Lead-free Coatings in High Speed Electronic Connectors

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Abstract

As a result of legislative pressures and customer demands, the connector industry is at a crossroads with respect to the selection of tangible 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. Two lead-free coatings, pure tin, and tin-copper have been proposed as possible alternative surface finishes. Whisker formation in these coatings is also a major concern. Higher reflow temperatures pose another concern because of questionable dimensional stability of resin materials. This paper critically examines the application of matte tin and bright tin-copper chemistries with respect to process applications in high-speed reel-to-reel operations. Results of process parameters, metrology, deposit characteristics, solderability, propensity of whisker formation and its mitigation are discussed in detail. In order to cope with higher solder temperatures and meet the challenges that arise from use of lead-free coatings, suitable resins for connector housings are proposed.

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Introduction

Proposed legislation in Europe and environmental directives from Council on Waste Electrical & Electronic Equipment (WEEE) for removal of toxic substances such as lead, mercury, cadmium, chromium in coatings and halogens in plastic materials is a hot issue. The implementation timetable is not fixed and continues to change. Currently, European countries are aiming to remove lead from electronic products by 2006. Japan and the Asia Pacific rim seem to be more advanced in this effort and OEMs are expected to roll out products by the end of year 2002. This puts an 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 approach 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. Some suppliers are also working on reducing the content of lead in their products rather than eliminating it altogether.

Presently, the electronic industry is facing crucial decisions in selection of coating finishes, of lead-free solders for superior joint reliability and suitable plastics for the housing materials to withstand higher re-flow temperatures. Initial lead-free development work was presented by the author earlier.[1-3] This paper will address issues relating to coating selection, re-flow temperatures, tendency of whisker formation, and resin material selection.

Experimental

Two matte tin and two bright tin-copper commercial baths were prepared according to vendors' recipes. Reel-to-reel electroplating was performed on stamped terminals of phosphor bronze 510 at line speed of 10 ft/min. A dedicated sump tank was employed for all lead-free work. This tank and two 14-inch long tin plating cells 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 2 ppm. Coupons of Alloy 42 were also plated in a two-liter bath for estimation of copper in Sn-Cu deposit. Tin-copper deposited coupon was dissolved in aqua regia and copper in the deposit was determined by atomic absorption spectroscopy (AAS). Current densities on the plating line were adjusted to obtain desired thicknesses of tin or tin-copper on the compliant section of the contacts with proper shielding of carrier strips. A thickness of 60-80 ìinches of matte Ni as underlayer was applied all over the test parts using sulfamate nickel bath. Plating thickness was measured by X-Ray fluorescence spectroscopy (XRF).[4] Samples for total carbon in the deposit were plated on oxygen-free high conductivity copper (OFHC) using a rotating disk electrode (RDE) and were determined by gas fusion analysis. Coating morphology rating (CMR) of the deposits was studied by SEM microphotographs. The adhesion test on coatings was performed according to ASTM procedure.[5] Solderability testing[6-7] of deposits was carried out using a Wetting Balance on samples "as is", after steam aging for 8 hours, and 72 hours using lead-free solder, Sn-Ag-Cu, and compared with 63Sn-37Pb solder as per ANSI/J-STD-002 method.

Whisker testing for these coatings was studied a) as is, b) after bending at 90°, c) @ 55° C, ambient humidity, and d) @ 55° C in the presence of 85% humidity. Three contacts were included for each set of conditions in whisker testing. Whisker growth examination was carried out every week or every two weeks depending on samples using SEM at 1000X –2000X at 15°-30° tilt.

The stress in coatings was monitored using Stress Analyzer. Commercial Be-Cu strips were plated at known current density and from the knowledge of total deflection between the legs, deposit stress was calculated.

Results and Discussion

The following baths were included in this study:

Bath A:Matte Tin vendor A
Bath B:Bright Tin-Cu vendor B
Bath C:Matte Tin vendor C
Bath D:Bright Tin-Cu vendor D

These proprietary baths were critically examined in view of general functioning and maintenance of their chemistries, smell, handling, stability, deposit characteristics, ease of operation on the plating line, and variability of the process.

Metrology

1. *Plating Thickness*: Samples were plated with 60-80 ìinches of matte Ni from a sulfamate bath. The compliant section was plated with various lead-free coatings and thickness varied between 120-300 ìinches in the compliant section. Determination of copper in Sn-Cu coating could not be measured accurately by EDX due to interference of copper substrate and lack of availability of proper XRF standards. Hence, copper values may not be accurate due to interference, spot size and non-uniform distribution of copper in the deposit. However, copper in tin-copper deposit was confirmed by plating alloy 42 test strips run on the plating line and also on laboratory coupons with subsequent dissolution in aqua regia and analyzed by AAS. Copper values ranged from 1.0-1.5% in tin-copper deposit.

2. *Adhesion*: Adhesion of all coatings was tested according to ASTM procedure[5] on samples as is and also bent at 90°. This test also indicated the ductile behavior of the coatings. All coatings qualified the test and no micro-cracks were noticed in the bend areas.

3. *Appearance:* All coatings were visually examined for general appearance. The Tin-Cu coatings were extremely bright, smooth and free of visual defects such as blisters, flakes, slivers, and cracks. Pure tin bath gave a satin-gray appearance. Bright tin-copper coating is preferred by customers due to its appearance and resistance to tarnishing while in storage.

4. *Morphology*: The morphology of these coatings is depicted in SEM microphotographs (Figures 1-4). Bright Sn-Cu appeared to be smoother with small grain size whereas matte tin coatings were comprised of larger grains. The CMR rating for these coatings was 2-3. This rating is empirical, 1 being the smoothest and 10 the coarsest.
5. *Solderability*: These coatings were subjected to solderability tests using 95.5Sn-4Ag-0.5Cu solder and were compared with a standard 63Sn/37Pb solder in: a) as is condition, b) after 8 hours of steam aging, and c) after 72 hours of steam aging using Alpha 100 flux. The results of this study are summarized in Tables I and II .

Wetting Times

i) All baths had wetting times < 1 second in as plated conditions. It is apparent that there is no significant difference in wetting times in lead-free solder vs. tin-lead.
ii) After 8 hours of steam aging, coating A exhibited highest wetting time in presence of both solders. The wetting times for both bright tin-copper coatings were still less than 1 second.
iii) After 72 hours of steam aging, wetting times of matte Sn coatings from baths A, D were still higher than both Sn-Cu. The wetting times for matte tin bath D were smaller than bath A. Wetting times for bright Sn-Cu bath C were the shortest.

Coatings of bright Sn-Cu from baths B show wetting times <0.6 seconds. The wetting times for a given coating vary with the type of solder used and trends change with duration of steam aging. Coating from bath A exhibited a wetting time of 0.6 sec. which increased to 1.5 secs. and this tended to behave worse after 72 hours of steam aging. It is probable that thicker surface oxide films after steam aging is responsible for this behavior.

Wetting Forces

i) All coatings exhibited appreciable wetting forces ranging from 321-415 ìN/mm in both solders in as plated conditions. The wetting forces for lead-free solder were higher compared to Sn-Pb, indicative of good bonding.
ii) After 8 hours of steam-aged samples, the matte Sn coating A showed the lowest and even negative forces with both solders. This indicates poor wettability. Both tin-copper samples indicated appreciable forces @ 4.5 seconds under these conditions.
iii) After 72 hours of steam aging, matte tin sample A performed poorly whereas both tin-copper samples displayed appreciable forces.
iv) The wetting forces for sample C were always higher than sample B under all conditions showing its better performance.

The wetting forces for these coatings without steam aging were >400 ìN/mm. The wetting forces for bright Tin-Cu after 8 hours were the highest for both solders and decreased for 72 hours steam aged samples. The matte tin coatings exhibited negative forces for steam-aged samples, which indicated poor wettability due to oxide films. This behavior improved considerably in presence of # 809 active flux.

Solder Coverage

i) All coatings showed > 99% coverage under “AS IS” conditions in both solders.
ii) For 8 hours steam aged samples, coating B (Sn-Cu) and D (matte Sn) displayed only 93% coverage with Sn/Ag/Cu, and failed the test.
iii) Among bright tin-copper, coating C always showed 100% coverage irrespective of duration of steam aging whereas coating B gave only 92% coverage. This may be due to excessive surface oxidation.
iv) All coatings exhibited > 95 % coverage with Sn-Pb solder under AS IS, 8 hours, and 72 hours of steam aging except Sn-Cu coating B.

Whisker Testing

The electronics industry has employed tin and tin-lead coatings extensively due to their superior properties such as solderability, corrosion resistance, and mechanical and electrical properties.

However, electro-deposited tin and tin alloy coatings are susceptible to whisker formation depending on the environment, the substrate, and any intrinsic micro-stress during the deposition process. Whisker formation seems to be a mechanical phenomenon and their appearance is aided primarily by stresses in deposited film. [8-14] Their growth may be accentuated by environmental factors such as temperature, humidity, IMC formation and its inter-diffusion in grain boundaries, and growth of oxide films. The whisker phenomenon is a major concern to electronic engineers. Table III summarizes the results of whisker growth to date when a set of three samples were subjected to 55° C dry heat, 55^{o} C and 85% relative humidity as is, and bent at 90°. The samples were examined every week and later on examined 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 exposing to various environmental conditions. Any relationship if any between carbon content and whisker formation was also sought. Figures 5-7 depict some of the representative microphotographs of whiskers found in this study. Samples not exhibiting whiskers are exposed in controlled chambers for ongoing observations. A critical examination of the results led to following conclusions:

- Except for a few instances, most of the whisker growth was noted in the presence of temperature and humidity. Only in some cases, whiskers were also observed in dry heat. This is not in concurrence with previously published reports.
- Some whiskers were observed on flat areas but more were observed near edges after 8 weeks. The preponderance of whiskers near the edges may be due to stress in the metal substrate caused during stamping operations.
- EDX analysis of whiskers showed the presence of pure tin. No indication of intermetallics, or presence of Cu or Ni was noted.
- 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 odd shape eruptions (OSE) and also twisted striated pillars with domes. A bright tin-copper exhibited OSE after 18 months but the size of these eruptions are so small that they may be of no consequence in practical applications. The length ranged from 5 ìm to 40 ìm and diameter ranging from 5-15 ìms.
- Whiskers were observed even in matte coatings with low carbon levels. For example, one matte Tin-Cu coating indicated whisker (10 ìm X 3 ìm) in the compressive area after 8 weeks and that grew to 60 um in length after 12 weeks.
- Whiskers were even observed for tin-lead coatings.

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 for six months under aggressive environmental conditions, one may feel more comfortable that the coating may not cause any significant failures during the normal service life of a product. 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, should also be considered.

The mechanism of whisker formation is complex and not well understood. However, tangible explanations have been put forward especially referring to compressive stress, carbon content, 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 dry heat at 55° C as well as in 55° C and 85% relative humidity. Rather, our data shows a preponderance of more whiskers in a hot, humid environment (Table III). 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.

Stress Measurements **:**

The stress in the deposit was measured by plating Be-Cu strips in a given bath at optimum current density. 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 formula:

$S = U \times K/3 \times t$

Where U is total deflection between the legs, K is a constant, and t is thickness of deposit in inches. The stress in these deposits was tensile in nature. It varied with current densities and was in the range of 2500-4000 Psi. (17-28 MPa) for bright tin- copper.

General Bath Comparisons

1. Most of the Sn-Cu baths contained MSA based chemistries containing at least two additives and a carrier. From practical considerations, these additives could be controlled by Hull cell results and or AMP/Hr usage. Concentrations in some baths could be determined using HPLC which may not be feasible in routine production. Cyclic Voltammetry Stripping (CVS) method for some bath components may be applicable.
2. The coating on the parts could be applied selectively either by control depth or by masking on a plating wheel. 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. Some parts can pose problems in plating the recesses or certain areas of parts where the solution could hardly reach depending on geometry of parts due to the limited throwing power of the bath.
3. The thickness of the deposit was controlled by varying the line speed and or 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 high amperes with micro-cracks.
4. Total carbon content of various baths did not seem to affect their solderability behavior.

Intermetallics and Oxide films:

The oxide formation and its thickness on matte tin coatings were studied by X-ray photoelectron spectroscopy (XPS). XPS utilizes an incident x-ray beam for ejecting photoelectrons from surface atoms of a coating. These photoelectrons have characteristic energies and are helpful in determining the concentration of surface species with a particular bonding type. It was noticed that oxide films grew in thickness with prolonged steam aging. The composition of the oxide layer was mainly due to SnO and SnO_2. The thickness of oxide layers were in the range of 25 -100 Angstroms depending on the duration of steam aging.

The tin-copper coating seemed to be more resistant to oxidation and grew thinner oxide films in comparison to pure tin coatings. This was also indicated from the solderability data of 8 hours, 72 hours steam aged samples.

Intermetallics formation was observed in samples with and without Ni under-layer. The IMC layer was thicker in samples without Ni under-layer and also its thickness increased with duration of annealing. This study also showed that the presence of Ni layer was helpful in mitigation of whiskers.

Housing Material Resistance to Higher Reflow Temperatures

Lead-free solders are expected to have an increase in their liquidus temperature of 30-50°C. This results in an increase of reflow temperatures on the printed circuit board (PCB) of an expected 20 - 40°C for surface mount/reflow soldering. The impending increase in reflow temperatures has caused concern about the thermal capability of polymeric dielectric materials used in connector housings. Therefore, simple screening experiments were performed to examine the impact of elevated reflow temperatures on various resin materials.

Surface Mount Reflow Resins

There are twelve resins commonly used in products that belong to six generic classes of polymers. These classes were: (1)Liquid Crystalline Polymer–LCP, (2)Polyphenylene Sulfide–PPS, (3)Syndiotactic Polystyrene–SPS, (4)Polycyclohexylene dimethylene terphthalate- PCT, (5) Nylon 4, 6 – PA46, and (6) Polyphthalamide – PPA. Table III lists the resin melting point, percent filler, and corresponding connector style used.

Three re-flow temperatures of 220°C, 260°C, and 270°C were studied. To reach these board temperatures, oven air temperatures of 251^{o}C, 287^{o}C, and 302°C were needed respectively. In all cases parts were placed on boards for oven travel, but no actual soldering was performed.

The samples were also exposed to two pre-conditioning treatments to simulate shipping and storage conditions: dry and wet (soaked). Drying was achieved by baking the samples in a dry heat oven for 4 hours at 110^{o}C. Wet samples were obtained via exposure in a steady state humidity chamber for 96 hours at 40^{o}C, 95% RH. Moisture content was obtained just prior to reflow using coulometric Karl Fischer titration analysis.[14]

Measured responses were both qualitative and quantitative. Qualitative measurements consisted of visual examination for blisters, discoloration, deformation/warpage, and melting. Quantitative measurements included quantity of blisters and connector physical dimension stability.

Materials LCP #4, PPS, SPS, and PCT #2 resins failed to withstand the industry anticipated 260°C peak reflow temperature for lead free soldering. LCP #4 failed at both 262°C and 272°C temperatures due to melting and warpage. Additionally, the wet samples exhibit blisters at these temperatures. PPS and SPS resins failed in both wet and dry states at the 262°C and higher temperatures. The locating posts of the PPS card edge sample exhibited melting and the SPS sample exhibited melting and housing warpage. PCT sample #2 exhibited a significant amount of bow at the 262°C temperature and some melting at 272°C. At 272°C, the wet samples of PCT #2 exhibited blistering also. PCT #1 and #4 failed only at 272°C in both wet and dry states due to melting and change in dimensions.

Both high temperature nylons passed at all reflow temperatures in the dry state. However, PA 46 and PPA failed at all reflow temperatures (even the current 223°C) in the wet state via blistering. The failures were due to the hygroscopic property of the material and not the reflow temperature.

In general, surface mount housing materials with a melting point of 285°C and lower exhibited visual and/or dimensional defects following exposure to 260°C and higher reflow temperatures.(Figs.8-9) All resins with melting points greater than 285°C successfully sustained the industry anticipated 260°C peak reflow profile without visual/dimensional damage.

Wave Solder Resins

An identical experiment was performed for wave solder resins. Two resins used in the electronics industry for thru-hole soldered connectors were studied: PBT (Polybutylene Teraphthalate) and PET (Polyethylene Teraphthalate). Melting points of both resins are 225°C and 250°C respectively. General composition of both resins was 30% glass filled.

Samples of both resins were conditioned wet and dry identically to the reflow resins. Samples were exposed to wave solder bath temperatures of 245°C (control), 265°C (predicted lead-free process temperature), and 280°C.

Both PBT and PET successfully withstood all wave solder bath temperatures in both wet and dry states without any dimensional and physical damage. Although this test was limited, the data indicates that both resins will sustain higher lead-free wave solder bath temperatures.

Compliant or Press-fit Applications

The purpose of this test was to determine the effect, if any, of pin–to-pcb insertion/retention forces of compliant pins possessing matte tin finish. Pin-to-pcb insertion and retention forces were measured on 25 of each compliant type in each pcb hole size and pth finish. Tables IV and V summarize the average insertion and retention force measurements on two types of contacts. Cu/OSP finish PTH exhibited the lowest insertion and retention forces of both contact styles. The behavior is similar to Sn-Pb coating. Experiments were performed for studying lead-free compliant pin in press-fit applications to determine any insertion/retention force effects of lead-free compliant pins in Cu/OSP and immersion tin, immersion silver plated thru holes both for minimum PTH (0.030 inches) and maximum PTH (0.033 inches) hole diameters. The test was performed for 3 insertions/withdrawal cycles using a virgin pin at each insertion for the same PTH. The results clearly indicate that lead-free finishes do not affect insertion or retention forces in immersion tin and copper plated thru holes.

One important facet of press-fit application involves the application of excessive stresses imposed on the substrate and the lead-free coating. The seal at the inner areas is supposed to be gas tight and whisker growth in those areas may or may not happen and is of no consequence. There is still a major 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. This is strictly coating dependent and extra care should be exercised in selection of a finish. We are conducting whisker studies on some press-fit parts. Another plausible solution is to anneal the part at 150-170°C for one hour to relieve any residual stresses.

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 in 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 the highest in matte tin coatings compared to bright 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 which 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, 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 coatings, for solderability, there is a need to qualify resin materials for with standing 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 a few resin candidates qualifying the tests. Considering all these aspects, it seems that industry has to adopt certain achievable specifications. In regards to propensity of whisker formation, the selected coating should behave similar to 90Sn-10Pb coating. Our preliminary results with bright Sn–Cu chemistry seem promising and this coating may be suitable for 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 on no-lead chemistries has begun 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 appear to be a viable solution whereas ternary alloys seem more difficult to control in plating composition of levels of total carbon. 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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References

1. S. Lal, *Proc. AESF SUR/FIN*'2001, Nashville, TN, (2001).
2. S. Lal, S. Angeli, J. Kopec, *Proc. IPC*'2001, Orlando, FL (2001).
3. S. Lal, S. Angeli, J. Kopec, Proceedings APEX 2002, San Diego, CA (2002).
4. Standard test method for measurement of coating thickness by X-Ray Spectrometry, ASTM Method B568-98.
5. Standard test method for adhesion of metallic coatings, ASTM method B571-97.
6. Standard test method for solderability , ASTM method B678-86 (1993)
7. Joint Industry Standard, ANSI/J-STD-002, April 1992, Test E.
8. R.M. Fisher, L.S. Darken & K.G. Carroll, Acta Metallurgica, **2**, 368 (1954)
9. K.N. Tu, Acta Metallurgica, **21**, 347,1973.
10. S. C. Britton, Trans. Of Inst. Of Met. Fin. **52**, 95, 1974.
11. U. Lindborg, Metall. Trans., **6A**, 1581, 1975.
12. T. Nagai, Natori, K and T. Furusawa, J. Japan Inst. Metals, **53**, 303, 1989.
13. Tin Whiskers, S.C.Britton, Publication 487, International Tin Research Institute, London.
14. L. Zakraysek, Plating and Surface Finishing, 38, March 1977.
15. K.M. Cunningham & M.P. Donahue, *Proc. 4th International SAMPE Electronics Conf*., 569, 1990.
16. Tin Whiskers in Electronics, G. W. Stupian, Aerospace Technical Report # 92, 2925,1992.
17. B. Z. Lee & D. N. Lee, Acta Metalurgica, **46**(10) 3701, 1998.
18. T. Hasigawa et.al. J. Mat. Science, **17**, 2560,1982.
19. Standard test method for determination of moisture content of Polyamide, ASTM Method D789-98 , Vol. 08.01, 2000.

Table I - Solderability Comparisons of Various Baths with 95.5 Sn/4.0Ag/0.5Cu Solder

Property	**Matte Sn Bath A**	**Bright Sn-Cu Bath B**	**Bright Sn Bath C**	**Matte Sn Bath D**
Deposit Appearance	Satin gray	Shiny Bright	Mirror Bright	Satin gray
Wetting Times, As Is, seconds	0.42	0.50	0.69	0.61
Wetting Time, 8 hrs Steam Aging, seconds	3.66	0.75	0.69	1.87
Wetting Time, 72 hrs Steam Aging, seconds	4.67	1.35	0.73	1.35
Wetting Forces @ 4.5 sec.,AS IS, ìN/mm	415	405	415	412
Wetting Forces @ 4.5 sec., 8 hrs steam, ì N/mm	15	448	449	51
Wetting Forces @ 4.5 sec., 72 hrs steam, ìN/mm	-40	298	414	298
% Coverage, AS IS	100	99	100	100
% Coverage, 8 hrs Steam	100	92	100	93
% Coverage, 72 hrs Steam	100	78	100	59

Table II - Solderability Comparisons of Various Baths with 63Sn/37Pb Solder

Property	**Matte Sn Bath A**	**Bright Sn-Cu Bath B**	**Bright Sn Bath C**	**Matte Sn Bath D**
Deposit Appearance	Satin gray	Shiny Bright	Mirror Bright	Satin gray
Wetting Times, As Is, seconds	0.0.54	0.53	0.63	0.68
Wetting Time, 8 hrs Steam Aging, seconds	4.83	0.83	0.79	1.35
Wetting Time, 72 hrs Steam Aging, seconds	4.63	1.82	1.13	2.42
Wetting Forces @ 4.5 sec.,AS IS, uN/mm	321	375	408	334
Wetting Forces @ 4.5 sec., 8 hrs steam, uN/mm	-55	371	394	197
Wetting Forces @ 4.5 sec., 72 hrs steam, uN/mm	-13	274	355	19
% Coverage, AS IS	100	100	100	100
% Coverage, 8 hrs Steam	100	100	100	100
% Coverage, 72 hrs Steam Aged	100	78	100	98

Table III – Whisker Study on Various Baths

BATH	TYPE	CONDITION	TIME FOUND	GROWTH	DIMENSIONS L/D* µm	% CARBON
A	Matte Tin	55 °C, 85% RH, bent	8 wks.	At 12 wks.	Multiple, small whiskers	0.0059
	Matte Tin	55 °C, 85% RH,un bent	30 wks.	Some growth	25/5	0.0059
B	Bright Sn-Cu	55 °C, 85% RH, unbent	30 wks.	N/A	Small whiskers	0.3550
	Bright Sn-Cu	55 °C, dry, unbent	22 wks.	N/A	Small whiskers	0.3550
C	Bright Sn-Cu	55 °C, 85% RH, unbent	8 wks.	None through 12 wks.	8/5	0.0575
	Bright Sn-Cu	55 °C, 85% RH, unbent	12 wks.	N/A	40/5	0.0575
D	Matte Tin	55 °C, 85% RH, unbent	8 wks.	At 12 wks.	Multiple, small whiskers	0.0024
	Matte Tin	55 °C, 85% RH, 90^0 bent	10 wks.	Multiple growth	25/5	0.0024
H	Bright Sn-Pb 90/10	55 °C, 85% RH, unbent	8 wks.	None through 12 wks.	Initial, one small whisker	0.4500

***** L/D = Length/Diameter

Table IV – Reflow Resin Sample Description

RESIN	Mp °C	% Filler	CONNECTOR TYPE
LCP #1	330	40	Ball Grid Array
LCP #2	335	30	Thru-hole Receptacle
LCP #3	335	30	SMT Mobile Phone
LCP #4	280	40	Press-fit Header
LCP #5	350	30	Thru-hole
PPS	280	40	Press-fit Card Edge
SPS	270	30	Surface Mount
PCT #1	285	30	Slot 1Thru-hole
PCT #2	285	40	Slot 1Press-fit
PCT #3	285	30	SMT Header
PA46 Nylon	295	45	Thru-hole
PPA Nylon	300	30	Thru-hole

Table V – Baby H Insertion/Retention Force (lbs)

PCB Hole Finish	Insertion		Retention		Avg. Drill Diameter (Inches)	
	MIN PTH	**MAX PTH**	**MIN PTH**	**MAX PTH**	**MIN PTH**	**MAX PTH**
Imm. Sn	13.2	12.38	9.64	10.83	0.0300	0.0332
Cu/OSP	10.9	4.39	8.21	3.57	0.0304	0.0334
Imm. Ag	14.01	15.07	8.36	11.68	0.0304	0.0328
SnPb	15.5	12.83	13.34	11.07	0.0304	0.0328

Table VI – EON Insertion/Retention Force (lbs)

PCB Hole Finish	Insertion		Retention		Avg. Drill Diameter (Inches)	
	MIN PTH	**MAX PTH**	**MIN PTH**	**MAX PTH**	**MIN PTH**	**MAX PTH**
Imm. Sn	4.41	3.55	2.15	2.96	0.0300	0.0332
Cu/OSP	3.41	1.82	1.98	1.70	0.0304	0.0334
Imm. Ag	5.12	4.04	2.05	3.58	0.0304	0.0328
SnPb	4.66	4.69	2.55	4.41	0.0304	0.0328

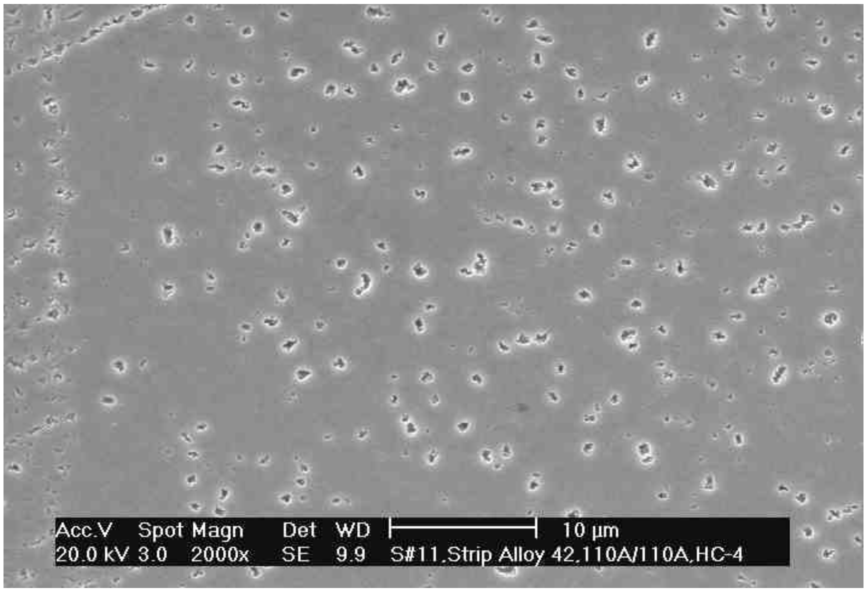

Figure 1. Bright Tin-copper Bath C Coating @ 10 ft/min

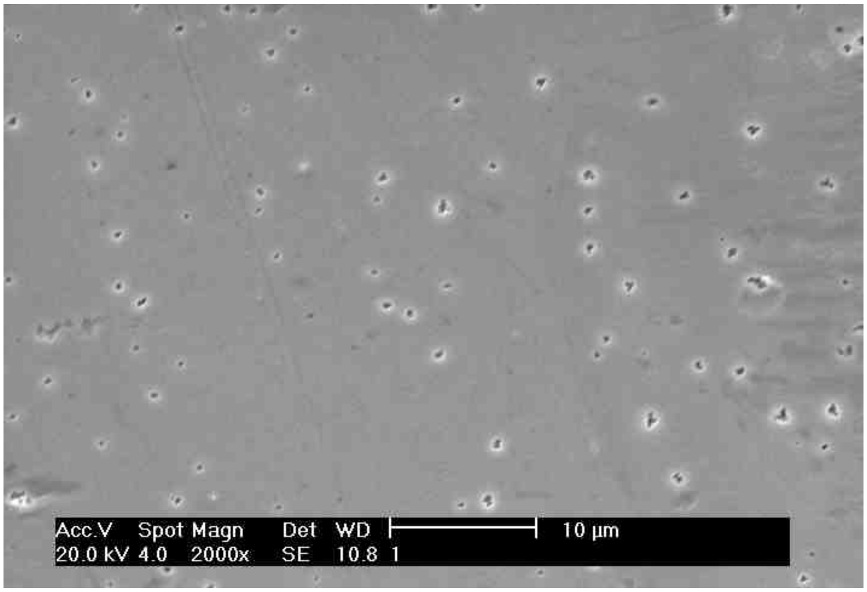

Figure 2: Bright Tin-copper Bath B coating @ 10ft/min

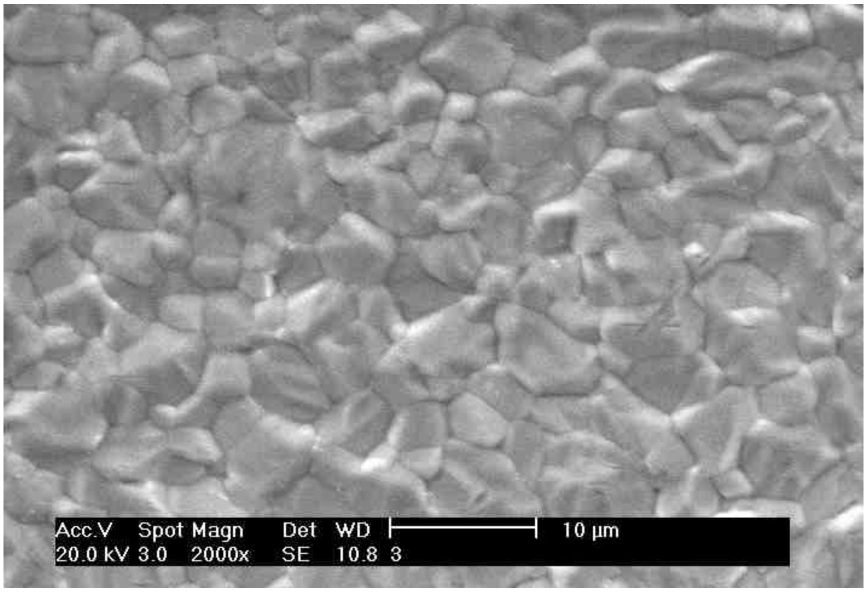

Fig. 3: Morphology of Matte Tin coating Bath D

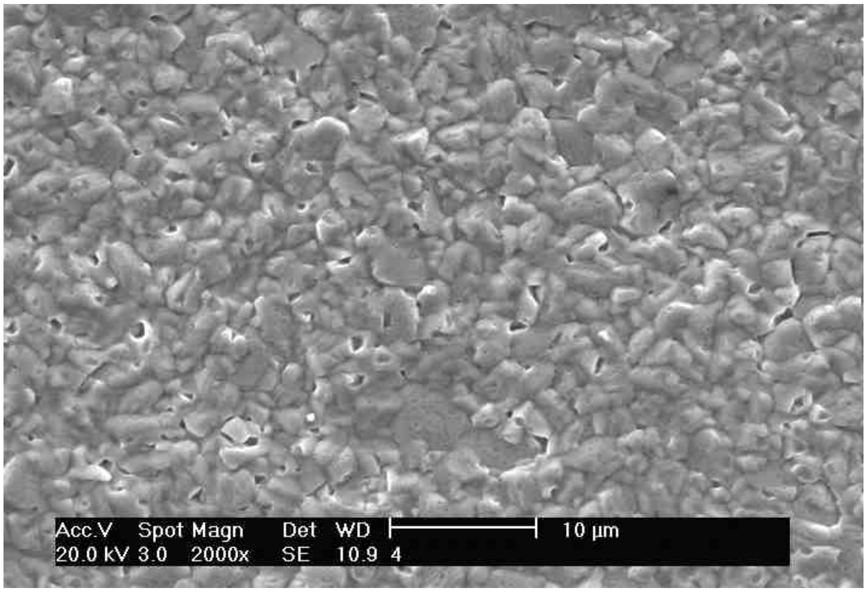

Fig. 4: Morphology of Matte Tin coating Bath A

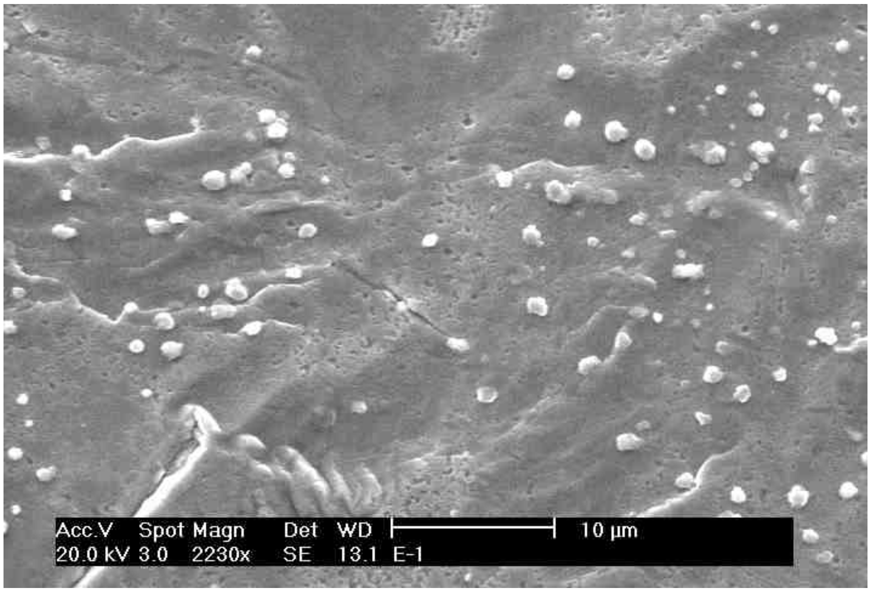

Figure 5. Odd Shape Eruptions in a bright Tin-copper coating after 18 months storage in central office environment

Figure 6. Typical Tin Whiskers in Tin Deposits

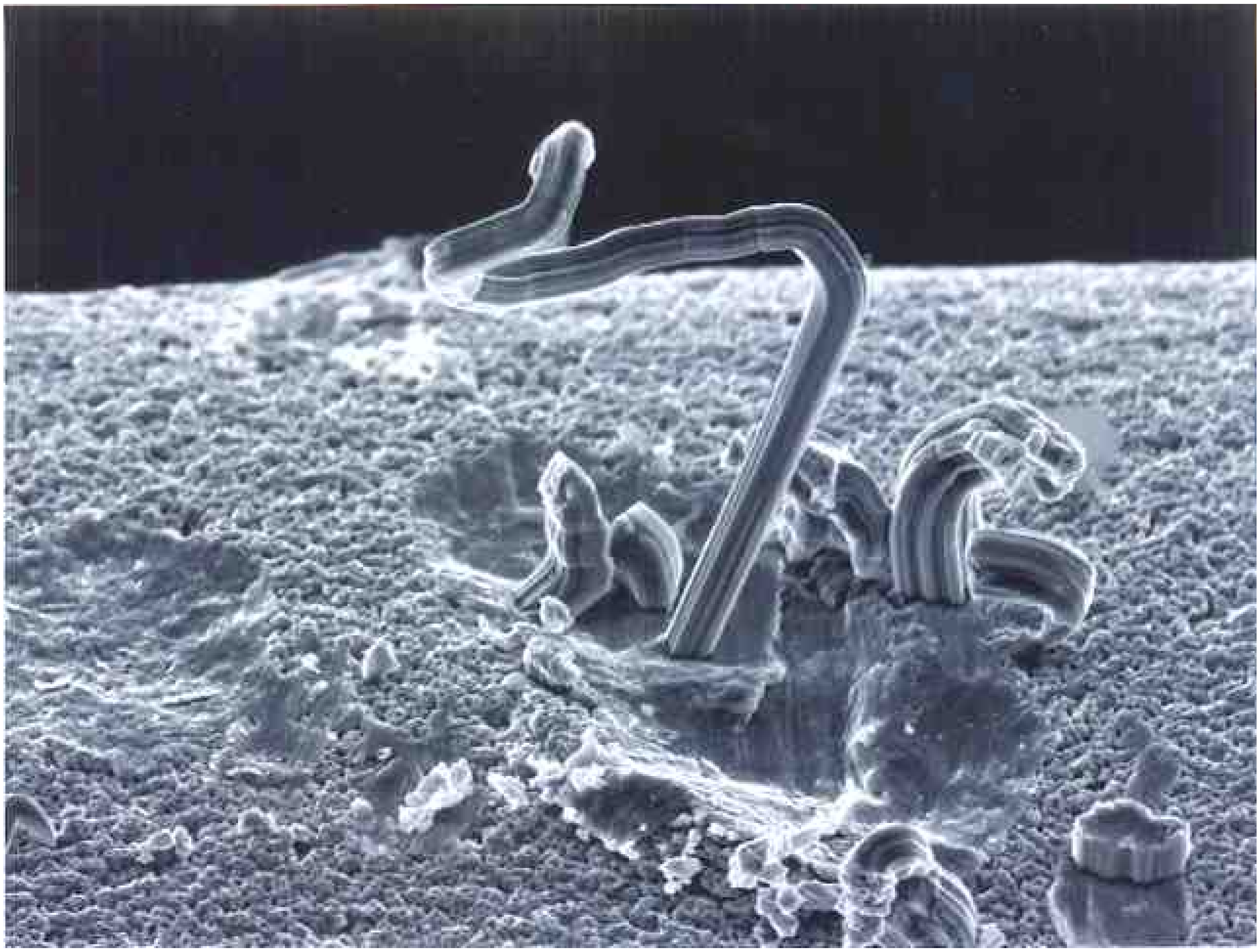

Figure 7: Tin Whiskers for Tin-copper coating after 12 weeks @ 55°C and 85% humidity