Tin Whiskers: Their Appearance & Minimization In Electronic Connectors

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The whiskering phenomenon has been a chronic problem plaguing the electronic industry for decades, especially with respect to pure tin coatings. With the advancements in tin bath chemistries and tin alloy plating with lead, this problem was surmounted to some extent. Recently, because of impending global environmental regulations and legislation, the expedition to eliminate lead from electronic components has picked up momentum. Concerns of whisker formation in lead-free finishes have resurfaced and have proved to be a nightmare to the electronic industry because of reliability and potential liability issues—especially in fine pitch applications. This paper addresses some of these concerns and attempts to examine the process variables contributing to whisker formation, employing several proprietary lead-free chemistries on a plating line. In manufacturing operations, several factors such as substrate, its surface preparation, micro-stresses in the deposits, nature of chemistry, and post-plating conditions were examined and their impact on whisker formation was evaluated. Applications in press-fit, plated-thru-holes (PTH), and solder to board are also discussed in this paper.

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Introduction

Impending legislation in Europe, environmental directives from Council on Waste Electrical & Electronic Equipment (WEEE), and Restrictions of Hazardous Substances (RHOS) for removal of toxic substances such as lead, mercury, cadmium, chromium in finishes and certain classes of flame retardants in plastic resins are extremely hot issues impacting the finishing industry. The implementation timetable has been fluid so far. Currently, European countries are required to remove lead from electronic products by July 2006. Japan and the Asia Pacific seem to be more advanced in this effort and OEMs are already producing lead-free products. This puts immense pressure on finishing companies, board finishers and component assemblers for qualification of lead-free processes in order to capture the market share of the business. An orderly transition from leaded products to lead-free products requires a systematic and smooth transition without disrupting the supply chain and causing concerns to end-users. Most likely, a gradual offering of lead-free products will occur alongside the eventual phasing out of leaded products.

The component suppliers in connector industry are required to develop, select, qualify and implement some suitable lead-free finishes in order to comply with upcoming legislation in Europe and Asia Pacific. Although there is no direct legislation in USA at present, on the global scene, companies need to participate and comply in order to earn business. Thus, at present, the connector manufacturers along with component finishers are in a quandary about the stringent conditions imposed by the OEM's for meeting certain specifications such as whisker-free coatings, joint reliability, and re-qualification of assembled lead-free products and also meeting the challenges of higher re-flow temperatures.

These legislative pressures and customer demands have led the connector industry to a crossroads with respect to the selection of appropriate lead-free coatings. The materials, components' finishes, and processes that make up the backbone of electronic assembly operations pose challenges to connector manufacturing companies. Lead-free solders and coatings require higher assembly processing temperatures. Consequently, plastics, printed circuit boards and connector housings must in turn be evaluated to determine if higher temperatures can be tolerated. Lead-free coatings such as pure tin, tin-copper, tin-silver, tin-bismuth and tin-silver-copper have been proposed as possible alternative surface finishes. However, the impending tendency towards whisker formation in these coatings is a major concern on the part of users. End users in high reliability applications such as space satellites, telecommunications, defense equipment, and crucial medical devices are highly reluctant to use pure tin or other alloys of tin (excluding lead). This is because of questionable reliability with fears of possible product failure and product liability. Higher re-flow temperatures pose another concern because of questionable dimensional stability of resin materials.

Initial lead-free development work using various coatings was presented earlier.[1-3] The present paper critically examines the application of vended matte tin and bright tin-copper baths in high-speed reel-to-reel operations. The effect of process parameters on metrology, deposit characteristics, solderability, propensity of whisker formation was studied and ways for whisker mitigation in connector applications are discussed in detail. Applications in press-fit, plated thru holes (PTH) and solder to board are also described in this paper. The impact of higher temperature re-flow of lead-free solders on resins has been described elsewhere.[4]

Experimental

Phase I of this study consisted of evaluating several matte tin, bright tin-copper, matte tin-copper and one bright tin-lead commercial baths. Extensive testing on select coatings was continued in Phase II. Reel-to-reel electroplating was performed on stamped terminals of phosphor bronze 510 at controlled current densities and line speeds to achieve desired plating thickness on the compliant section of contacts. A dedicated sump tank was employed for all lead-free work. The sump tank, two 16-inch long tin plating cells, and associated plumbing were leached first with 15% NaOH and then with 15% methane-sulfonic acid (MSA) overnight with thorough rinsing in between the steps repeatedly in order to free the leachate from lead and copper contaminations to less than 5 ppm. Copper content in the deposit was estimated by plating a coupon of Alloy 42, its dissolution in aqua regia and solution analysis by atomic absorption spectroscopy (AAS). A thickness of 60-80 ìinches of matte sulfamate Ni as under-layer was applied all over the test parts. Plating thickness was measured by X-Ray fluorescence spectroscopy (XRF) [5]. Total carbon in the deposit was determined using gas fusion analysis on oxygen-free high conductivity copper (OFHC) plated strips using rotating disc electrode (RDE). Coating morphology rating (CMR) and grain size of the deposits was studied by SEM microphotographs. The adhesion test on coatings was performed according to ASTM procedure.[6] Solderability testing[7-8] of deposits was carried out using a Meniscograph on samples "as is," after steam aging for 8 hours using lead-free solder, Sn-Ag-Cu, and compared with 63Sn-37Pb solder.

Whisker testing for these coatings was studied in two phases. Phase I consisted of examination of all test samples: a) as is after plating, b) after bending at 90°, c) exposure to 55° C, ambient humidity (15-30 %), and d) at 55° C and of 85% relative humidity. Three contacts were included for each set of conditions in whisker testing.

Phase II comprised of first subjecting samples to 500 accelerated thermal cycles (ATC) from –40°C to 95°C with dwell time of 10 minutes each in cold and hot chambers in order to induce stresses and evaluate any whisker formation. A set protocol was followed for SEM examination of whiskers. The samples from chambers were mounted with copper tape on a carbon coated Al stub and introduced into SEM chamber. Initially, the entire lead was examined at low magnification of 20X for location identification. We then searched for whiskers in pre-selected areas at appropriate magnifications (500-2000 X) at 20 KV and at 15 degrees tilt. Whisker growth examinations were carried out after every three weeks. Grain size was also estimated from SEM photos @ 3000X.

The stress in coatings was monitored using commercial Stress Analyzer. Be-Cu strips were plated at known current density and from the knowledge of total deflection between the legs, deposit stress was calculated. The type of bend (concave or convex) also indicated if the stress was compressive or tensile in nature. Stress on select samples was monitored by X-Ray Diffraction (XRD) technique.

Results and Discussion

The selected finishes were examined for their appearance, adhesion, morphology, thickness and solderability properties. Most of these baths were suitable for plating processes in reel-to-reel applications. Figures 1 and 2 depict morphology of some of these coatings.

A. General Bath Comparisons

1. Most of the Sn-Cu baths contained MSA based chemistries with at least two additives and a carrier. Some baths were sulfuric acid-sulfate chemistries. From practical considerations, these additives

could be controlled by Hull Cell tests and or AMP/Hr usage. Additive concentrations in some baths could be determined using HPLC which may not be feasible in routine production. Cyclic Voltammetry Stripping (CVS) method for monitoring additives in some baths was applicable.

2. The coatings on the parts could be applied selectively either by control depth or by a plating wheel with masking belts. This was contingent on the ability of the bath not to generate extra foam in the plating cells and also in the sump. In some cases, sporadic sprays of de-foamer were necessary in order to diminish foaming in the sump and or cells. Due to the limited throwing power of a bath, some parts can pose plating problems in the recesses or other areas of parts where the solution could not reach efficiently.
3. The deposit thickness was controlled by varying the line speed and or applied dc amperage. At higher amperage most of these baths appeared less efficient, and treeing was also noticed with burning on the edges. The appearance also got darker at higher amperes with dendritic growth and micro-cracks in deposits.
4. All coatings passed solderability tests with solder coverage > 95 %. The bright tin-copper coatings seemed to be more resistant to oxidation and had thinner oxide films as compared to pure tin coatings. This was indicated by the solderability data of steam-aged samples. The wettability and wetting forces were similar to tin-lead finishes.
5. Some tin finishes after steam aging showed poor solderability with a non-active flux. This behavior improved with an active flux which removed oxides films more effectively.
6. Some tin coatings exhibited tarnishing and discolorations after re-flow operations
7. Intermetallics (IMC) formation was observed on copper substrates without Ni under-layer. The IMC layer grew with prolonged annealing time and was thicker in samples without Ni under-layer.

B. Intermetallics and Oxide films

In presence of nickel under-layer, the IMC formation was retarded. However the outer surface of tin films tend to oxidize in air and in heat. The oxide formation and its thickness on matte tin coating were studied by XPS. It was noticed that oxide films grew in thickness with prolonged steam aging. The composition of the oxide layer was mainly due to SnO. The thickness of oxide layers at ambient conditions ranged between 25-50A° and grew to 100 A° after 8 hours of steam aging.

C. Reflow of Coatings

Reflow process is known to diminish internal stresses in electrodeposits.[9] Reflow experiments were performed on various coatings following a pre-selected temperature profile with peak temperatures of 250°C, 260°C in the presence of nitrogen with and without flux. Generally, reflow of matte finishes with low carbon (100 ppm) progressed smoothly without any surface defects, cosmetic defects and puddling. The bright coatings with higher carbon content tended to outgas causing pinholes, islands of solder with voids (measling), dewetting, and discoloration of coatings. The outgassing causes deleterious effects on solderability and joint strength. Surface conditions before and after reflow with and without flux in nitrogen are depicted in Figure 3.

The peak temperatures for many lead-free solder alloys range from 240-260°C, which will require higher temperature thermal profiles. In order to accommodate higher temperatures, newer reflow soldering equipment, and extra preventive maintenance will be required for better output. Prolonged exposure to high temperatures at lower belt speeds may damage the boards and components. Also for improved wetting, reflow soldering may be desirable in inert atmospheres.

D. Stress Measurements of Coatings

The intrinsic stresses in coatings vary with the nature of plating bath, deposition of organic and inorganic impurities in deposits and operating conditions such as agitation, temperature and current density. The macro-stress of coatings was monitored by employing a commercial Stress Analyzer, similar to that described by Kanani et al.[10] Be-Cu strips were plated at known current density in a plating cell. The Be-Cu strips are coated with photo-resist on opposite sides of legs so only one side of each leg gets plated. The nature of bend on the plated legs dictates the stress (concave bend for tensile stress and convex bend for compressive stress). After measuring the total deflection between the legs, the stress in the deposit is calculated by the simplified formula based on Stoney's equation.[11]

The stress in tin deposits was tensile in nature. It varied with current densities and was in the range of 2500-4000 Psi when plated.

Residual micro-stress measurements were also measured using the $\sin^2 Ø$ method by X-Ray Diffraction on selected coatings. The detector searches for specific peaks while the sample is tilted through a range of values. A least square fit of peak position with $\sin^2 Ø$ along with elastic constants, helps to compute residual stress. The precision of stress measurements of tin coatings by XRD technique is poor.[12] Stress is known to change with coating thickness, plating chemistry, current density, under-layer, thermal annealing and inter-metallic formation and even handling of a film.

E. Whisker Studies

Tin coatings are notoriously known for generating short and long whiskers depending on the type of deposit (matte or bright). Designed experiments studied this tendency towards whisker formation in various finishes under controlled conditions including: after accelerated thermal cycling, ambient temperature storage, 55°C dry heat and 15-20% RH, 55° C and 85% RH.

Table I summarizes the results of whisker growth for different finishes under varying conditions. The samples were initially examined every week and thereafter every second week when whisker growth on the samples was detected. The purpose of the study was to evaluate the tendency of coatings to produce whiskers by inducing external stress either by mechanical bending or exposure to various environmental conditions. Any relationship between carbon content and whisker formation was also sought. Samples not exhibiting whiskers are being exposed in controlled chambers for ongoing observations.

Types of Whiskers

The representative types of intrinsic[13] whiskers found in this study are shown in Figures 4 -8. There were no dendrites present, which are basically generated due to extraneous factors such as high current density and or imbalance in plating bath composition. The typical shapes are comprised of odd shape eruptions (OSE's), needles, branched whiskers, and striated whiskers with pillars with caps at the ends. Samples on brass without Ni under-layer and tin-lead coating were also employed in the study as controls.

a) Whisker Growth

Large OSE's and whiskers of all sizes of varying aspect ratios, especially at the sheared edges, were observed in matte tin coating from bath J without nickel under-layer when subjected to ambient temperature, dry heat @ 55°C (RH 15-20%), and @ 55°C (85% RH). In the presence of Ni layer, this coating (grain size < 1µm, carbon content = 50 ppm) did not grow any whiskers for up to 14 weeks with exposure to all conditions. Some samples plated at high current densities exhibited denderitic growth right after plating, which are plating defects due to extrinsic[12] conditions and not whiskers. Growth of whiskers in matte tin and tin-copper films in absence of Ni is shown in Figure 9. Whiskers tend to grow faster after the initial incubation period and then the growth subsides due to relief of intrinsic stresses.

Matte tin coating from Bath I with and without Ni under-layer exhibited multiple OSE's (rating = 4) and whiskers under all environmental conditions. Thermal shock cycling (-40ºC to + 95ºC) for 500 cycles induced formation of OSE's and whiskers even in the presence of a nickel under-layer. The large grain size and low carbon in the deposit did not seem to alleviate the whisker problem. The episode of whiskering occurred in the thickness range of 100 µinches - 750 µinches.

Design of Experiments (DOE) on bright tin-copper deposit bath C at varying copper concentrations (1.3 g/l to 10.3 g/l) showed many OSE's after thermal shock cycles. At all concentrations of copper in absence of nickel coating, OSE's and long whiskers were observed. OSE's are known to be precursors to whisker formation and many such instances were noted in this study. In most cases OSE's were observed in the presence of nickel layer. In general, for copper varying from 1.3 –10.3 g/l, whiskers (17-170 µm) were observed in all samples without Ni underlayer. In presence of nickel, small whiskers and OSE's were observed. These designed experiments conclusively point to the fact that Ni helps in the retardation / mitigation of whiskers.[14-19]

b) ***Whisker Evaluation in Connectors***

The risk of long needle whiskers with large aspect ratios is a major concern in reliability of connectors where a possible shorting may cause malfunction producing a ripple effect in failure of other devices in the electronic circuits with fine pitch applications.

We tested various types of termination styles i) Press fit ii) Plated thru holes iii) Surface mount using Sn-Ag-Cu solder iv) Ball grid array (BGA) assembly using Sn-Ag-Cu spheres . These assembled samples were subjected to 55C/ambient humidity, 55C/85% RH. Similar tin-lead finish connectors were used as controls for these termination styles also. So far we have not detected any whisker formation under these conditions after 3 months of different environmental exposures.

The press fit contacts (Eye of needle, Baby H) have low plating thickness (10-30 µinches) and we have not noticed any whiskers under all test conditions. Although there are mechanical stresses at the contact boundaries on the inserted terminal in plastic housing, due to low thickness, no whiskers formed due to limited coating material. One important facet of press-fit application involves the application of excessive stresses imposed on the substrate as well as the lead-free coating. The seal at the inner areas usually is gas tight and whisker growth in those areas may or may not happen and is of no consequence. There may be some concern with respect to the exposed areas of the eye of the needle inside the hole. In addition, the lead-free coated pin protruding from either side of the board may tend to whisker. However, due to low coating thickness, chances of whisker formation seem remote[12]. This is strictly coating dependent, and extra care should be exercised in selection of a finish. We are currently conducting whisker studies on some press-fit parts (Figure 10) and have not observed any whiskers so far. Another plausible solution is to anneal the part at 150-170°C for one hour to relieve any residual stresses in materials.

For surface mount, BGA and other re-flow applications, no whiskers were observed where the solder and coating have the opportunity to transform to a liquidus state thus relieving any stresses in deposits. The risk for whiskers may still exist due to the proximity of passive components on the board and the absence of reflow of tin coating above the heel joint. We would like to determine whether reflowed Sn-Ag-Cu (SAC) results in whiskers or not.

c) General Observations

1. Except for a few instances, most of the whisker growth was noticed in the presence of temperature and humidity. Arnold[14] also reported more whiskers generation in warm, moist atmosphere. Only in some cases whiskers were observed in dry heat.
2. Some whiskers were observed on flat areas but more were observed on sheared edges. The preponderance of whiskers near the shear break edges is possibly due to mechanical stress in the metal substrate caused during stamping operations.
3. EDX analysis of whiskers indicated the presence of pure tin. Absence of Cu, Pb, Ni, intermetallics was shown. Presence of impurities in grown whiskers is still polemic according to some reports. Radioactive tracer studies may help in elucidating the diffusion- migration / recrystallization mechanism.
4. The size of whiskers varied from coating to coating and also with environmental stresses. There was no hard and fast rule for their growth size and shapes. We observed OSE's, hillocks, mounds, striated pillars, needles, bifurcations, flowers, and whiskers that abruptly changed direction during growth. Also, instances of whiskers emanating from OSE’s were found. However, OSE’s may not pose any potential risks of shorting in electronic devices with fine pitches due to their short sizes.
5. Whisker lengths varied from 5 µm to 170 µm depending on the coating and environment with varying aspect ratios (length/diameter).
6. Whiskers were observed even in matte coatings with low carbon levels (.005%).
7. We observed whiskers even in matte tin coatings with large grains (5-10 µm).
8. Sporadic incidences of whiskers were even observed in tin-lead coatings.
9. The whisker density and sizes may not be reproducible in identical plated samples.

There are several mechanisms and explanations[17-28] postulated for whisker growth but none of these can be ascribed universally to explain unusual behaviors. Recently, a survey article summarizing the previous work on tin whiskers, is compiled by Galyon[29] under NEMI modeling project. The phenomenon of whiskering is unpredictable and irreproducible. The general consensus is that growth results from the presence of compressive stresses arising from mechanical impacts on substrates, internal micro-stress in the deposit, induced stress due to intermetallic formation, and environmental impact due to temperature, humidity and thermal shocking. The following conditions are known to diminish whisker occurrences:

1. Low stress in the substrate
2. Chemical pretreatment of substrate
3. Stringent control of bath chemistry
4. Control of inorganic impurities in the bath
5. Minimum carbon in the deposit
6. Achieve tensile stress in deposit by process optimization
7. Reduce IMC role by using 80 ìinches Ni under-layer
8. Annealing of substrate @ 150-180º C

9. Post annealing of plated material
10. Avoid post plating forming operations
11. Re-flow tin coatings

A critical examination of the results led to following conclusions:

The size of whiskers varied from coating to coating. There was no hard and fast rule for their growth size and shapes. We noticed all kinds of OSE's and also twisted striated pillars with domes. A bright tin-copper exhibited OSE's after 18 months but the size of these eruptions/mounds were so small that the possibility of shorting seems remote. The length ranged from 5ìm to 40ìm and diameter ranged from 5-15 ìms.

It is well known that the incidence of whisker formation can be minimized by optimizing plating conditions with decreased micro-stresses, but its formation may not eliminated entirely. There is no accelerated standard procedure to grow whiskers. NEMI group is engrossed in conducting a DOE for this purpose. All tin and tin-copper coatings may be amenable to whisker formation. However the whisker density and dimensions should be taken into consideration for product recommendation keeping in view that even tin-lead coatings form whiskers. Mechanical and external environmental factors contribute to inducing whiskers on existing coatings. However, if a given coating does not produce appreciable whiskers after thermal cycling and under aggressive environmental conditions for six months, one may feel a bit more comfortable that the coating may not cause any significant failures during the normal service life of a product. Coatings with whiskering tendency should not be employed in devices having extended life requirements such as servers, telecom central switches, automobiles, and aerospace and military applications. The selection of a given coating for potential electrical contacts should not just be made in consideration of its resistance to whisker formation. Other important properties such as formability, ductility, solderability, fretting corrosion, porosity, and tribological properties, need to be considered in applications.

The mechanism of whisker formation is complex and not well understood. Many variables have been identified as potential contributors towards tin whisker formation and several speculative mechanisms have been postulated. However, tangible explanations have been put forward especially referring to compressive stress, carbon content, and matte vs. bright coatings. Due to lack of a standard whisker growth test, several international consortiums are attempting to come up with a standard protocol. The task seems difficult due to complexity of multi-variables that tend to influence the outcome. Our data does not point to any generalizations as we have observed whiskers both in a) @ 55°C, ambient humidity as well as b) @ 55°C and 85% relative humidity. Rather, our data shows a preponderance of more whiskers in a hot, humid environment (Table I). The compositional study of grown whiskers showed mostly pure tin in all cases. No indication of intermetallics such as Cu_3Sn, Cu_6Sn_5 or Ni_3Sn_4, $NiSn_3$ was noted. Our results of 500 thermal shock cycles (-40ºC to + 95ºC) followed by dry heat and controlled heat and humidity environments were fairly instrumental in growing OSE's and whiskers in a given coating.

d) *Reflowing Whiskers*
These experiments were conducted with the purpose to determine whether whiskers could be reflowed and the contacts could be used for assembly without any imminent dangers of shorting. Experiments at 250ºC, 260ºC, and 300ºC did not reflow the whiskers in absence of flux. The resistance to the meltdown

of whiskers may be due to the presence of mixed tin oxides such as SnO, SnO_2 (some of which have with melting points of up to 1100ºC) on the surface. In the presence of mild flux, we could melt down the whiskers as shown in the figure 11. The ideal situation is that the parts should be whisker-free to begin with; but in case some whiskers are formed on the contacts, soldering operations during assembly will abolish the condition.

Conclusions

- Both matte tin and bright tin-copper baths were suitable for control depth plating. Some baths required de-foamers to quell excessive foaming.
- All coatings qualified standard tests such appearance, adhesion, solderability in as plated conditions. Solderabilty response for steam-aged samples for matte tin coatings was poor in presence of non-active flux due to presence of oxide films. The behavior improved dramatically in presence of highly active flux, which seemed aggressive for removal of passivated surface films.
- The propensity of whisker formation was similar in matte tin coatings as compared to tin-copper finishes. The whisker tendency could not be correlated to total carbon in the deposit.
- There were odd shape eruptions and whiskers near the edges of terminals. This is explicable due to the stress in the substrate that is introduced during stamping of the raw material.
- The macro-stress in these deposits was tensile in nature. This possibly transforms into compressive stress due to contributions from stresses of the substrate, under-layer, environment, IMC or impurities in plating baths. The role of tin–copper IMC formation diminishes in presence of 80 µinches of nickel under-layer.
- In tin-copper and pure tin coatings, for solderability operations using hot air and wave solder, there is a need to qualify resin materials so they are capable of withstanding higher temperatures. This will impact the production cost contributed by equipment, materials and energy.

This study summarizes our overall experience in utilizing the bright tin-copper and matte tin as lead-free chemistries for desired surface finishes. It is apparent that there is no direct easy solution for replacement of tin-lead coatings. The tin-lead coating processes have been utilized for the past 50 years and our knowledge base and experience in using these coatings is mature. On the other hand, alternative baths for lead replacement are being developed and tested and are still in their infancy. There are several important issues confronting lead-free processes such as stable bath formulations, stability on storage, long term behavior on high speed plating lines, additive replenishment, uniformity in alloy compositions, deposits' metrological and tribological properties, uniformity in coatings, stability and shelf life of coatings, phenomenon of whisker formation, solderability characteristics, and high reflow temperatures, etc. The elevated temperatures required for reflow pose another challenge, and our results show only selected resins qualify the tests. Considering all these attributes, it seems that the industry has to adopt certain achievable specifications. With regard to propensity of whisker formation, the selected coating should behave similar to 90Sn-10Pb coating. Our results with some Sn–Cu and matte tin chemistries seem promising, and these coatings may be suitable in lead-free applications. It is apparent that implementation of lead-free processes will impact production costs due to special additives, multiple baths, and increased reflow temperatures and special resins needed for coping with high temperatures. However, the evolution of no-lead chemistries has begun with great zeal, and with further developments and experimentation, the engineering community will collect enough data to meet the demands of customers as well as satisfy the environmentalists. Binary alloys may appear to be a viable solution whereas ternary alloys seem to be more difficult in process control and alloy composition. We have also sporadically observed whiskers in tin-lead (90-10) baths. Based on the specifications, substrate, type of product, and its product cycle, one may select a suitable lead-free coating for a given application.

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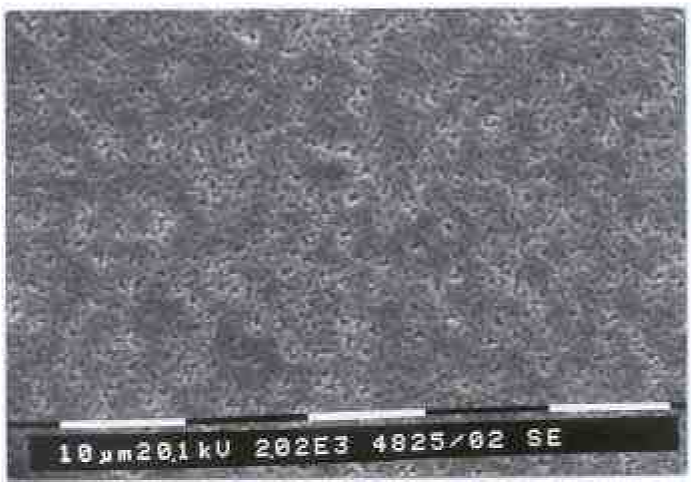
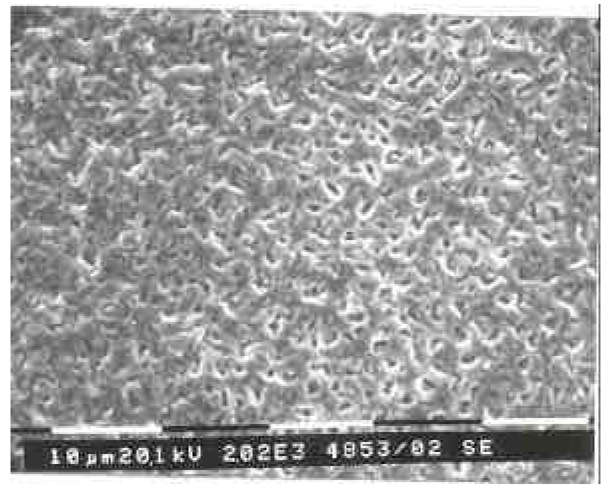
Table I– Whisker Study on Various Baths

BATH	TYPE	CONDITION	TIME FOUND	GROWTH	DIMENSIONS L/D* µm	% CARB ON	Grain Size, ìm
A	Matte Tin	55^{0} C, dry, unbent	6 wks.	None through 12 wks.	3 /12	0.0028	2-5
A	Matte Tin	55^{0} C, 85% RH , unbent	6 wks.	None through 12 wks.	3/12	0.0028	2-5
A	Matte Tin	55^{0} C, 85% RH, unbent	8 wks.	None through 12 wks.	70/12	0.0028	2-5
A	Matte Tin	55^{0} C, 85% RH, unbent	21 wks.	Many New Whiskers	20/7	0.0028	2-5
A	Matte Tin	55^{0} C, dry, 90^{0} bent	8 wks.	None through 12 wks.	12/3	0.0028	2-5
A	Matte Tin	55^{0} C, 85% RH, 90^{0} bent	8 wks.	None thru 12 wks.	12/3	0.0028	2-5
A	Matte Tin	55^{0} C, 85% RH, 90^{0} bent	29 wks.	N/A	Small whiskers	0.0028	2-5
B	Bright Sn-Cu	55^{0} C, 85% RH, unbent	30 wks.	N/A	Small whiskers	0.3550	<0.5
B	Bright Sn-Cu	55^{0} C, dry, unbent	22 wks.	N/A	Small whiskers	0.3550	<0.5
C	Bright Sn-Cu	55^{0} C, 85% RH, unbent	8 wks.	None through 12 wks.	8/5	0.0575	<0.5
C	Bright Sn-Cu	55^{0} C, 85% RH, unbent	12 wks.	N/A	40/5	0.0575	<0.5
D	Matte Sn-Cu	55^{0} C, 85% RH, 90^{0} bent	8 wks.	At 12 wks.	40/20	0.0042	<1-2
D	Matte Sn-Cu	55^{0} C, 85% RH, unbent	14 wks.	Some growth	20/4	0.0042	1-2
E	Matte Tin	55^{0} C, 85% RH, bent	8 wks.	At 12 wks.	Multiple, small whiskers	0.0059	1-3
E	Matte Tin	55^{0} C, 85% RH, unbent	30 wks.	Some growth	25/5	0.0059	1-3
F	Matte Tin	55^{0} C, 85% RH, unbent	8 wks.	At 12 wks.	Multiple, small whiskers	0.0024	< 1
F	Matte Tin	55^{0} C, 85% RH, 90^{0} bent	10 wks.	Multiple growth	25/5	0.0024	<1
G	Matte Sn-Cu	55^{0} C, 85% RH, 90^{0} bent	8 wks.	None thru 12 wks.	Many small whiskers	0.0029	1-2
G	Matte Sn-Cu	55^{0} C, 85% RH, unbent	8 wks.	Multiple at 12 wks.	45/4	0.0029	1-2
H	Bright Sn-Pb 90/10	55^{0} C, 85% RH, unbent	8 wks.	None through 12 wks.	Initial, one small whisker	0.4500	<0.5
I	Matte Tin	Thermal Shock 55^{0}C, 85% RH	2 wks.	OSE/whiskers with and without Ni	10 ìm-85 ìm	0.005	2-8
J	Matte Tin	55^{0} C, 85% RH, unbent	12 wks.	OSE / Whiskers without Ni layer	20 ìm-65 ìm	0.005	< 1

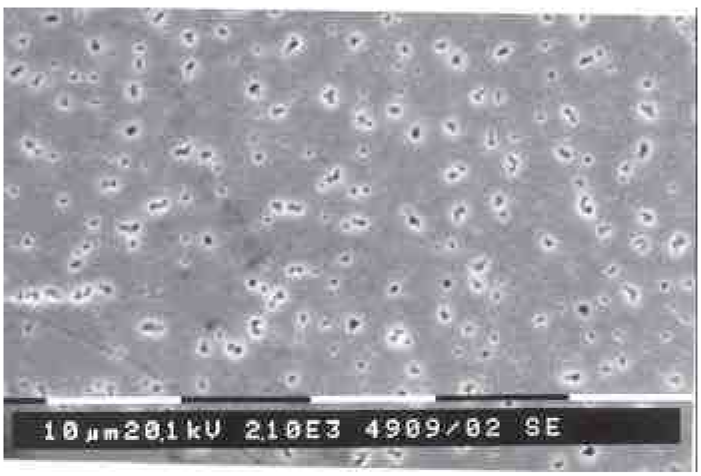
* L/D = Length/Diameter



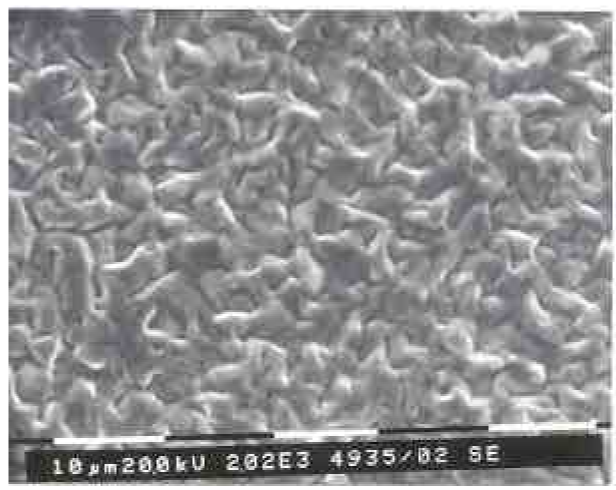
Bright Tin-Copper Vendor (B)



Matte Tin-Copper Vendor (D)



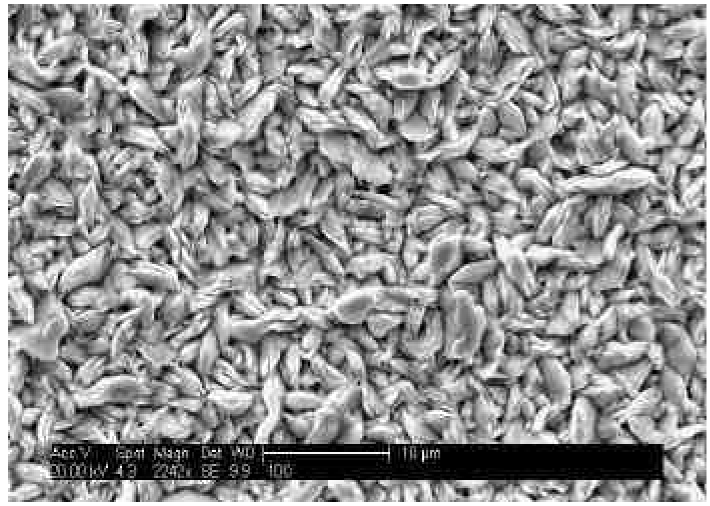
Bright Tin-Copper Vendor (C)



Satin Matte Tin Vendor (A)

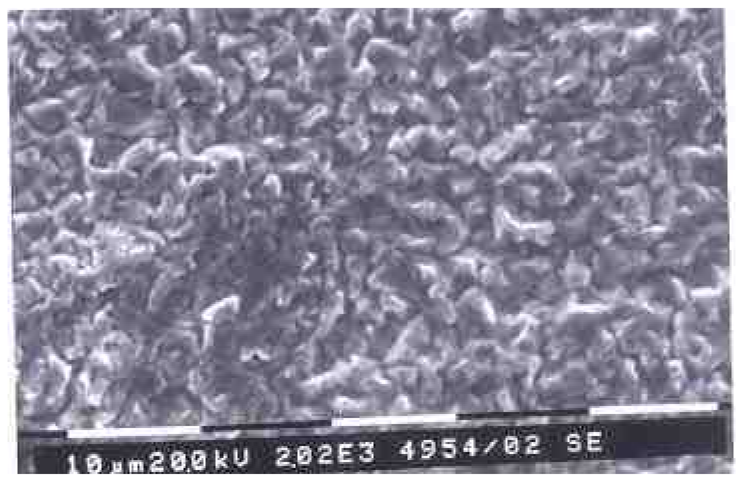
FIGURE 1. Morphology of Selected Coatings

Matte Tin Vendor (F)



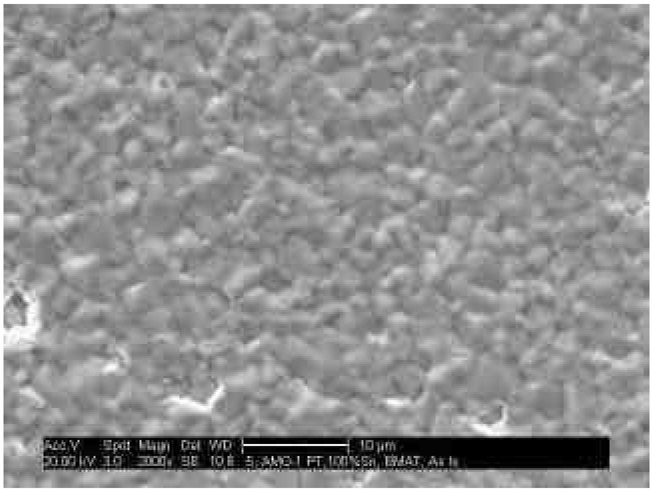
Matte Tin-Bismuth over Ni, Ph. Bronze 510

Bright Tin-Lead (90/10) Vendor (H)

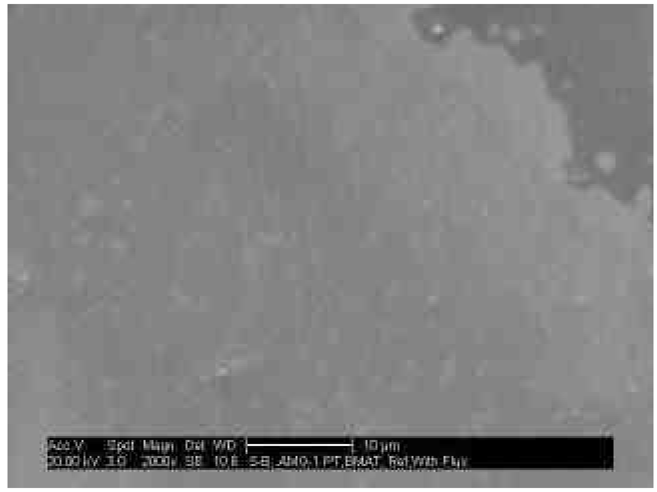


Satin Bright Tin Vendor (J)

FIGURE 2. Morphology of Selected Coatings

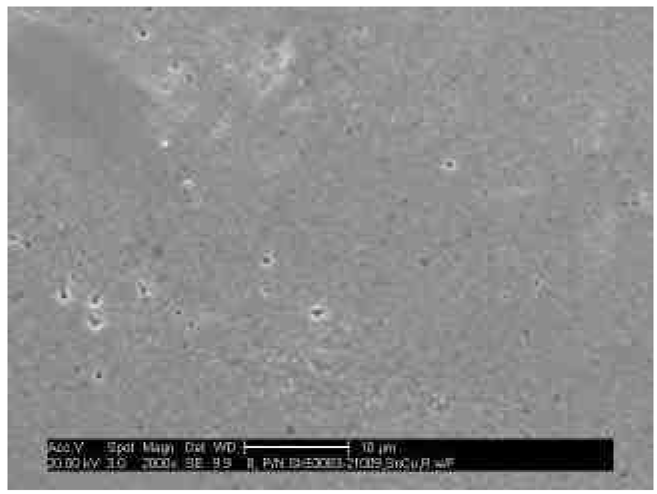


Tin-Lead Before Reflow



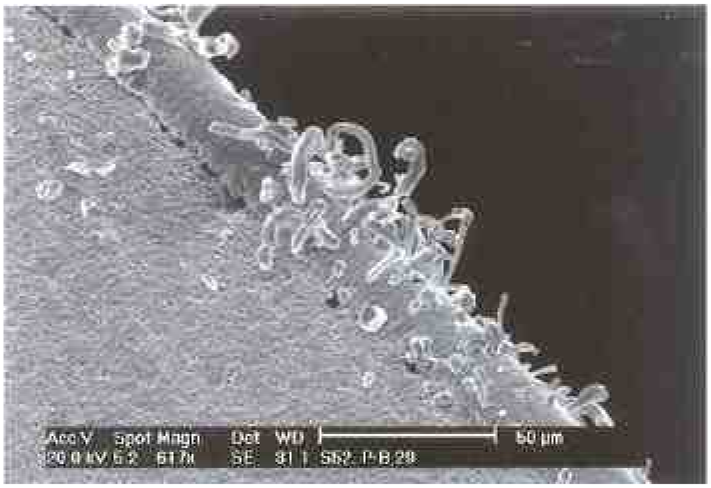
Tin-Lead After Reflow with Flux

Bright Tin-Cu Before Reflow

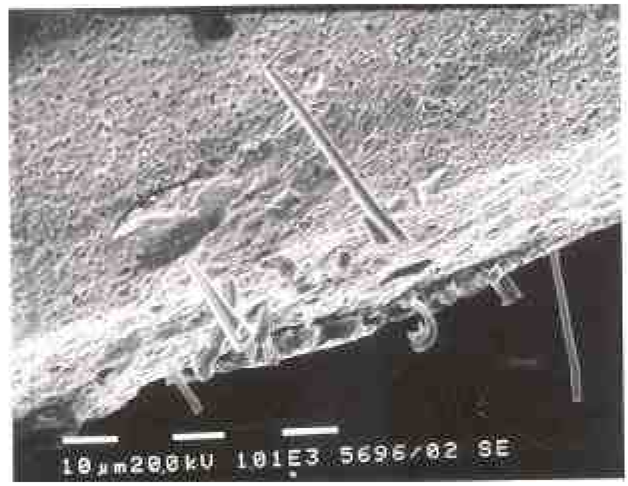


Bright Tin-Cu After Reflow with Flux

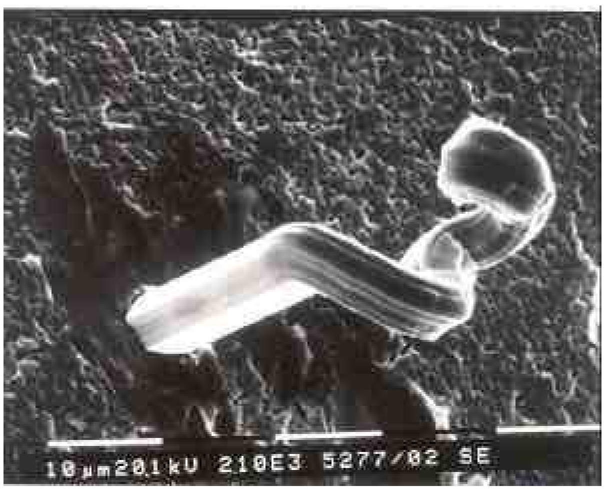
FIGURE 3. Re-flow of Bright Tin-Cu, Tin-Lead with Flux in Nitrogen



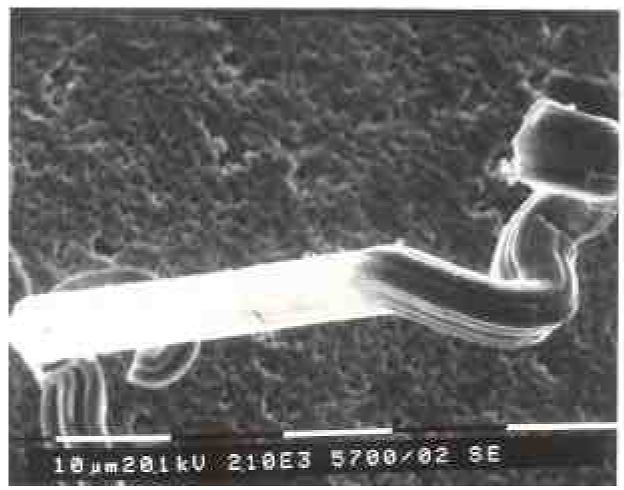
Matte Tin-Copper (G) after 29 weeks @ 55°C/DH/bent



Matte Tin-Copper (G) after 12 weeks @ 55°C/85%RH



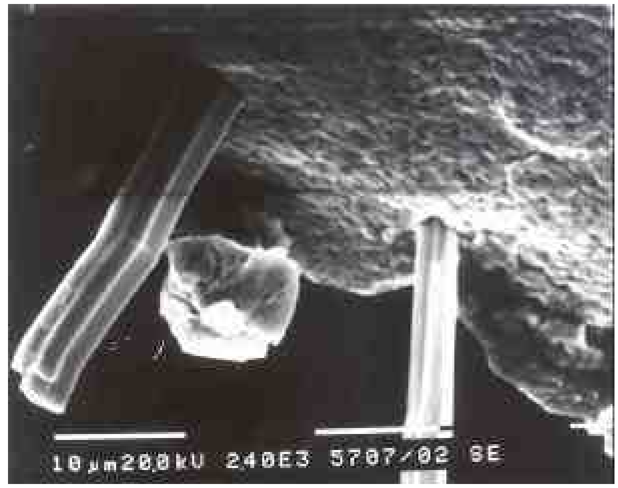
Matte Tin-Copper (G) after 8 weeks @ 55°C/85%RH



Matte Tin-Copper (G) after 12 weeks @ 55°C/85%RH

FIGURE 4.

Matte Tin-Copper (G) after 12 weeks @ 55°C/85%RH showing depletion of tin in the vicinity

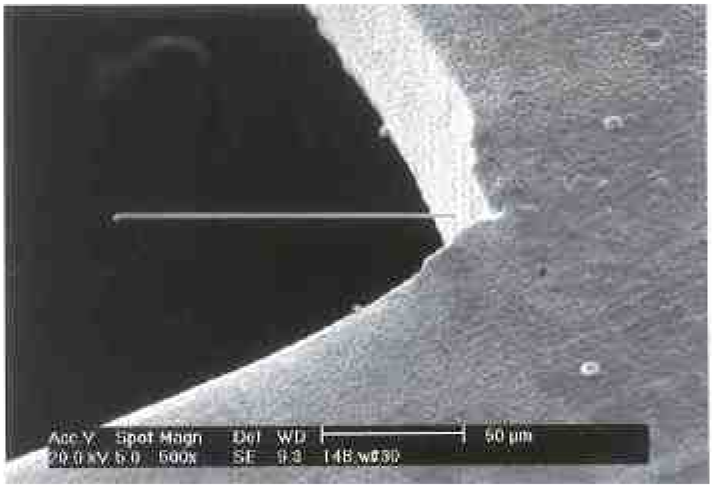


Matte Tin-Copper (G) after 12 weeks @ 55°C/85%RH

Matte Tin-Copper (G) after 12 weeks @ 55°C/85%RH

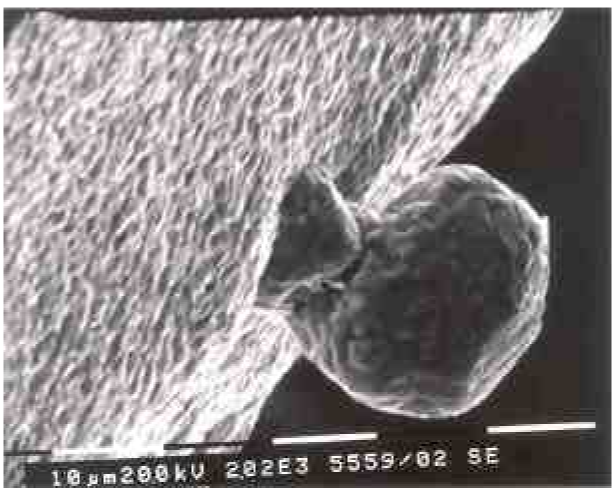
Matte Tin-Copper (G) after 12 weeks @ 55°C/85%RH

FIGURE 5.

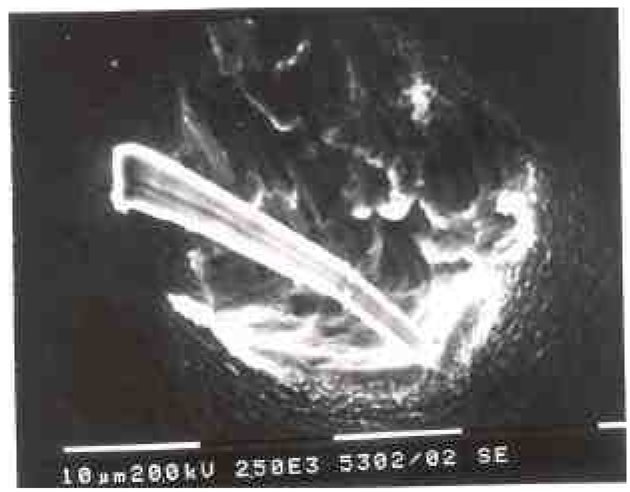


Matte Tin-Copper (D) after 30 weeks @ 55°C/85%RH

Satin Tin (A) Whisker after 14 weeks @ 55°C/85/RH on flat surface



Matte Tin (F) growth @ 55°C/85%R.H. after 10 weeks and no change after 14 weeks

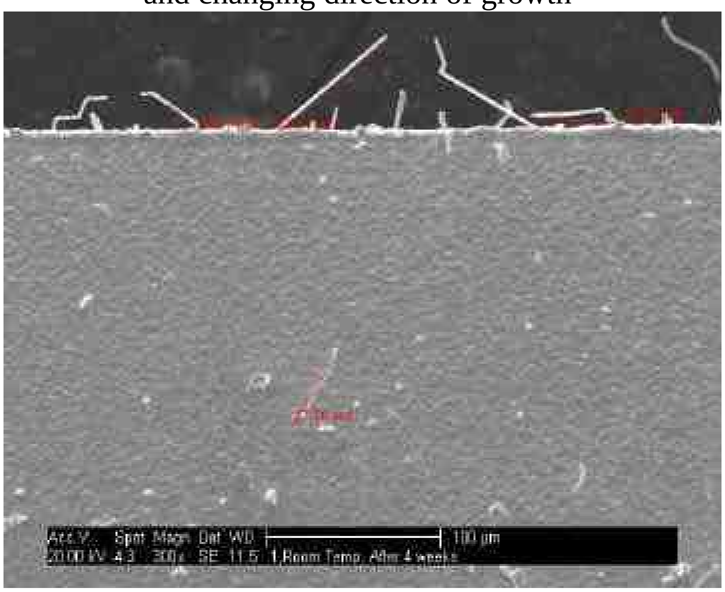


Bright Tin-Lead (H) (90/10) after 12 weeks @ 55°C/ Ambient Humidity (15%)

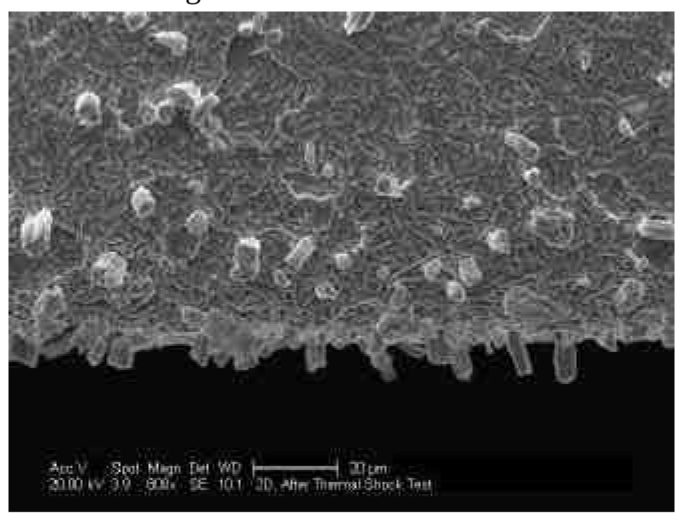
FIGURE 6.

Long Whisker coming out of OSE
and changing direction of growth

OSE's in a bright Tin-copper coating after 18 months
of storage in central office environment



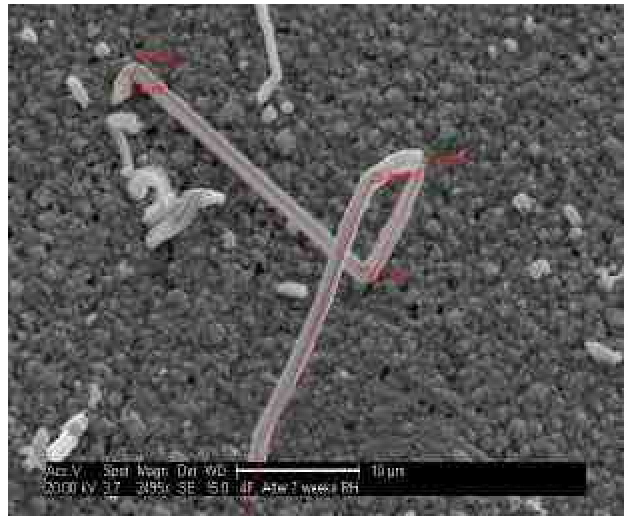
Matte Tin coating @ 55C/ 85% RH and after 500
Thermal Shock Cycles



Matte Tin with Ni underlayer after 500 thermal shock
cycles, 55C and 85% RH

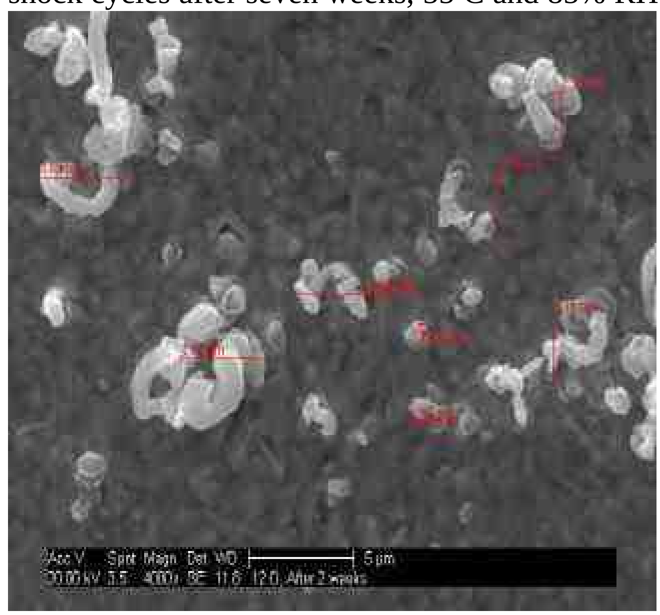
FIGURE 7.

Matte Tin-Cu, without Ni underlayer, 500 thermal shock cycles after seven weeks, 55 C and 85% RH



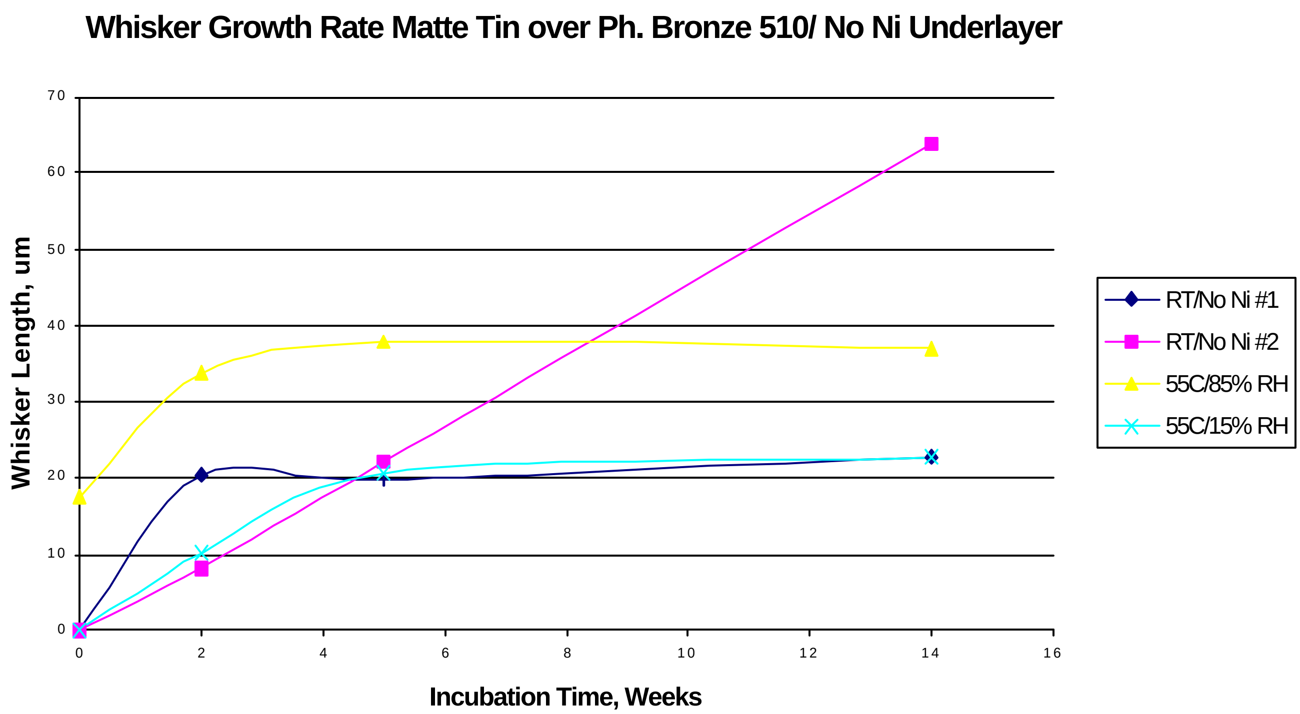
Matte Tin-Cu, without Ni underlayer, 500 thermal shock cycles after seven weeks, 55 C and 85% RH

Tin Whiskers for matte tin-copper coating after 12 weeks @ 55ºC and 85% humidity and ambient storage for 4 months



Matte Tin-Bismuth over Ni, 500 thermal shock cycles and after two weeks at 55ºC and 85% RH

FIGURE 8.


Whisker Growth Rate Matte Tin over Ph. Bronze 510/ No Ni Underlayer
Whisker Length, um
Incubation Time, Weeks
RT/No Ni #1
RT/No Ni #2
55C/85% RH
55C/15% RH
0
10
20
30
40
50
60
70
0
2
4
6
8
10
12
14
16

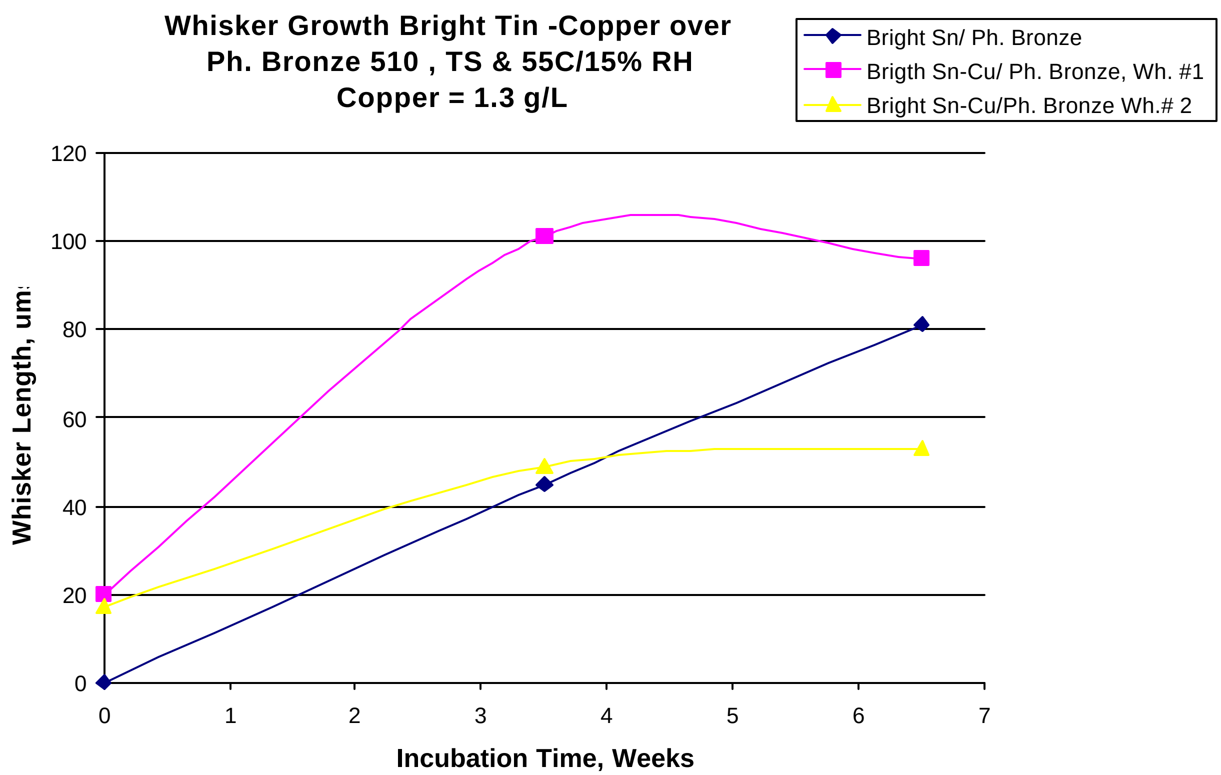
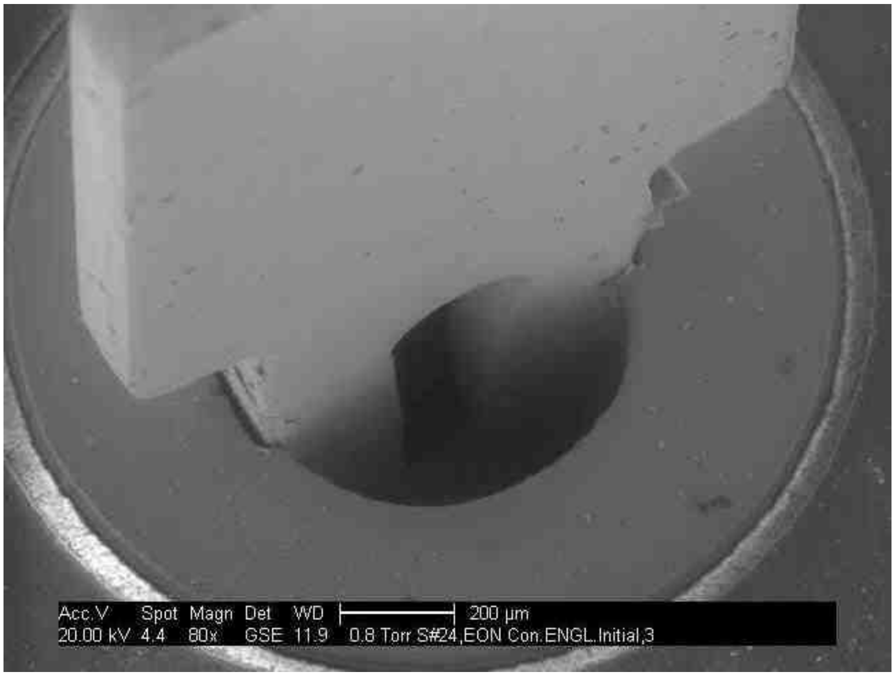
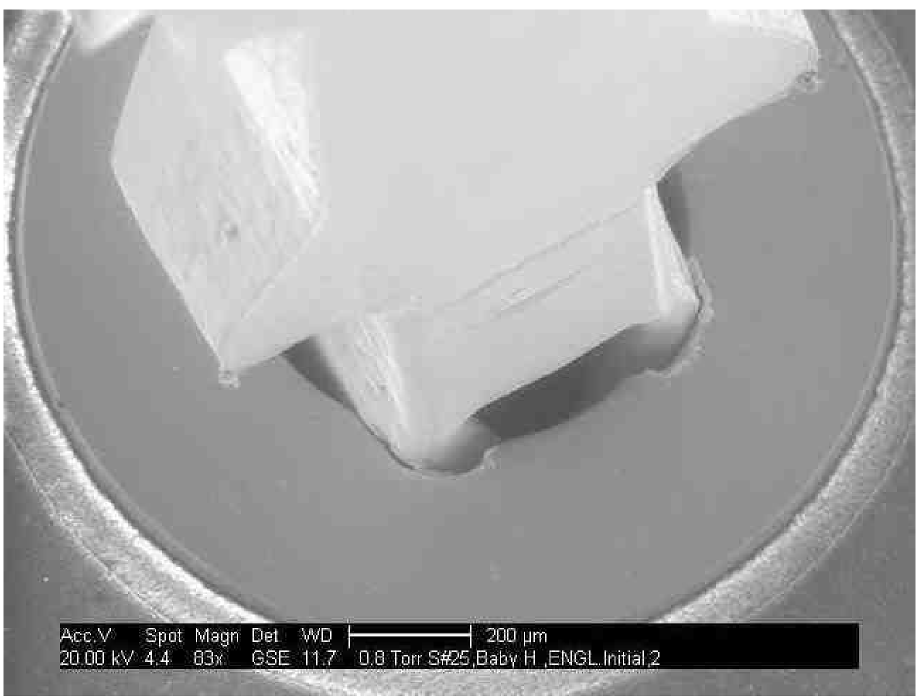

Whisker Growth Bright Tin -Copper over
Ph. Bronze 510 , TS & 55C/15% RH
Copper = 1.3 g/L
Bright Sn/ Ph. Bronze
Brigth Sn-Cu/ Ph. Bronze, Wh. #1
Bright Sn-Cu/Ph. Bronze Wh.# 2
Whisker Length, um
Incubation Time, Weeks
0
20
40
60
80
100
120
0
1
2
3
4
5
6
7

FIGURE 9.

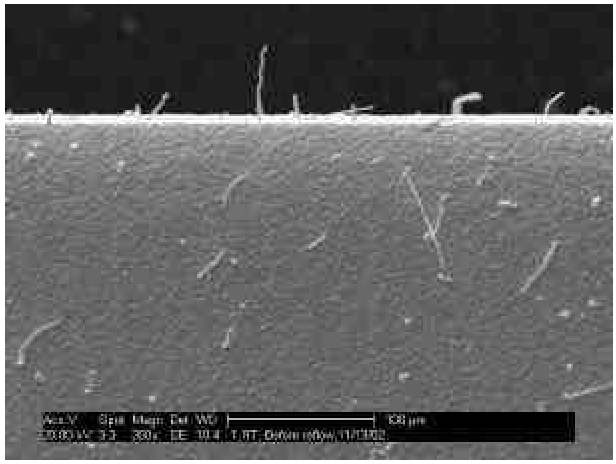


Eye of Needle Contact with Bright Sn-Cu, 55º C & 85% Rel. Humidity

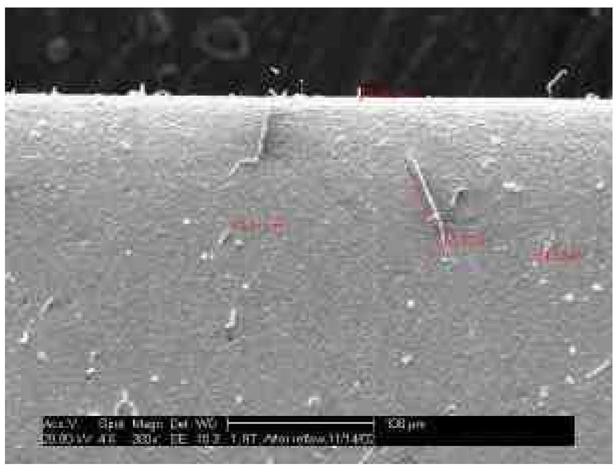


Baby H Contact with Bright Sn-Cu, 55º C and 85 % Rel. Humidity

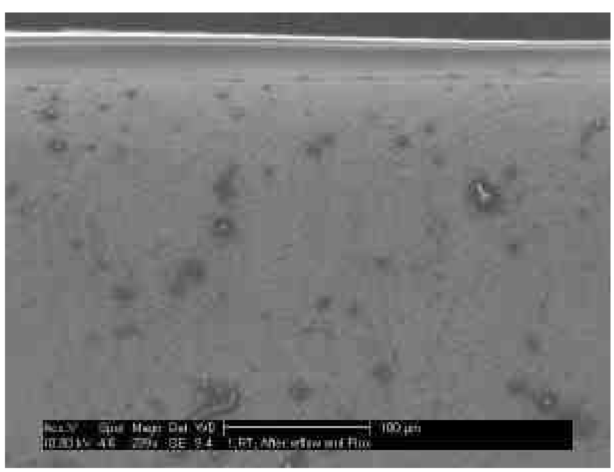
FIGURE 10. No Whiskers on Press-fit Parts



A) Matte Tin Whiskers over Ni plated Ph. Bronze 510



B) Tin Whiskers reflow @ 260C, without flux in nitrogen



C) Tin Whiskers reflow @260C with flux in nitrogen

FIGURE 11. Reflow of Whiskers