paste deposit to adhere to when solder mask define pads are used. However, the challenge with solder mask at these small apertures is the registration of the solder mask to the pad. Achieving this precise registration can become difficult for the board supplier.

Reflow Profile

Improving the stencil printing process with finer particle solder pastes affects the reflow process, often minimizing the reflow process window for acceptable results. As the particle size decreases, the total surface area for the same volume of solder paste increases. This increase in total surface area also means an increase in total surface oxide and increases the demand on the flux to remove them.

The demand on the flux is further challenged as the reason for selecting a finer particle solder paste to print into a smaller stencil aper-



$$V_{square} = S^2 \times h \times 50\%$$

$$SA_{square} = 4(s \times h) + s^2$$

Figure 10: Relationship of surface area to available flux as aperture size decreases.

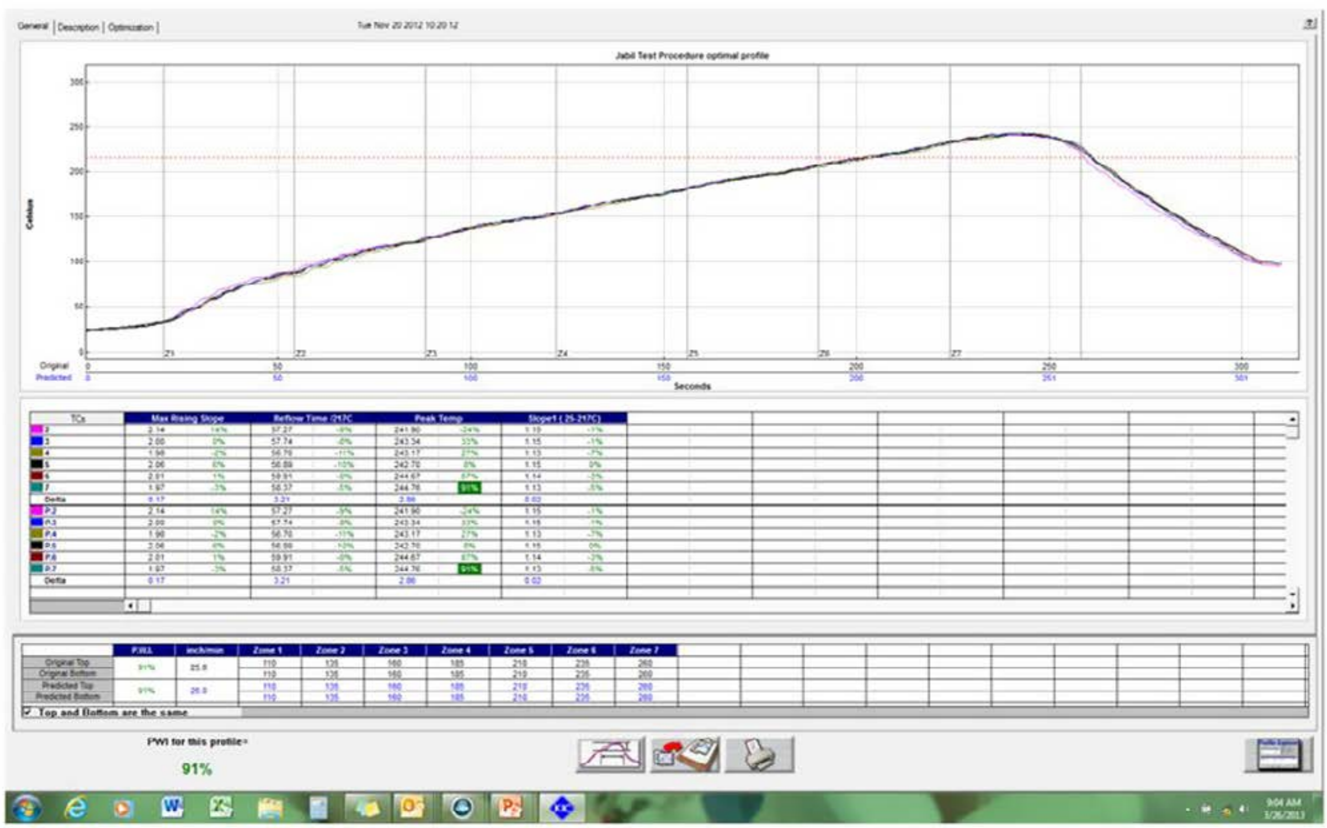


Figure 11: Optimal reflow profile.

ture, resulting in a smaller paste deposit. Figure 10 illustrates the relationship of increased surface area to available flux as the paste deposit decreases. Note that the ratio of flux available to the surface area decreases as aperture width decreases. This situation will result in less available flux to protect against surface oxidation when aperture widths are small.

Profile Types

Two reflow profiles were selected. One is for optimal conditions the other for harsh environments. These profiles were chosen to compare powder types and flux chemistry.

An optimal reflow profile is shown in Figure 11. This profile is a ramp to peak with a peak temperature of 240–245˚C, a time above liquidus of 50–70 seconds, and an average slope from 25–217˚C of 1–1.5˚C/s. This profile works well for these smaller paste deposits and has a gradual ramp, which is also best for the components and the PCB.

A more demanding profile (Figure 12) was also used to challenge the different powder types and flux chemistries. It had a peak temperature of 250–255˚C, time above liquidus near two minutes (120 seconds), and a soak from 150–200˚C between 160–180 seconds.

Results

Particle size

Figures 13 and 14 compare both ends of the particle size spectrum, which were tested to observe any trends when progressing from type 3 to type 6 solder pastes. In addition, the effect of the different flux chemistries on solder joint appearance could be determined. The samples shown were reflowed with the ramp to peak profile. The solder joint appearance was slightly affected. Type 3 solder paste was not as bright and shiny and was a bit grainy compared to the finer type 6 solder paste, but overall the appearance was fairly good, especially with the no-clean formulation.

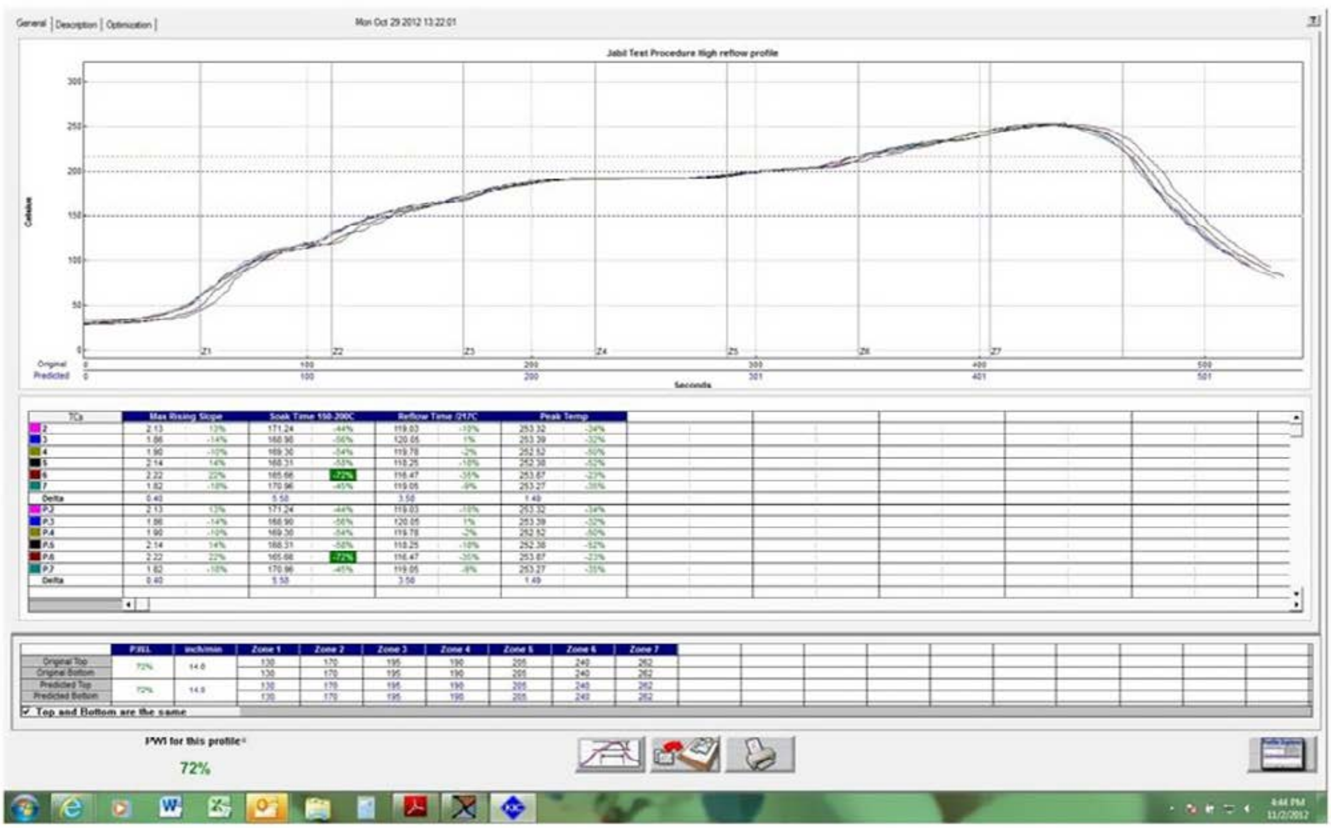


Figure 12: Harsh profile.

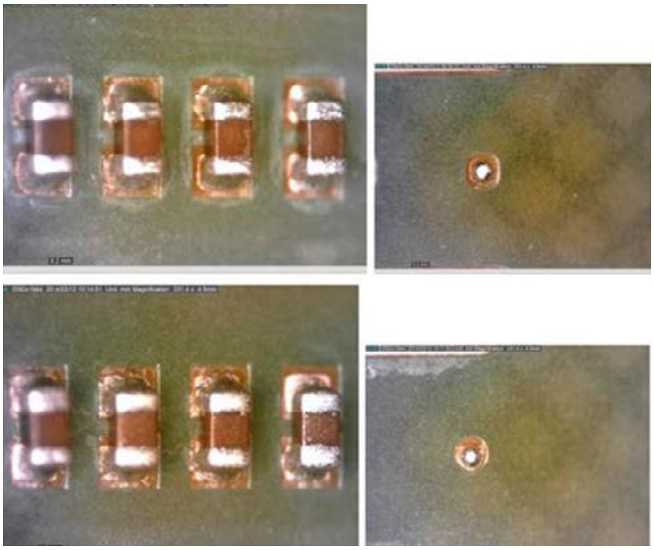


Figure 13: 0201 components and 6 mil dot, water soluble paste (Indium6.4): type 3, top; type 6, bottom.

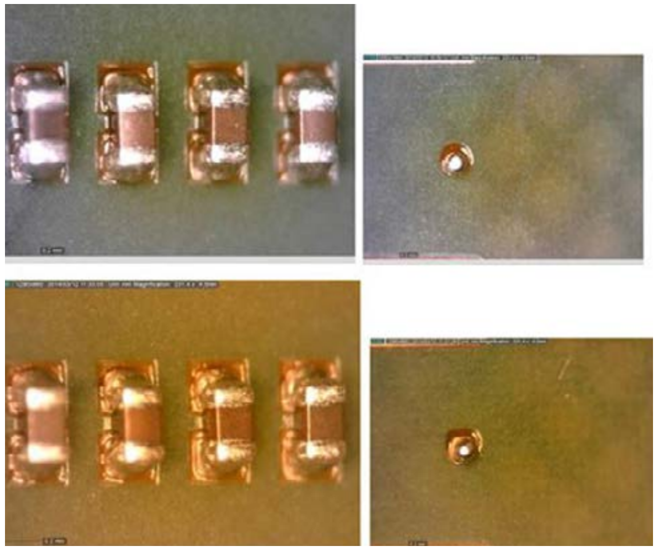


Figure 14: 0201 components and 6 mil dot, no-clean solder paste (Indium8.9): type 3, top; type 6, bottom.

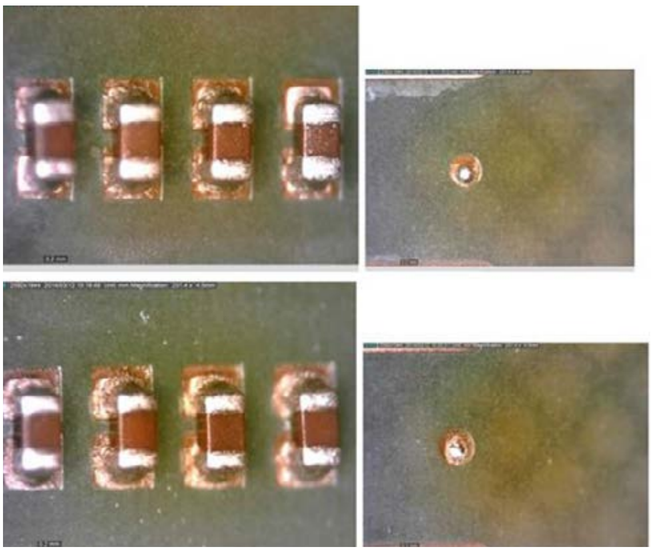


Figure 15: 0201 components and 6 mil dot, water soluble Indium6.4 type 6: ramp to peak, top; soak, bottom.

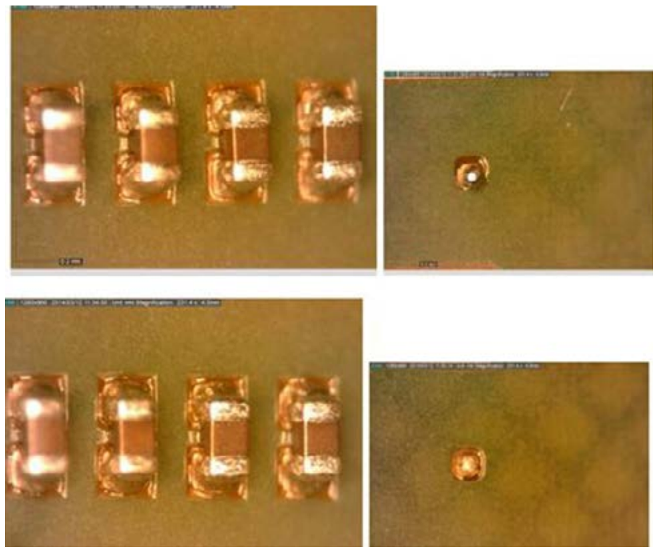


Figure 16: 0201 components and 6 mil dot, no-clean Indium8.9 type 6: ramp to peak, left; soak, right.

A couple of observations can be made from Figures 15 and 16. First, a dramatic effect is seen in the type of reflow profile; the harsh environment imposed by the hotter, longer profile exhausts the flux activity and oxidative resistance. The solder joints show observable effects of flux exhaustion giving an appearance of some dewetting and graping (oxidized solder particles that do not coalesce into the solder joint). The type of reflow profile used shows the effect on the solder joints, as seen in the observable results.

The second observation is in regards to flux formulation. Note that a more dramatic ef-

fect is observed between the ramp to peak and soak profiles for the water soluble formulation. This result is consistent with prior experience and due to lower oxidation resistance of water soluble fluxes. It is true that water soluble formulations are more active, but the oxidation resistance is poor in comparison to rosin/resin based no-clean formulations. Activity refers to the ability to remove existing surface oxides; oxidation resistance refers to the ability of the flux chemistry to prevent re-oxidation, which occurs later in the reflow process. Rosin/resin provides an excellent oxidative barrier, widening the reflow process window. This is especially true if a ramp to peak type profile is not attainable.

Summary

The utilization of ultrafine solder powders can improve transfer efficiency in the stencil printing process and effectively reduce the area ratio acceptance level to 0.50. Some contributing factors need to be considered such as square vs. circle and solder mask defined pads vs. copper defined to attain desireable results.

A trade-off when choosing ultrafine solder pastes is the premature flux exhaustion due to an increase in total surface oxide, and sensitivity of the smaller paste deposit-utilized for the oven environment. The total heat excursion that the solder paste endures may need to be optimized. Striving for a ramp to peak type profile with a peak temperature 240–245˚C (SAC305), time above liquidus 45–60s, and an average ramp rate 1–1.5 ˚C/s is ideal. No-clean flux formulations provide more oxidation resistance than water soluble formulations and can widen a reflow process window, especially if a ramp to peak profile is not attainable. **SMT**

Acknowledement

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Efficient Thermal Cooling and Heating

Thermal systems use heat to produce cold, and vice versa. To do so, a material must dissipate water vapor particularly well and quickly. A new method applies this property as a layer onto the components.

Refrigerators have the human body as an example: When we perspire, water evaporates on our skin and cools it. If the process is transferred to a vacuum, water evaporates at a few millibar and a temperature of 10 degrees. For the devices to continuously cool, vapor must be removed. This is achieved, for example, by an electric compressor.

An alternative is the thermal compressor; the operating power is not electrical, but thermal. Heat pumps or chillers produce cold from heat, and vice versa. So far, however, these have not been able to prevail entirely over their electricity-powered counterparts.

Researchers at the Fraunhofer Institute for Solar Energy Systems ISE have now closed this gap. Their metal organic frameworks (MOFs) are well suited to absorb water vapor.

These layers can be directly applied without further auxiliary layers. In prototypes, MOFs are directly crystallized onto metals. For other materials, such as ceramics, the scientists have accomplished this with binder-based coatings.

In both methods, the components of the device are immersed in a fluid containing the essential components of the material. The temperature needed for direct crystallization occurs only on the surface of the component, with minimum waste.

News Highlights from SMTonline this Month

1 IPC Certifies Conflict Minerals Data Exchange Standard

IPC-1755 was developed under a globally recognized, industry-consensus standards process, which makes it easier for companies to use a single standard for all international operations. Support from AIAG, CFSI, and JEITA highlight the global support for this effort. The association's experience in developing industry-consensus data exchange standards helped standardize the data fields.

2 Varitron Expands Presence; Acquires Altronics

"Varitron and Altronics provide similar services, but also have complementary offerings intended for different markets," notes Michel Farley, president of Varitron Group. "By pooling our expertise, we will be able to serve more customers and to provide added value in terms of volume with the aim of consolidating the U.S. market and developing new niches."

3 Newbury Extends Free Parts Listing for PCB Components

Newbury Electronics is increasing its list of free parts for use in its PCB assembly to over 1,000 different components with immediate effect. The free parts scheme has been on trial for some time but has now been greatly extended to include a wider range and more expensive components. This new approach to costing will apply across the company's PCB Train assembly operation.

4 Lower Mfg Volumes in Europe Hurt Incap's Q1 Revenue

The Group's revenue was EUR 5.5 million, down approximately 51% year-on-year (Q1/2013: EUR 10.7 million) due to the decreased manufacturing volumes in the company's factories in Europe.

5 Flextronics Expands Capabilities; Joins OpenDaylight

"With the advent of convergence, SDN and cloud, we see rapid shifts in the end-markets of our OEM customers. By leveraging open source platforms such as OpenDaylight, our OEM customers are able to get ahead of these shifts in the IT space," said Dharmesh Jani, VP, Cloud Strategy.

6 Enics Slovakia Receives ISO/TS 16949 Compliance

The plant has received an ISO/TS 16949 compliance letter from Bureau Veritas stating its conformity with ISO/TS16949:2009—the Quality System Requirement used in the automotive industry. "This is a remarkable achievement and proves that the people, processes, and systems are in place to meet most stringent quality requirements from the customers," said Jari Utriainen, quality director.

7 SMT's Recovery Continues to Gain Momentum in FY2014

SMT's recovery continues to gain momentum. We are seeing increases in demand from most of our existing customers, in particular those from Europe. There are new projects and new customers. Our outlook is positive. However, the escalating operating costs in China remain challenging.

8 Incap Concludes Vaasa Factory Negotiation; Trims Jobs

The negotiation process started on March 24, 2014 and total of 74 persons were invited to the negotiation process to discuss the actions to adjust the Vaasa factory organization, operations, and cost structure to match the current and estimated situation.

9 Deswell Suffers Sales Decline in FY 2014

Deswell's net sales for the fourth quarter ended March 31, 2014 were $7.9 million, down by 16.5% compared to net sales of $9.5 million for the same quarter ended March 31, 2013.

10 EMS & ODM Vendors Benefit from High Capacity Utilization

EMS and ODM services refer to the services for brand vendors except brand marketing, including product development and design, raw material procurement, manufacturing, assembly, and after-sales services.

EVENTS

For the IPC's Calendar of Events, click here.

For the SMTA Calendar of Events, click here.

For the iNEMI Calendar, click here.

For a complete listing, check out *SMT Magazine's* full events calendar here.

SEMICON West TechXPOT: Driving Automotive Innovation
July 8–10, 2014
San Francisco, California, USA

Ohio Expo & Tech Forum
July 17, 2014
Cleveland, Ohio, USA

SusTech 2014
July 24–26, 2014
Portland, Oregon, USA

Advancements in Thermal Management 2014
August 6–7, 2014
Denver, Colorado, USA

Philadelphia Expo & Tech Forum
August 12, 2014
Cherry Hill, New Jersey, USA

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Assembly of Printed Electronics

SEPTEMBER:
Automation

OCTOBER:
Alternatives to Solder