Surface Technology White Papers
98 (6), 18-27 (September 2011)

Investigation of Tin Whisker Formation

by
Grazyna Koziol,[1] Aneta Arazna,[1] Wojciech Stęplewski,[1] Kamil Janeczek[1] and Jerzy Bielinski[2]*
[1]Tele- and Radio Research Institute, Ratuszowa, Poland,
[2]Warsaw University of Technology, Faculty Chemistry, Noakowskiego, Poland

ABSTRACT

Tin and its alloys have been widely used in electronics as surface finish materials in printed circuit boards and connectors. SnAgCu and SnCu alloys have been applied in lead-free reflow and wave soldering processes. It is known that tin whiskers can form on pure tin or tin-alloy finished surfaces and grow up to several millimeters in length with a diameter of a few micrometers. Since the smallest distance between components can be less than a few hundred micrometers, whiskers can create reliability problems. Tin whisker formation was investigated on different types of immersion tin and SnAgCu alloy (HASL) surface finishes for printed circuit boards, and electroplated tin and tin-bismuth for connectors after lead-free soldering processes. After longtime storage and accelerated tests, it was found that whisker formation is a long term process and the important factors contributing to whisker formation on electroplated tin were high humidity, enough to produce condensation at elevated temperatures and variable environmental hazards. For immersion tin coatings thinner than 1.0 µm, the tests performed produced some small areas in which tin was completely transformed into SnCu intermetallic compounds rather than whisker growth.

Keywords: Tin whiskers, electroplated tin, electronic components

Introduction

Immersion tin and lead-free hot air solder leveling (HASL) coatings based on SnCu or SnAgCu alloys are widely used as surface finish materials for printed circuit boards (PCB). These coatings prevent the underlying copper from corrosion and preserve its solderability during lead-free assembly processes and for a long storage life of PCBs. A new generation of immersion tin coatings has higher densities and smaller grains with a much lower propensity towards oxidation, dendrite and whisker growth.[1,2]

Excellent solderability, low deposition cost, ease of manufacturing and compatibility with existing lead-free assembly technologies are the reasons that pure electroplated tin is often applied as a lead-free surface coating for electronic components.

However, the properties of tin coatings change during long storage times. The occurrence of an excess growth of intermetallic compounds (IMCs) can affect the solderability of tin.[2,3] Another drawback of tin-based finishes is whisker growth. Tin whiskers are electrically conductive, crystalline structures of tin that sometimes grow from the tin surface. Tin whiskers may grow long enough to cause shorts in electrical circuits and interfere with other devices in an application. Some investigations have revealed whisker growth from lead-free solder joints and identified reliability problems created by them.[4-9]

The mechanisms by which tin whiskers grow have been studied for many years and a single accepted explanation has not yet been established. Some theories suggest that tin whiskers may grow in response to a mechanism of stress relief (especially compressive stress) within the tin coating. Other theories maintain that growth may be attributed to recrystallization and abnormal grain growth processes affecting the grain structure. Many factors have been suggested as contributing to whisker formation, including factors relevant to the plating chemistry, the plating process, substrate materials and environmental conditions.[4]

Despite the progress that has been made in understanding whisker formation, there is still no simple answer as to which particular factor will initiate the process of tin whisker nucleation, when the process will begin, and what shape and length of

* Corresponding author:
Dr Grazyna Koziol
Tele and Radio Research Institute
03-450 Warsaw
Ratuszowa 11, Poland
E-mail: grazyna.koziol@itr.org.pl

whiskers will form. Accordingly, some of the accelerated tests described in the current JEDEC, JEITA and IEC standards do not guarantee that whiskers will or will not grow under field life conditions. Shibutani and co-authors[10] indicate that key problems include lack of data collection, lack of agreement on proper techniques for measuring whisker length, lack of established acceleration transforms for prescribed tests, and disagreement over acceptance criteria. They also stated that more studies on tin whisker growth are required to establish acceleration transforms.

This paper presents the results of our investigation of tin whisker formation on different types of immersion tin, SnCu and SnAgCu alloy (HASL) surface finishes on printed circuit boards, electroplated tin on connectors and lead-free solder joints. Accelerated test conditions are selected based on the tests described in the current standards and on environmental work on devices manufactured at the Tele- and Radio Research Institute.

Experimental

Immersion tin coatings were deposited on printed circuit boards (Cu laminated FR-4 laminate) from two commercially available processes presenting a guaranteed minimum risk of whisker formation and plated in two thiourea-type baths prepared in our laboratory. These baths were based on stannous chloride or tin methanesulfonate and did not contain additives for reducing whisker growth.

Tin-copper and $SnAg_{0.3}Cu_{0.3}$ alloys were deposited by the HASL method on PCBs. The following types of electronic components with electroplated pure tin finishes were tested: 8- and 16- lead small outline integrated circuit packages (SOICs), lead frame type packages (PLCC, PQFP), resistors, capacitors and components for through-hole assembly. These components were also studied after lead-free soldering processing was carried out with solder paste SAC305 (surface mount technology) and SnCu alloy (wave soldering). Tin-bismuth as a finish material on PLCC 44 lead frames was also evaluated.

The accelerated tests used in the studies are described in Table 1. Some of the samples were subjected repeatedly to some of these tests.

Table 1 - Test conditions for evaluation of the whisker phenomenon.

Test	Condition	Duration
Ambient storage	Room temp. 20 ± 5°C	3 & 7 years
Climatic chamber	-20°C	6 months
Air-to-air temperature cycling	-40°C/125°C	1000 & 2000 cycles
Air-to-air temperature cycling	-20°C/2.0 hr; 60°C/30 min	27 cycles
High Temperature/humidity	55±1°C; 85±5% RH	1000 & 2000 hr
High Temperature/humidity, enough to produce condensation	55±1°C; ~90% RH	500 hr
Lead-free soldering	SAC paste - SMT SnCu alloy - wave	---

The surface of the tin coatings was examined by optical microscopy and scanning electron microscopy (SEM) equipped with an energy-dispersive x-ray spectrometer (EDS).

The tin thickness values measured by energy dispersive x-ray fluorescence spectrometry ranged from 5 to 12 µm for electroplated tin and tin-bismuth, 4 to 16 µm for HASL and 1.2 to 1.4 µm for immersion tin coatings.

Results and discussion

Electroplated tin and its alloys

Some surface changes of were found on electroplated pure tin on component leads after three years of storage at room temperature, but no whiskers. The surface deterioration observed (Fig. 1) was probably caused by oxidation or corrosion processes. Prolongation of the storage time up to seven years still did not yield any whiskers.

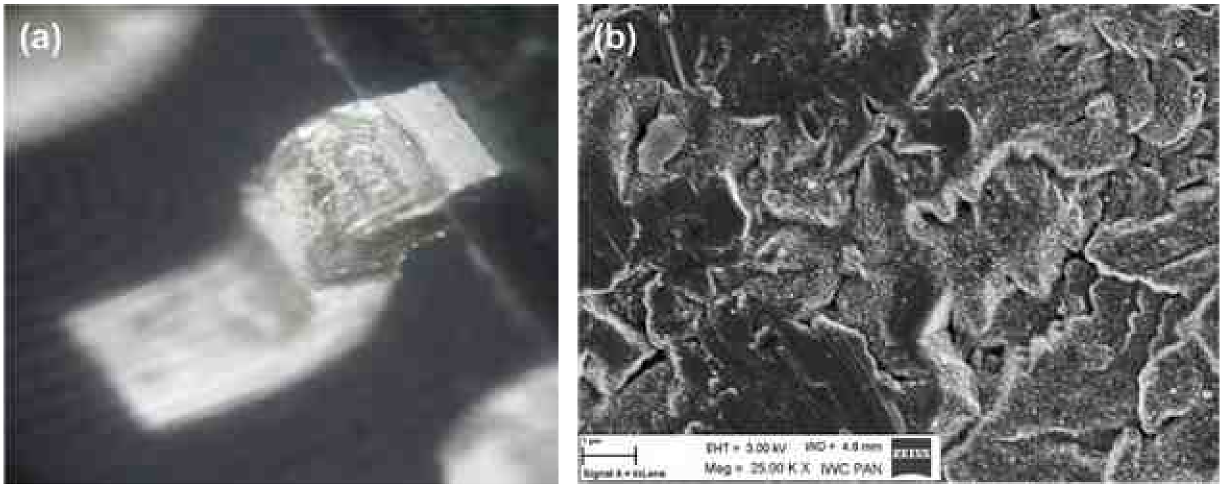

Figure 1 - Surface changes on electroplated tin after three years of ambient storage: (a) optical microscope, 5×; (b) SEM image, 25,000×.

Samples preconditioned to introduce stress by lead-free assembly processes (surface mount and wave soldering) before storage at ambient conditions also did not exhibit whisker growth after three years of storage. Some small whiskers were observed on component leads after the next four years, but whiskers were not found in the area of the solder joints.

This could be an indication that, during the solidification process, the soldering process could have induced some stresses that were greater than those inherent in the plated tin coating and further stress during storage at room temperature. Stress accumulation could introduce the whisker growth process which would then continue despite the removal of the initiating environment.

To date, understanding the influence of the soldering process on whisker formation has not been unambiguous. On one hand, it is believed that the stress relief via the reflow process would be beneficial in suppressing whisker formation.[11] On the other hand, some experimental data showed whiskers on the soldered components. We recognize that assembly processes can result in an increase in whisker growth on connectors, but not in the area of solder joints.

Examples of whiskers on electroplated pure tin terminations of soldered PLCC 28M component sockets (SMT) and choking-coils (PTH) are presented in Figs. 2 and 3.

We noted that the whisker morphology for the tin-bismuth coatings was quite different from the morphology noted for the pure tin deposits. As seen in Fig. 4, the whisker structures appeared to have a growth direction nearly parallel to the surface of the tin-bismuth coating.

The air-to-air temperature cycling test (-40°C/125°C) and the temperature/humidity test (55°C and 85% RH for 1000 and 2000 hr) did not introduce any changes in the connectors, soldered components and SnAgCu PCB finishes studied. All samples survived both tests with no whisker growth, even when they were first stored for three years at room temperature. However, some whisker filaments were observed on electroplated tin component finishes after 500 hr of the temperature/humidity test performed at 55°C and humidity of about 90%, enough to produce condensation. Some of the whiskers were longer than 50 µm (Fig. 5) and did not meet the acceptance criteria provided by the JESD 201 standard. According to JESD 201, the maximum allowable tin whisker length for Class 2 components is 40 µm for isothermal storage or 45 µm for temperature cycling. For Class 1 components, the criteria depend on the component type. The maximum allowable length is 50 µm for high frequency components, 67 µm for lead components and 100 µm for components with large spacing.[12] The results confirmed the accelerating effect of humidity on whisker growth presented in other studies.[11]

98 (6), 18-27 (September 2011)

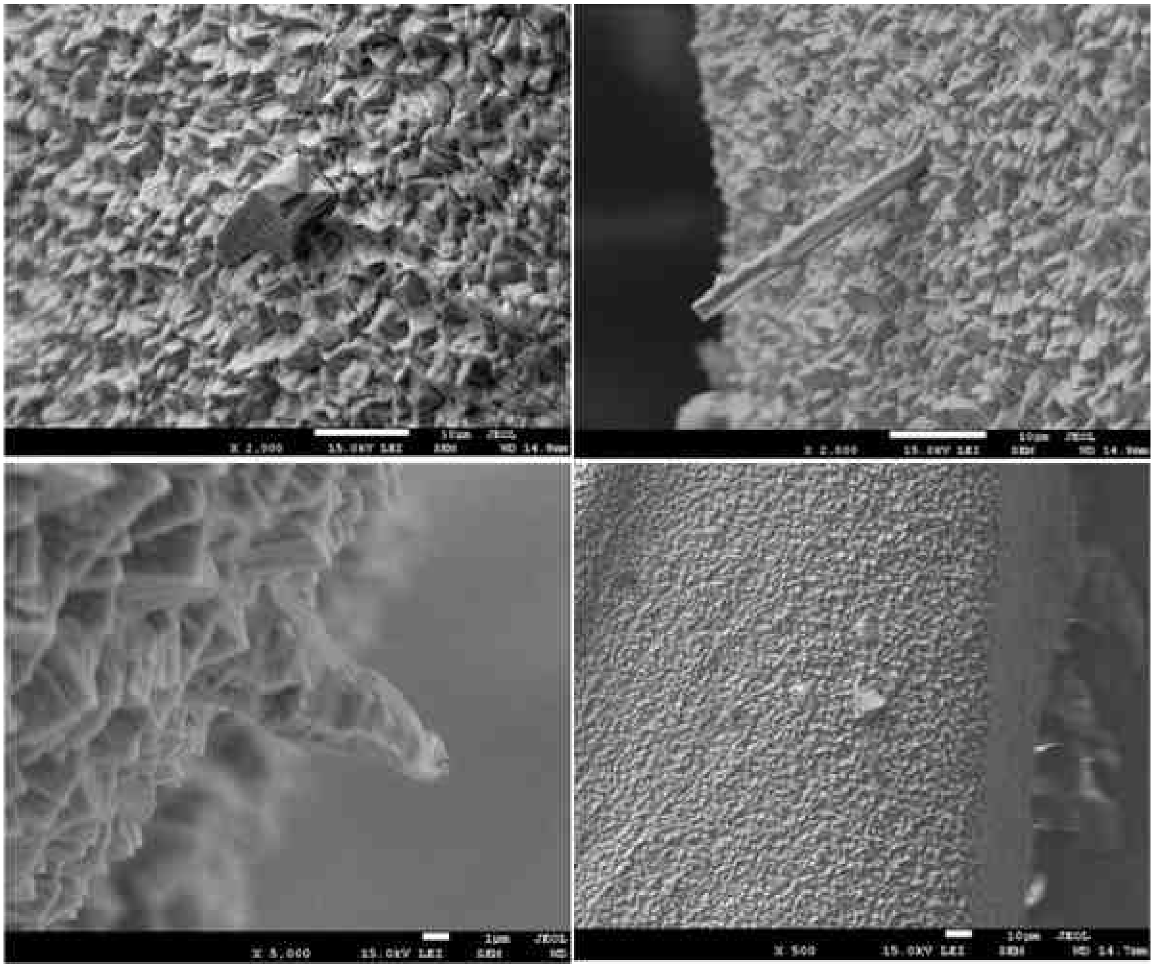

Figure 2 - SEM images of whiskers on electroplated tin (lead frame PLCC) after soldering and seven years of ambient storage.

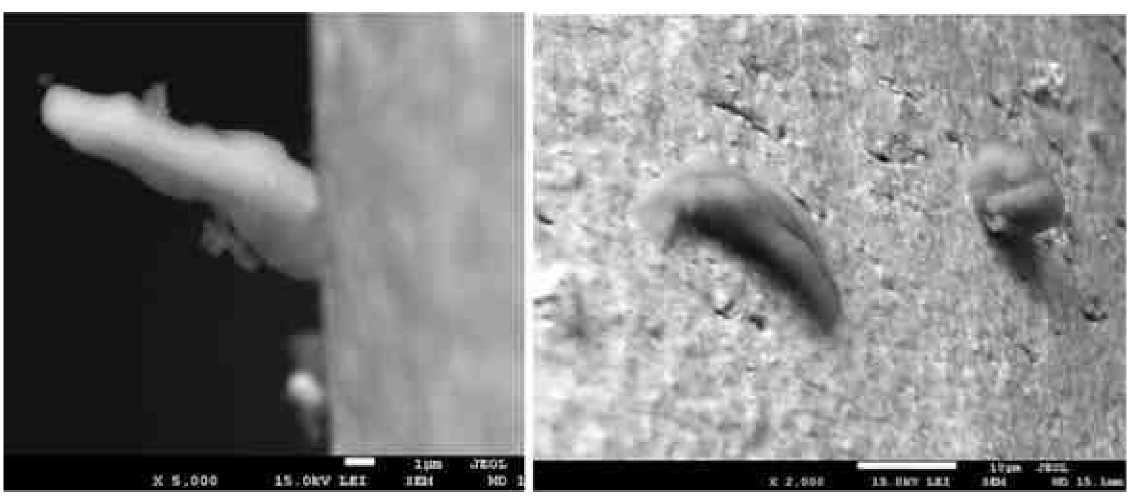

Figure 3 - Whiskers on electroplated tin (choking-coil lead) after wave soldering and seven years of ambient storage.

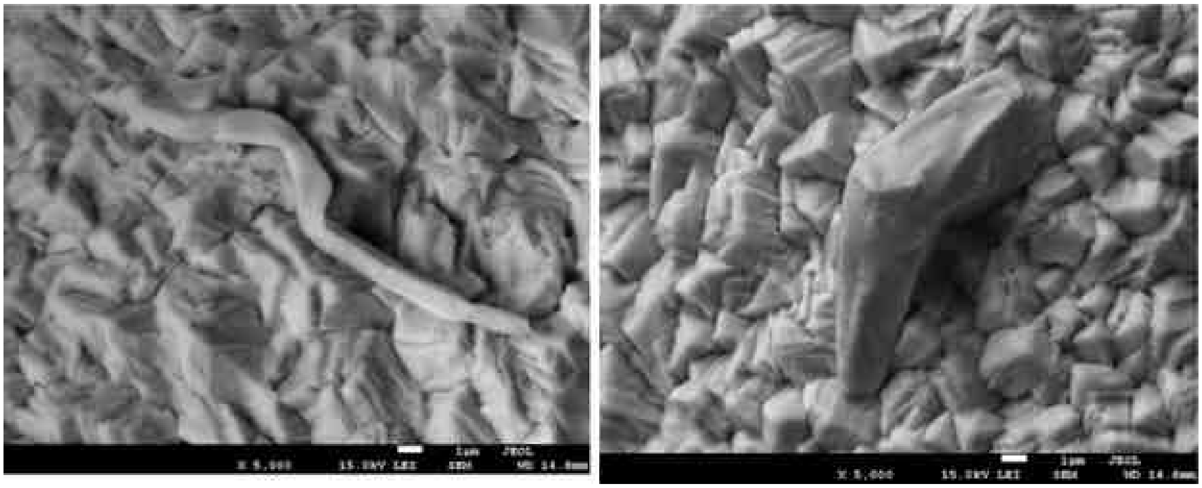

Figure 4 - SEM image of a tin-bismuth coating after surface mount soldering and seven years of ambient storage.

Figure 5 - An example of a 100-μm long filament whisker on a pure tin electroplated PLCC 44 DE lead frame.

Based on the harsh work environment encountered by devices manufactured at the Tele- and Radio Research Institute, a temperature hazards test was performed under conditions as follows: two hr at -20°C and then 30 min at 60°C. Twenty-seven test cycles caused considerable change in the surface structure of electroplated tin on component leads (Fig. 6a).

Next, these coatings were checked after 50 days of storage at ambient temperature and two months at -20°C. SEM observation revealed further degradation of the tin surface and the growth of whiskers (Fig. 6b). The changes in the tin surfaces could be caused by tin corrosion, but in our opinion, the results also indicated the beginning of transformation of white tin (β-Sn) to gray tin (α-Sn). The surface appearance became rough and contained cracks probably because of the very brittle nature of gray tin and the increase in volume that accompanied the white tin allotropic phase change (Fig. 7). Similar changes referred to as "tin pest" occurred during storage at temperatures ranging between -40 and 60°C has been described in the literature.[13]

Immersion tin

The observed changes in immersion tin coatings on printed circuit boards strongly depended on their thickness and type of tinning process used. SEM/EDS analysis of immersion tin finishes of thicknesses below 0.9 μm plated from laboratory-prepared solutions and stored three years at room temperature indicated some areas in which the tin was almost completely transformed into CuSn intermetallic compounds (Fig. 8). Whisker growth was not noted.

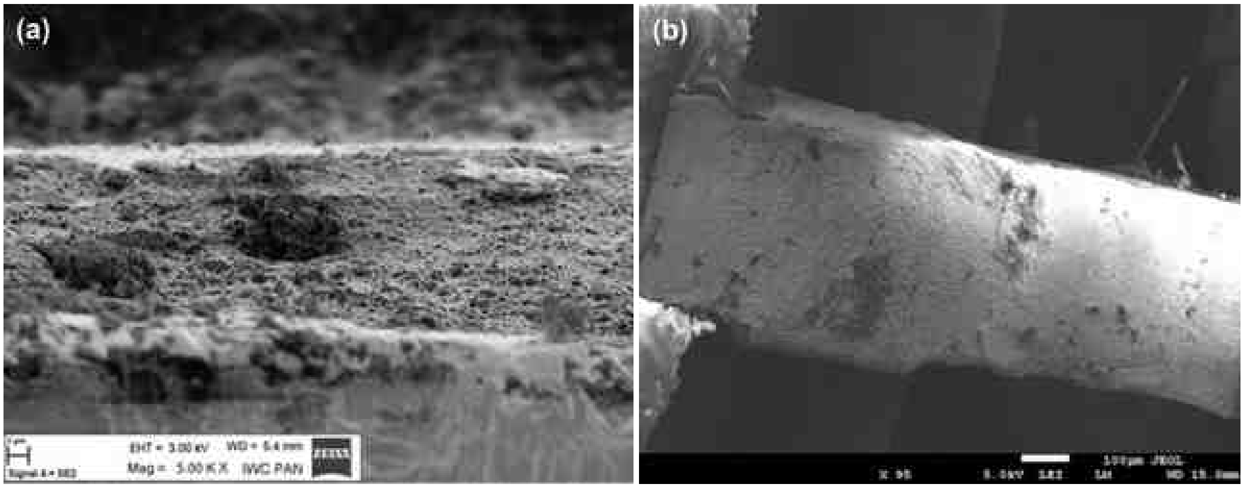

Figure 6 - Images of the surface of electroplated tin on a SO16 component: (a) after 27 cycles of the temperature hazards test and (b) after a further 50 days of storage at room temperature and two months at -20°C.

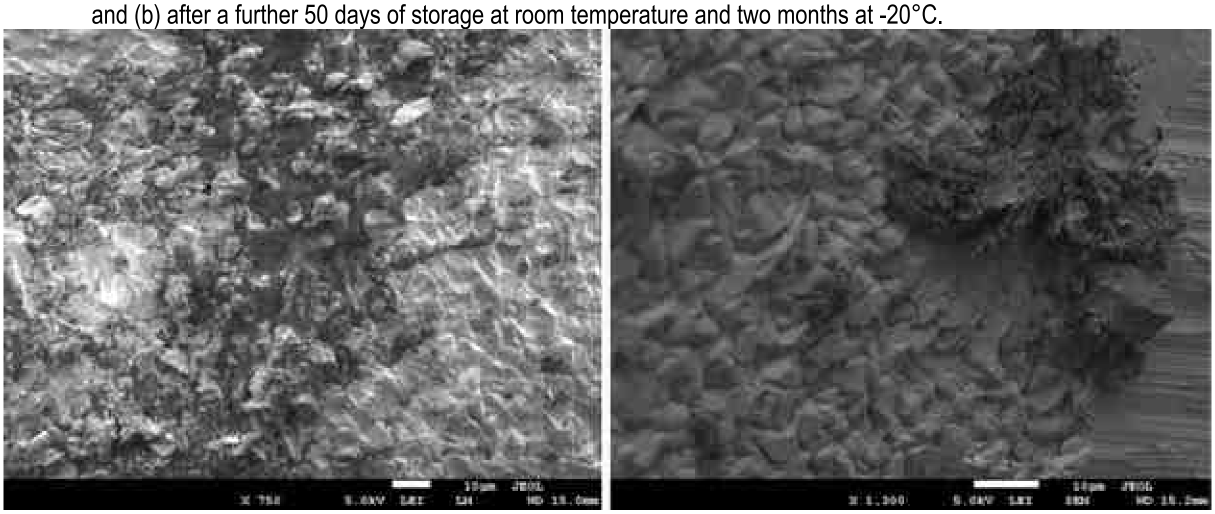

Figure 7 - SEM images of a tin surface with visible changes that could indicate tin-pest transformation.

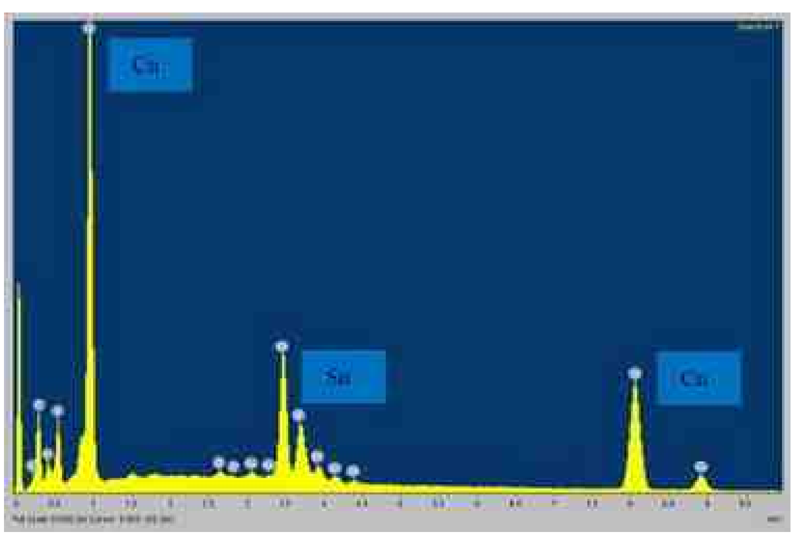

Figure 8 - Results of EDS analysis of an immersion tin coating of thickness 0.8 µm stored for three years.

Immersion tin coatings of thicknesses higher than 0.9 µm and plated from commercial processes including additives suppressing whisker formation were more stable. SEM observation of immersion tin coatings plated from one of the commercial baths revealed several whiskers of small diameter (1-3 µm) and length from 4 to 18 µm after three years of storage (Fig. 9). By contrast, this second type of immersion tin coating did not exhibit whisker growth.

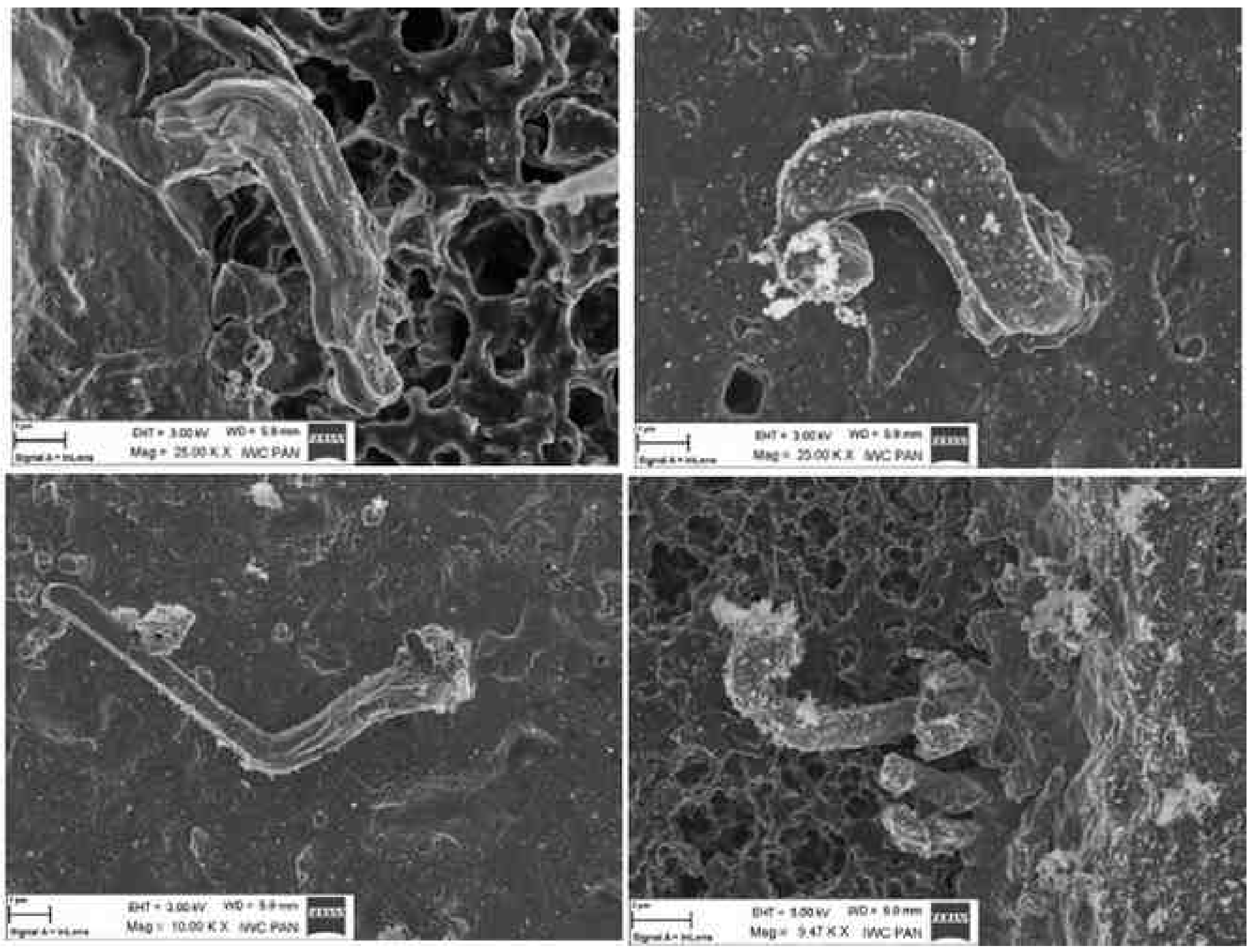

Figure 9 - Examples of whiskers growing on immersion tin after three years of ambient storage.

Air-to-air temperature cycling at -40°C/125°C had the same influence on all types of immersion tin coatings of thicknesses higher than 1.2 µm. Similarly, after 1000 temperature cycles, only a very few small, foliate structures were observed on the tin surfaces. After the next 1000 cycles almost the entire surfaces were covered by these structures, indicating extensive tin coating deterioration (Fig. 10).

A few hillocks were noted on both types of commercial tin finishes after 1000 hr of temperature/humidity test at 55°C and 85% RH (Fig. 11a). The number of these formations significantly increased after the next 1000 hr (Fig. 11b). According to the JEDEC Standard No. 22A121.01, “Hillocks may be precursors to whiskers in some cases, but are not considered whiskers for the purpose of the test method.”[14]

After 500 hours of temperature/humidity test performed at 55°C and humidity about 90%, enough to produce condensation, no whiskers were noted on commercial immersion tin. Many whiskers were observed on tin coatings plated from a bath prepared in the laboratory, particularly from a methanesulfonic acid-based solution. The diameters of the whiskers were about 0.5 µm and lengths ranged from 1 to 14 µm. In addition to the tin whisker filaments, many hillocks were formed and the tin structure showed significant coating degradation under the test conditions (Fig. 12).

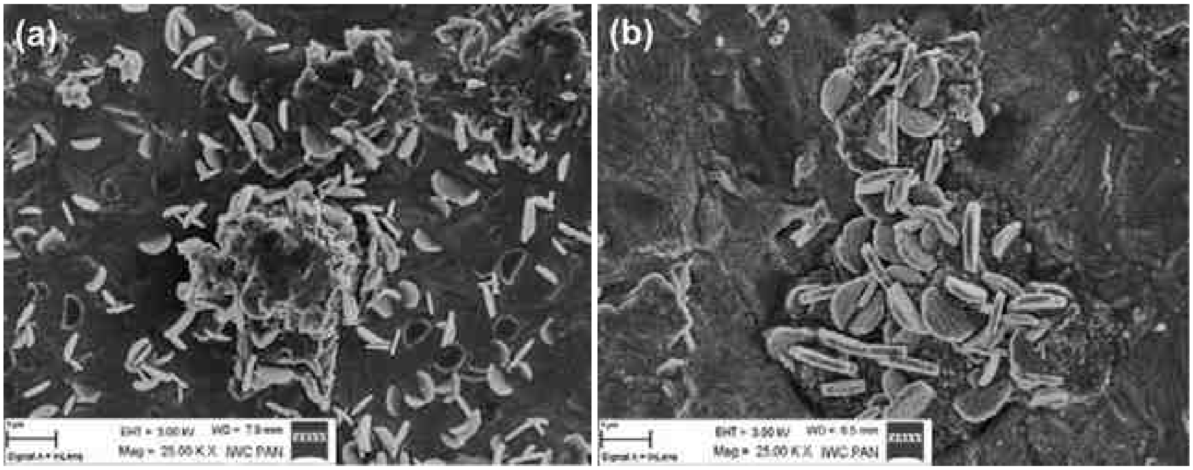

Figure 10 - SEM image of immersion tin coatings after (a) 1000 and (b) 2000 temperature cycles.

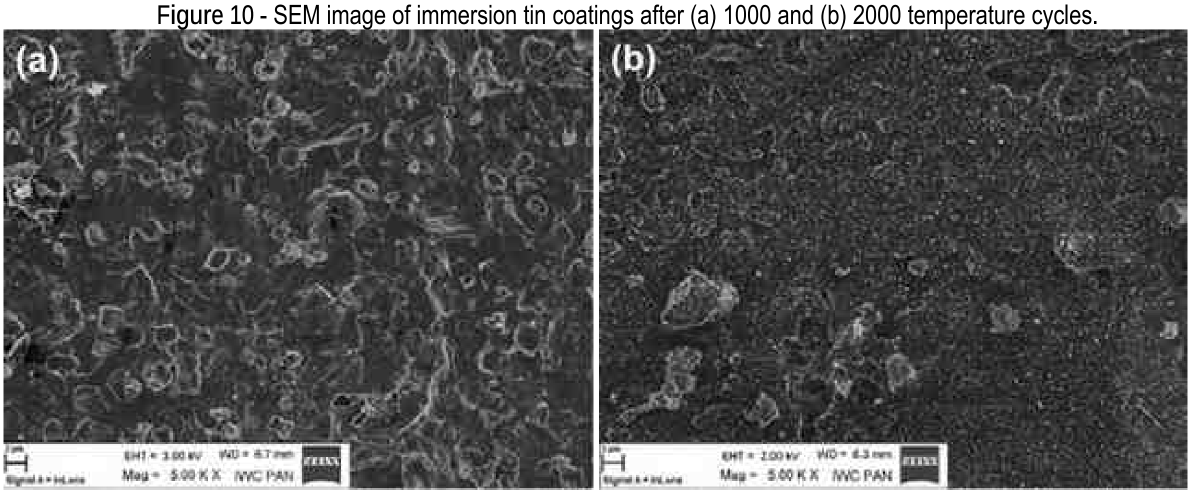

Figure 11 - SEM images of columnar crystals on immersion tin coatings after (a) 1000 hr and (b) 2000 hr of temperature/humidity testing.

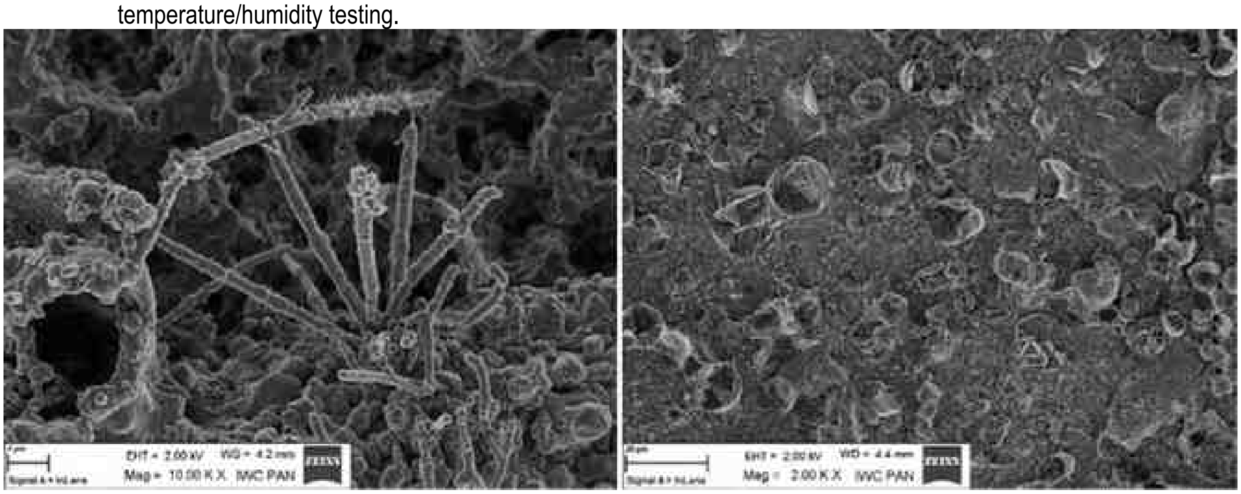

Figure 12 - SEM images of immersion tin plated from a methanesulfonic acid-based solution after a temperature/humidity test, with enough humidity to produce condensation.

Conclusions

The investigation of tin whisker formation on pure tin and tin-bismuth electroplated, commercially available electronic components and immersion tin finishes on printed circuit boards plated from two different commercial processes, as well as from laboratory-prepared solutions, have been performed. Based on the results, the following conclusions can be reached:

- For tin-electroplated coatings of thicknesses higher than 9 µm, whisker incubation periods have lasted many years, particularly where components were in storage under ambient conditions.
- Using a tin-bismuth alloy finish in place of pure tin did not suppress whisker growth.
- Humidity accelerated whisker growth.
- Assembly processes can result in an increase in whisker growth on connectors, but not in the area of solder joints.
- None of the environmental conditions tested alone could be described as a driving force for whisker growth. Interactions among the various factors have to be involved to cause tin whisker growth.

References

1. N. Arendt, *et al*., *CircuiTree*, 18 (1), 10 (2005).
2. G. Koziol, *et al*., *Proc. IPC/JEDEC 3rd International Conference on Lead Free Electronics*, IPC, Bannockburn, IL, 2005.
3. W. Zhang, *et al*., *IEEE Transactions on Electronics Packaging Manufacturing*, 29 (1), 85 (2005).
4. A. Vicenzo, "Tin Whiskers Standards," www.europeanleadfree.net (2005-2007).
5. R. Schetty, *Circuit World*, 27 (2), 17 (2001).
6. S. Lamprecht & C. Hutchinson, "Immersion Tin - Kinetics of Whisker Growth," http://www.atotech.com/data/publications/pcb/Immersion_Tin-Kinetics_of_Whisker_growth.pdf (2004).
7. E. Chason, *et al*., *App. Physics Letters*, 92 (17), 171 (2008).
8. T. Fang, *et al*., *Circuit World*, 33 (1), 5 (2007).
9. NASA GSFC, *Tin Whisker (and Other Metal Whisker) Homepage*, http://nepp.nasa.gov/whisker.
10. T. Shibutani, M. Osterman & M. Pecht, *IEEE Transactions on Components and Packaging Technologies*, 32 (1), 216 (2009).
11. B. Rickett, *et al*., *Circuit Assembly*, 16 (12), 38 (2005).
12. JEDEC Standard JESD 201, *Environmental Acceptance Requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes*, JEDEC, Arlington, VA, 2006.
13. K.J. Puttlitz & G.T. Galyon, *J. Mater. Sci.: Mater. Electron.*, 18 (1-3), 347 (2007).
14. JEDEC Standard JESD 22A121A, *Test Method for Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes*, JEDEC, Arlington, VA, 2008.

About the authors

Dr. Grazyna Koziol is the Head of the Printed Circuit Research Department of the Tele- and Radio Research Institute (ITR), Ratuszowa, Poland. She is also the Coordinator of the Centre for Advanced Technology of Electronic Interconnections at ITR. She obtained her Doctor of Science degree from the Chemical Department of Warsaw Technology University in 2000.

Aneta Arazna is a Research Assistant at the Printed Circuit Research Department of the Tele- and Radio Research Institute (ITR). She received her M. Sc. Eng. degree from the Department of Technological Chemistry of Warsaw University of Technology (PW) in 2002. She is currently working at ITR and is also a Doctoral student at the Warsaw University of Technology.

Wojciech Steplewski is a Research Assistant at the Printed Circuit Research Department of Tele- and Radio Research Institute (ITR). He received his M. Sc. Eng. degree from the Mechanical Department in Material Engineering at Cracov University of Technology (PK) in 2000.

Kamil Janeczek is a Research Assistant at the Printed Circuit Research Department of the Tele- and Radio Research Institute (ITR). He received his M. Sc. Eng. degree from the Electronic Department of the Warsaw University of Technology (PW) in 2009. He is now working at ITR and is also a Doctoral student at the Warsaw University of Technology.

Dr. Jerzy Bielinski is a Professor Dr. Sc. at the Warsaw University of Technology, where he is Head of the Applied Electrochemistry Laboratory in the Department of Inorganic Chemistry and Solid State Technology. The area of his work includes electroless and electrodeposition of metals and alloys. He is also Member of European Academy of Surface Technology (EAST) and the International Society of Electrochemistry.