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WHISKER GROWTH ON SAC SOLDER JOINTS: MICROSTRUCTURE ANALYSIS

Polina Snugovsky, Zohreh Bagheri, Marianne Romansky
Celestica International Inc.
Toronto, Ontario, Canada
Polina@celestica.com

ABSTRACT

Sn whisker growth on electronics continues to be a widespread industrial concern. In this study, detailed metallurgical analyses were done on whiskers growing from solder joints formed on leaded components. The whiskers appeared after life testing for 10 days at 60°C and 20-30% RH with voltage cycling.

Optical and Scanning Electron Microscopy (SEM) with EDX following by cross-sections through whiskers were performed. The analyses revealed that Sn whiskers originated not from the component lead plating as was expected, but from bulk SAC405 or SAC305 solder. A high precision metallographic technique using progressive polishing was developed to examine the details of whisker formation.

This paper discusses the microstructural relationship between the whiskers, hillocks, and shell-like protrusions and the following factors: solder microstructure and its modification during oxidation and corrosion, Alloy 42 lead frame material, lead plating quality, component contamination and flux on solder.

Key words: Whisker, Lead-Free solder, Alloy42, microstructure,

INTRODUCTION

Tin whiskers pose a significant risk to electronic assemblies related to transient or permanent shorts. It is believed that whiskers are specific to Tin plating and in general do not grow from solder.

Recently there were several publications discussing whisker growth from lead-free solder. Tung-Han Chuang and Shiu-Fang Yen discovered that Sn whiskers appeared in Sn3Ag0.5Cu0.5Ce solder joints of ball grid array packages after storage at room temperature [1]. The high propensity to whiskering was attributed to the $CeSn_3$ particles that exist in solder after reflow and oxidize rapidly during natural aging. The surface oxide of the $CeSn_3$ consumes more Ce than Sn. The Ce depleted layer that contains almost pure Sn is left behind the oxide layer. The abnormal whisker growth was attributed to the compressive stress in the Ce depleted layer Sn layer. Similar conclusions were drawn by authors who [2] studied oxidation-induced whisker growth on the surface of Sn and rare-earth-containing alloys. The driving force for whisker growth was, as the authors concluded, the compressive stress induced by the volume expansion of $(La0.93Ce0.07)Sn_3$. The tin atoms released by the oxidation reactions were extruded through the oxide film. In addition, the huge compressive stress accumulated by the volume expansion of the drastically oxidized intermetallics extruded the Sn-La-Ce matrix around the oxides to form the coarse hillocks.

Referencing the previously described theory, the authors of the paper "Can Whiskers Grow on Bulk Lead-Free Solder?" answered negatively [3]. Studying the influence of various levels of residual stresses, they came to the conclusion that localized residual stress do not result in formation of whiskers in bulk Sn3.5Ag solder. A bulk specimen, even in the presence of localized mechanical stresses, does not undergo stress relaxation via spontaneous whisker growth, but instead the stress is relaxed into the bulk, presumably through creep. It was suggested that thin-film geometry is required for whisker growth.

Therefore, whisker growth is expected in a Sn plated layer in combination with stresses related to thermal mismatch, interdiffusional stress from intermetallic Cu-Sn compounds, and the oxidation of Sn at the surface.

Since the widespread introduction of lead-free solder to electronics assembly, there have been several observations of spikes growing from the bulk solder of leaded and ball grid array joints. These spikes, which looked like whiskers, were observed at the Celestica Laboratories. This paper is focused on the metallurgical analysis of leaded components that demonstrated whisker and hillock formation.

EXPERIMENTAL

History of the Examined Samples

Whiskers were observed on leaded components with low stand-offs assembled using both SAC405 and SAC305 solder pastes. The lead-frame material on components with a high whiskering propensity was Alloy 42 with electroplated matte Sn finish. The whiskers appeared after life testing for 10 days at 60°C and 20-30% RH with voltage cycling. A high amount of chloride, sulfate and ammonia was detected on the assembled devices.

Inspection and Analysis

Assemblies

The assemblies were examined visually using optical microscopy under 30X - 50X magnification to select samples for further analysis. The samples with clearly visible whiskers were placed into the variable pressure scanning electron microscope (SEM) Hitachi S-3000N for more detailed observation and X-ray spectroscopy (EDX).

Individual whisker analysis was performed to insure that an accurate composition was determined without interference from the bulk solder. Several whiskers were removed from the devices using a microscalpel under the optical microscope and placed on the SEM sample holder covered with carbon tape. These whiskers were analyzed using EDX to detect elemental composition.

Selected locations with whiskers were cross-sectioned followed by progressive polishing. The cross-sections were done longitudinally and perpendicular to the leads. Because whiskers are not flat, it is impossible to catch the whole whisker in one particular cross-section. The locations from which whiskers or hillocks started growing were targeted. Progressive polishing revealed more details and recreated a three dimensional image. The polishing was done using 15µm, 9µm and 1µm diamond pastes. In each polishing step, a layer 1 to 2 µm was removed. Multiple polishing of the location of interest such as a whisker or hillock allowed the details of the three dimensional structure and different microstructural features (intermetallics, voids, recrystallized grains, etc.) to be revealed Metallurgical and field emission SEM Hitachi S-4500 were used for the analyses.

<u>Virgin Components</u>

Two types of leaded components – one that demonstrated whiskers and the other without whiskers were analyzed. Both were used for the same product and had the Alloy 42 lead frame with Sn finish and low stand-off. The components were compared in terms of lead frame and Sn finish composition, the Sn layer thickness and irregularities.

In addition, ion chromatography was used to compare the level of ionic contamination. Five components of each type were placed in Kapak plastic bags. Ionic extraction of all the samples was performed using 10% IPA/90%water initially at room temperature for one hour. A small quantity of sample was removed to perform cation analysis. The samples were then resealed and extraction was done at 80°C for one hour and allowed to cool to room temperature before performing cation analysis (again) and anion analysis. The results were calculated and reported in µgms/sq in for each of the ionic and organic species.

RESULTS AND DISCUSSION

Visual and SEM Inspection of Solder Joints before Cross-Section

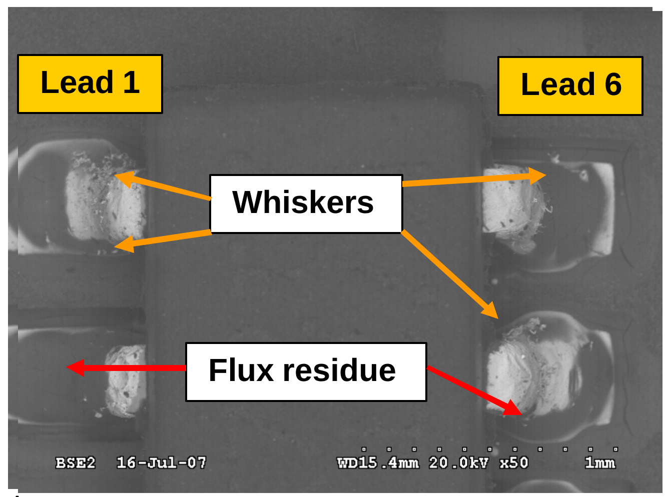
<u>Appearance</u>

Optical and scanning electron microscopy under low magnification showed many whiskers and hillocks protruding through flux residue, and also growing from solder without flux residue (Fig.1).

The whiskers and hillocks we observed had different sizes and could be divided into three categories: thin long filaments (1), thicker and shorter rods (2), and hillocks that did not have an obvious preferable size in any of three dimension (3) (Fig. 1 and 2). There were also several protrusions found that could not be categorized by any of those three groups. They looked like thin shells and shown in Figure 3.

Both thin long filaments and thicker rods were straight, kinked or hooked. Some of the observed whiskers consisted of two connected rods often separated at the top (shown with short thick red arrow on Figure 2a). At least in one case a whisker crystal had a spiral shape (Fig. 2D).

The length of thin filaments varied from short - 10 to 20 µm to long - up to 140 µm. The typical thickness was about 1.5 to 2.0 µm. It appeared that thin whiskers often grew from hillocks. Thicker rods usually had a striated surface (Fig.3C), which was not obviously visible on thin whiskers.



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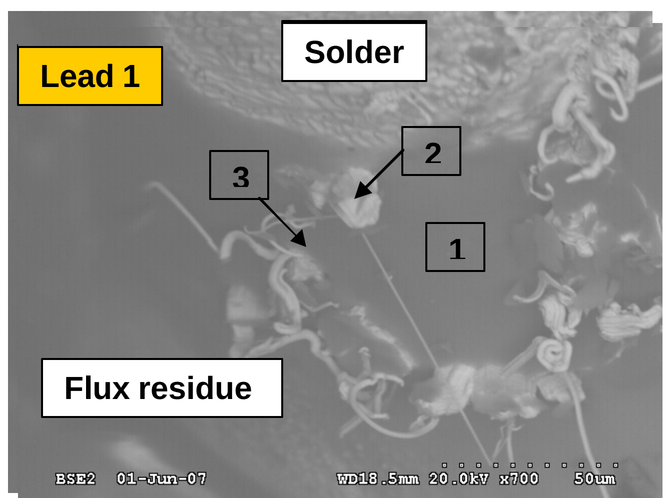

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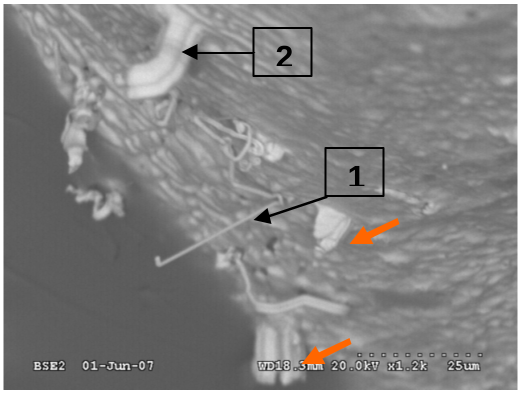
Figure 1. Whiskers and hillocks (1 - thin long filaments; 2 - thicker and shorter rods; 3 – hillocks) protruding through flux residue and growing from solder free of the flux residue, SEM: a – 50X; b – 700X.



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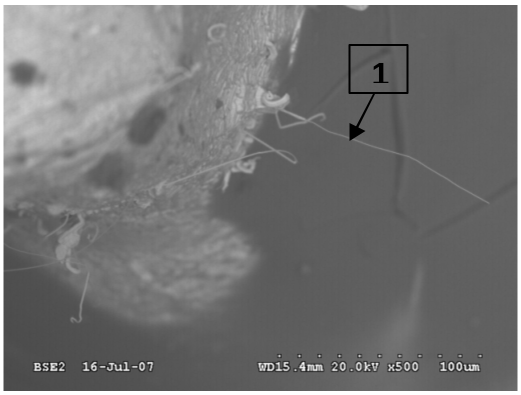

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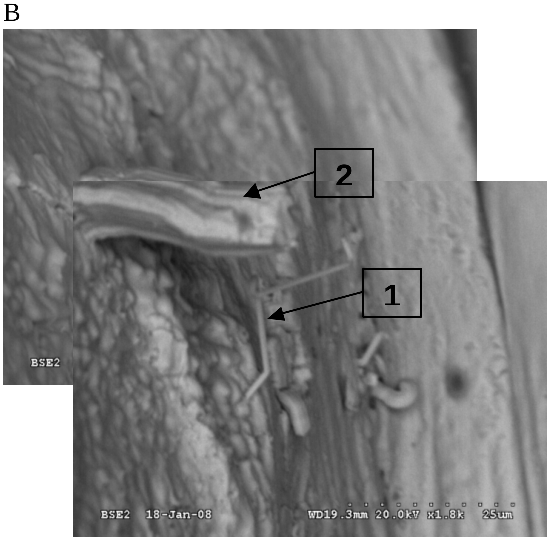

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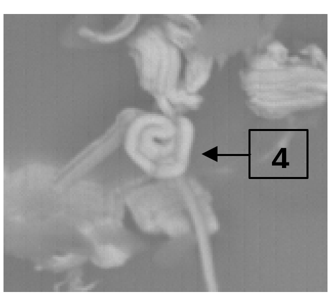

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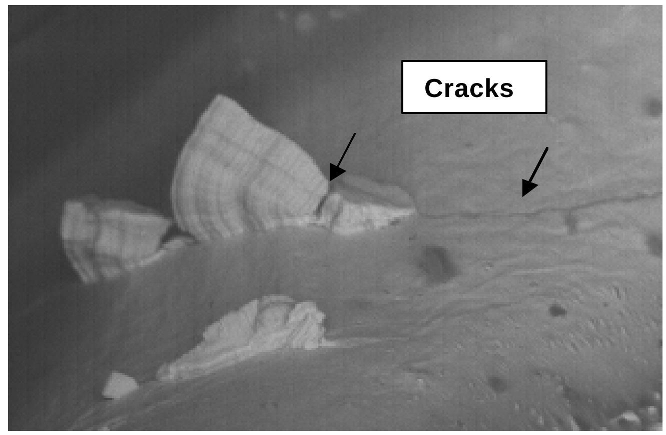
Figure 2. Whiskers with different sizes and shapes: thin long filaments (1) thicker and shorter rods (2), and with spiral shape (4), SEM: a – 1,200X; b – 500X; c – 1,800X, d – spiral, 700X x 3

The shell–like protrusions are shown in Figure 3. The photos were taken from two opposite points of view and allow viewing of the length, width, and thickness of the protrusions. It appeared that they grew from a crack in the surface layer that may be an oxide or crystallized flux film. The shells have clearly visible striations in two directions. The stripes were parallel to the edges of the shells. The protrusions were also cracked. The cracks followed the vertical striations.



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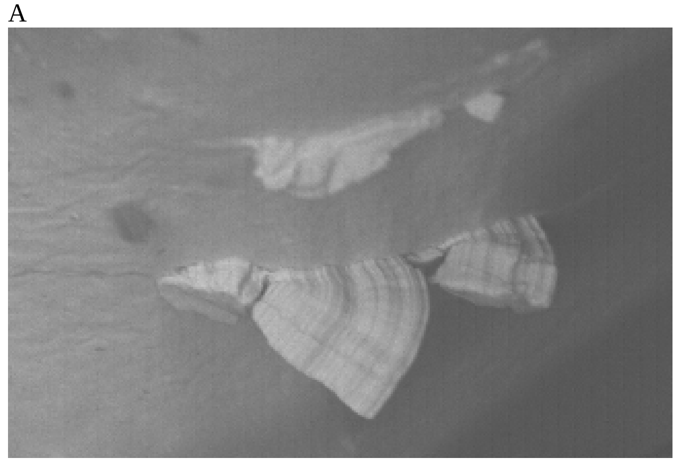

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Figure 3. Shell-like protrusions, SEM, 450X x 2.5

<u>Composition</u>

A thin long whisker with the diameter of 1.8μ and length of 172μ was cut out from the joint using a microscalpel and placed on the SEM sample holder is shown in (Fig. 4a). Only Sn was detected by EDX analysis (Fig. 4a). This composition was confirmed on other thin long filaments. Contrarily, EDX analyses on thicker and shorter rods detected not only Sn, but also Ag and sometimes Cu. Because it was difficult to remove short rods from the solder joint surface, theses scans were taken without whisker separation. Therefore, the EDX results were ambiguous. The following cross-sections confirmed that Ag and Cu were present in whisker rods. Rod composition is described in the Cross-section Analyses section of this paper.

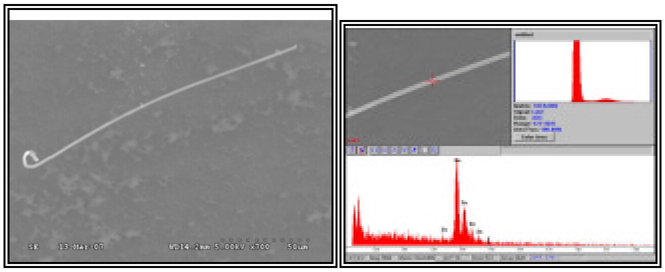

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Figure 4. Thin long whisker appearance (a) and composition (b)

Cross-section Analyses of Solder Joints

The typical longitudinal cross-section of a sample with whiskers is shown in Figure 5. Figure 5a shows an optical image of lead 1 of a device of interest. The image of the lead before cross-section was shown earlier in Figure 1. The whisker is visible through the potting epoxy on the front part of the lead – area 1 in Figure 5a. In a rear part of the lead, a hillock is situated in the cross-section plane – area 2 in Figure 5a. Each area was analyzed using metallurgical light and scanning electron microscopes. Under the metallurgical microscope, parts of two thin whiskers and a hillock are visible in area 1 (Fig. 5b, c). A big hillock is evident in area 2 (Fig. 5d). It is important to stress that whiskers and hillocks were found at both toe and heel sides of the cross-sectioned lead on different devices.

Hillock Microstructure

The details of this hillock, examined using SEM, are depicted in Figure 6 It is different from the bulk solder microstructure and contains the recrystallized Sn grains and very few intermetallic particles. It seems that the hillock emerged through the hole in a surface Sn oxide film (white layer) (Fig. 6 a, b).

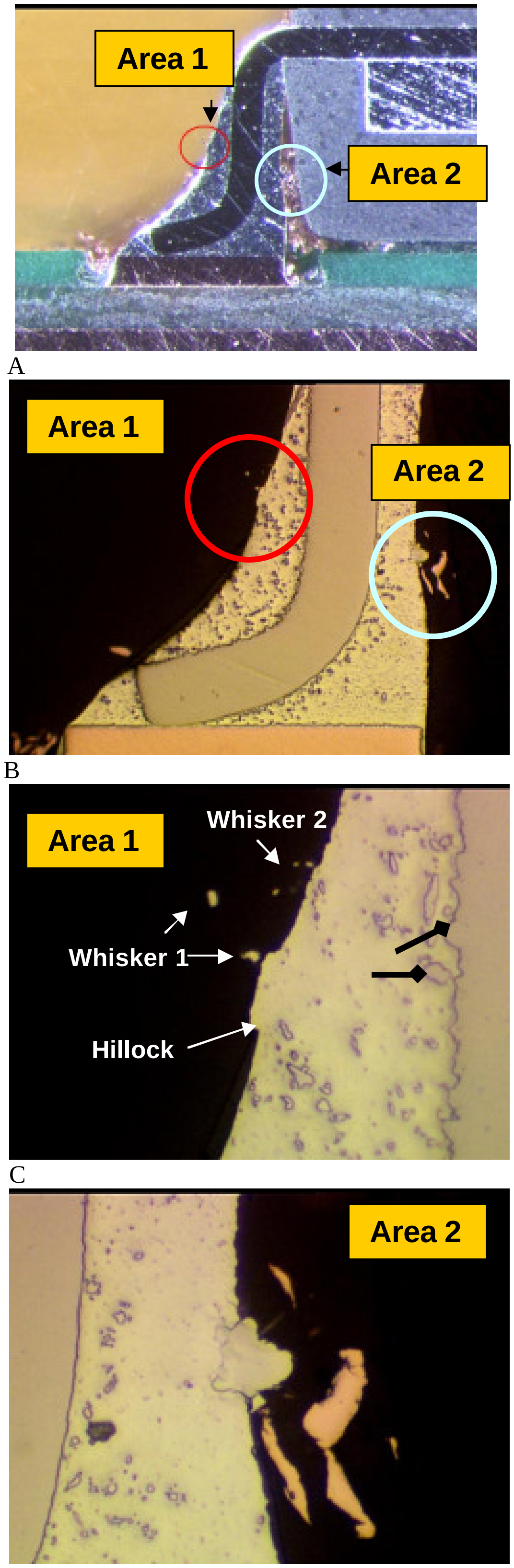
The intermetallic particles are distributed non-uniformly and located only in the centre of the hillock. They contain either Ag or Cu in addition to Sn (Figure 6c). The particles have similar size and shape as the original eutectic particles Ag_3Sn and Cu_6Sn_5 in the bulk solder. The rest of the protrusion is pure Sn. It is possible that the solder was depleted of Ag and Cu by extensive diffusion caused by oxidation or corrosion.

The recrystallized grain size is smaller at the base of the hillock than in the hillock itself (Fig. 6 a, b). This may explain the mechanism of hillock formation. The depleted solder is under compressive stresses that causes recrystallization and grain growth. It is well known in metallurgy of deformation that under relatively low stresses, abnormal grain coarsening occurs. One or several grains larger in size or with lower surface energy begin to grow, consuming the smaller grains.

Hillock Shape Evaluation and Connection with Whiskers

Although it was observed under SEM before cross-sectioning that whiskers are often connected with hillocks, it is important to analyze more details of their relationship.

The results of progressive polishing of area 1(Fig. 5) are shown in Figure 7.



A B C D

Figure 5. Longitudinal cross-section of lead 1 from Figure 1: a – optical microscope, 30X; b – 100X, c, d – 400X

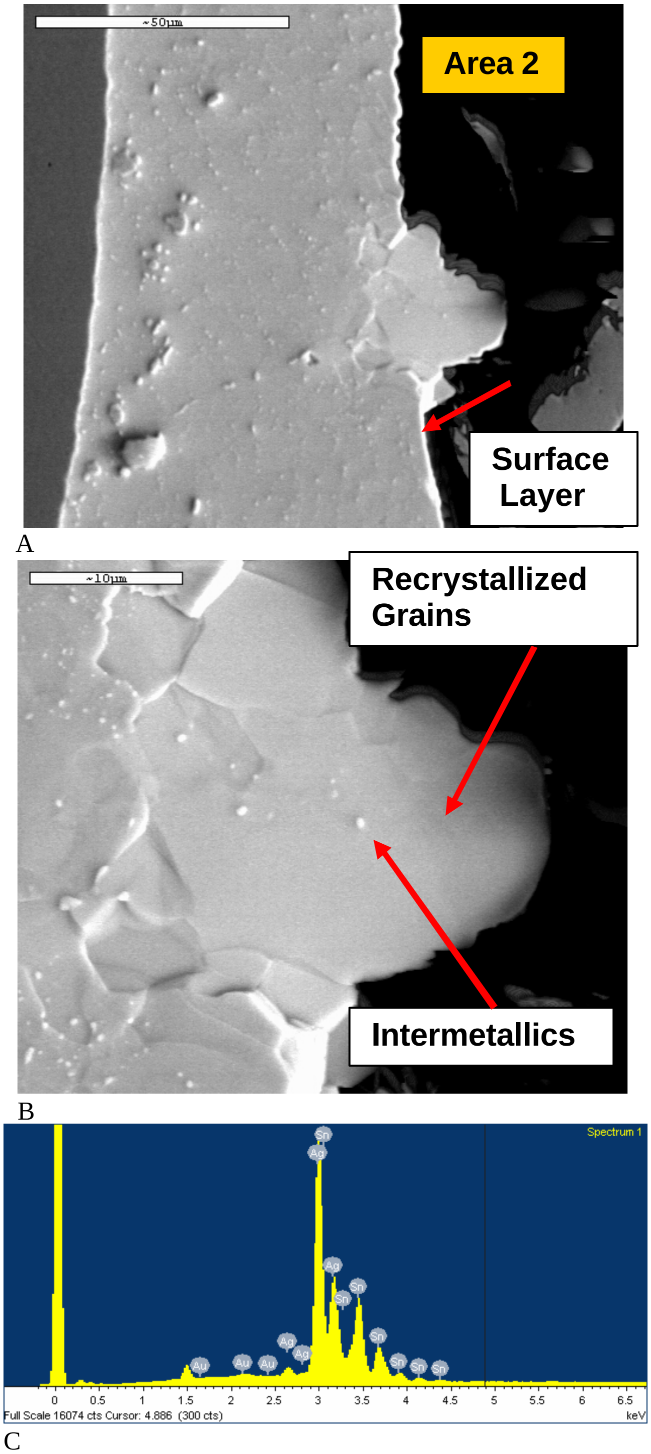


Figure 6. Hillock microstructure and composition: a – SEM, 1,000X; b – SEM, 3000X, c- EDX on intermetallic particle inside the hillock, 20 keV

It can be seen how whisker 1 changes its shape and the hillock transforms into two whiskers. Note the void which appeared in Figure 7c (Indicated by the arrow). It is a corrosion mark that will be discussed below.

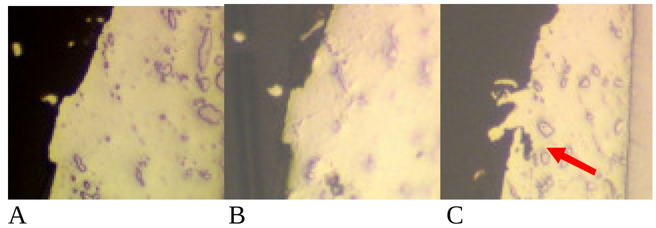


Figure 7. Polishing in sequence, 400X

Several more examples are shown in cross-sections perpendicular to the leads (Fig. 8). Whiskers and hillocks were detected from both left and right sides of the several leads.

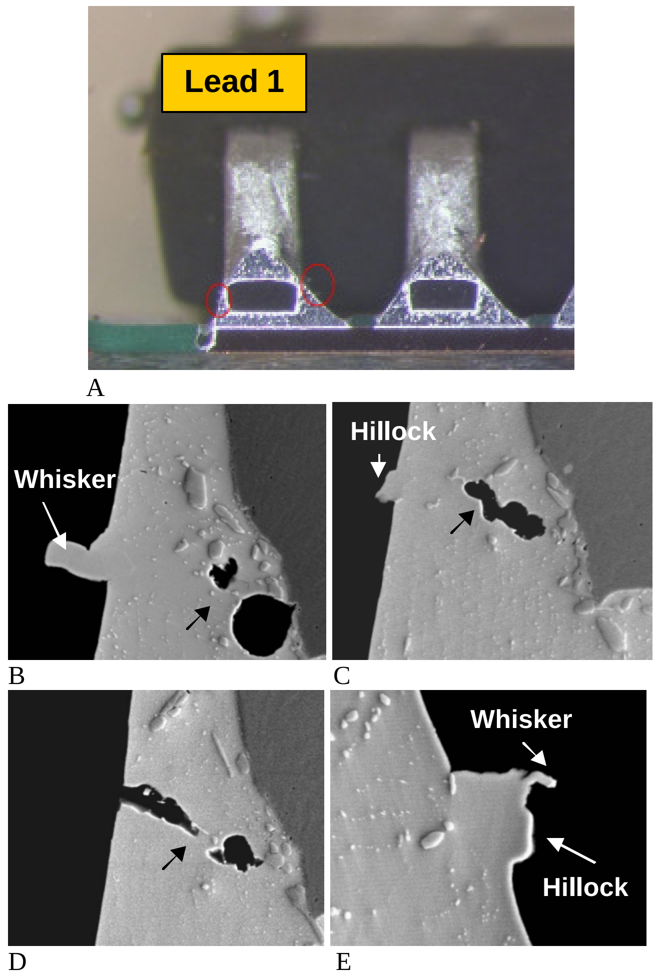


Figure 8. Perpendicular cross-section of lead 1: a – optical microscope, 30X; b, c, d – cross-sections in sequence, SEM, 1,800X; c – 1,400X

<u>Inter-granular Corrosion and Lead/Solder Interface Roughness in Connection with Whisker and Hillock Growth</u>

One of the main observations from progressive polishing is the co-existence of voids with hillocks and whiskers. Examples are shown in Figure 9 as well as in Figures 7c and 8 b, c, and d.

Figure 9a illustrates a longitudinal cross-section of lead 6. The appearance of this lead before cross-sectioning is shown in Figure 1a. Whiskers and hillocks formed from both toe and heel sides of the lead. All three locations of this cross-section have visible signs of interdendritic corrosion marked by a black arrow on Figures 9b and 9c.

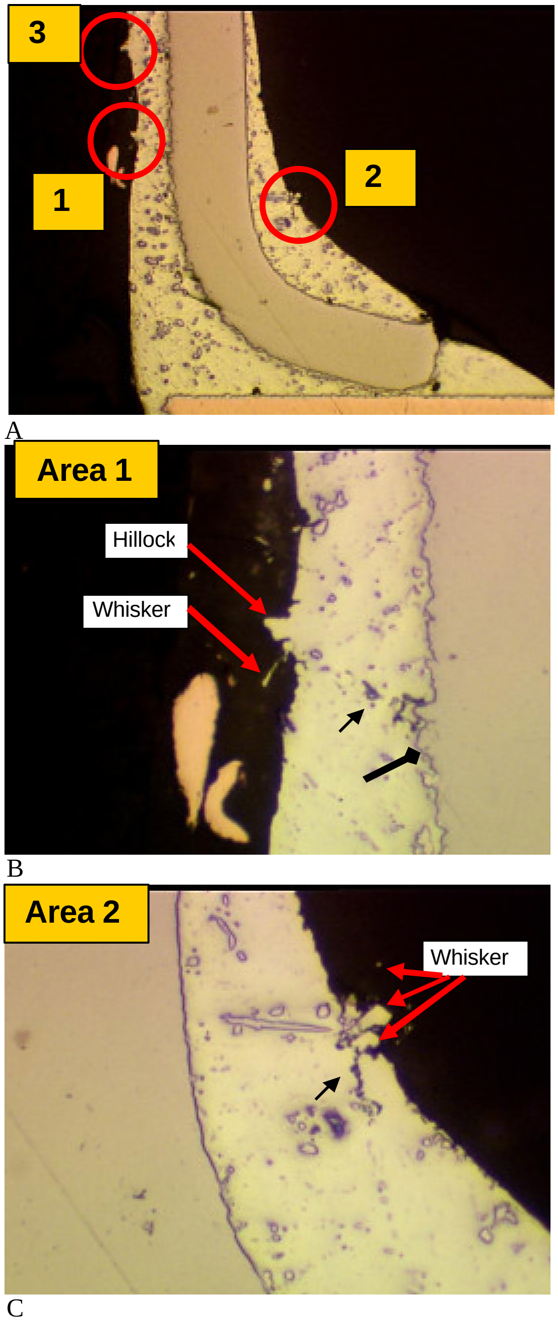


Figure 9. Longitudinal cross-section of lead 6 from Figure 1: a – 100X, b, c – 400X

The details of area 1 and area 2 (Figure 9) are depicted in Figure 10 and 11. The corrosion voids propagate through the solder from the solder surface to the component lead/solder interface. The solder around the voids is depleted of Ag and Cu. The number of intermetallic particles is much less than in bulk solder. The particles are also larger in size. The corrosion voids are surrounded with the re-crystallized grains.

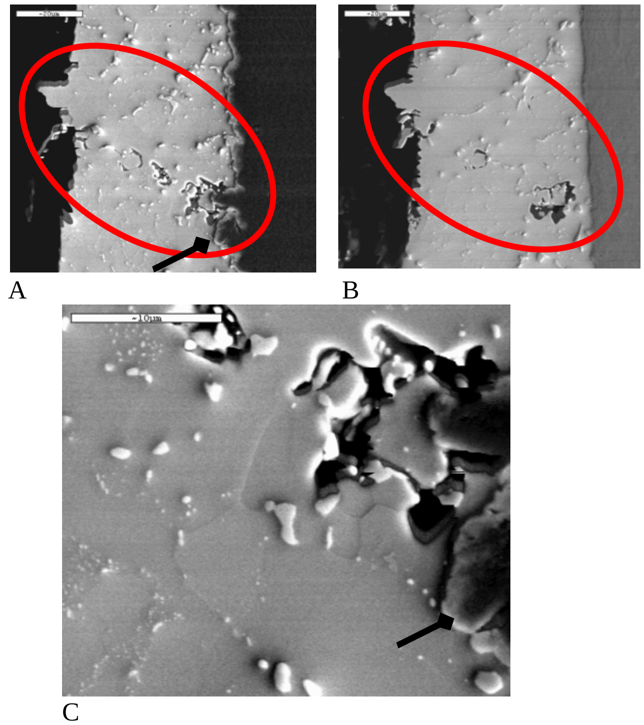


Figure 10. Longitudinal cross-section of lead 6, area 1, Fig. 9, SEM: a – 1,300X, b, c – 4,000X

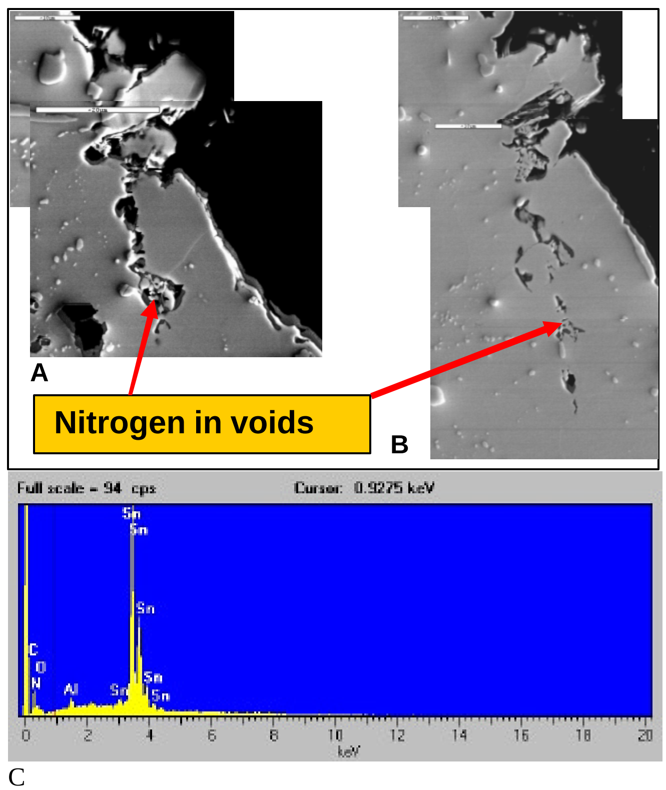
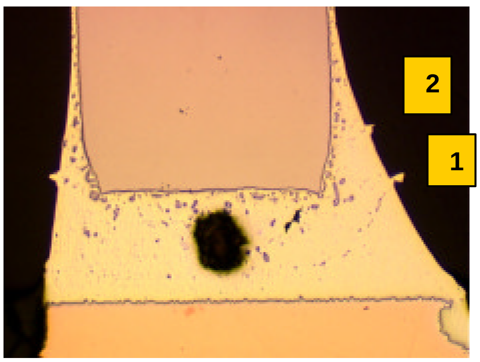


Figure 11. Longitudinal cross-section of lead 6, area 2, Fig.9 and EDX on voids: a – 1,000X, b - 3,000X; c – EDX on voids, 20 keV

The progressive polishing always reveals corrosion channels near the rod whiskers or hillocks. They propagate through the eutectic structure in spaces between the dendrites' arms and have a dendritic shape. In some cross-section planes ,they look like separate voids, but sequential polishing shows that they are always connected.

Very often the corrosion channels are traceable to large round voids (Figure 8 b - d) that have their origins from flux or other gas related sources such as surface or plating contaminations. Another example is shown in Figure 12. The cross-section was done perpendicular to the leads. The large outgassing void is located between the lead and the pad. Two protrusions on the right side of the lead have corrosion channels connecting them to the void (Fig. 12 a) (The left side protrusion is shown in Figure 8). The details of the corrosion path to protrusion 1 are shown in Figure 12 b, c. Corrosion propagates through the intermetallic particle/solder interfaces.



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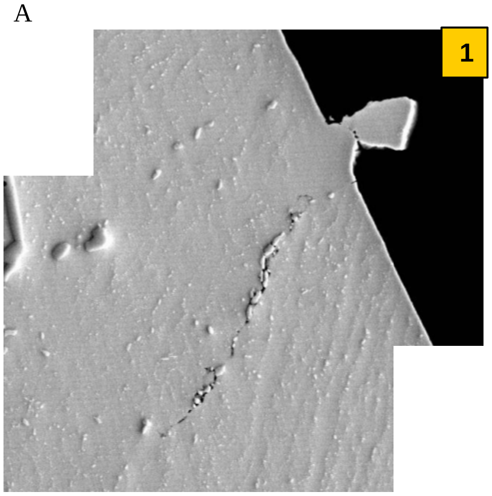

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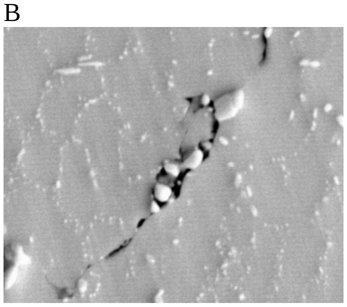
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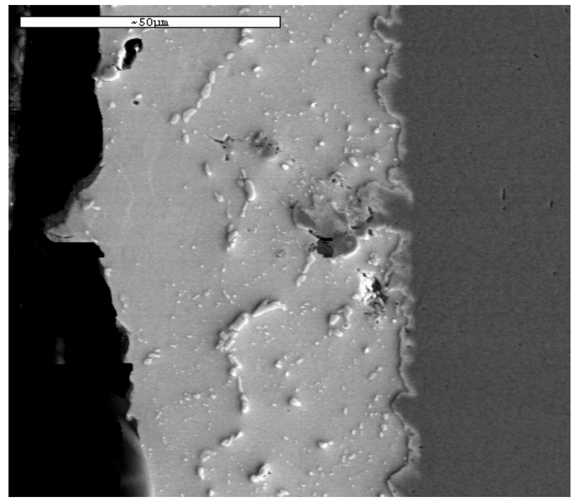
Figure 12. Perpendicular cross-section of lead 1 (Fig.9): a – 200X, b – SEM, 1,800X; c – SEM, 6,000X

Another microstructural characteristic found in this study that may play a significant role in whiskering is Alloy42 lead/solder interface roughness. The leads with whiskers or hillocks had rough surfaces. Some pieces of the lead-frame material that may be debris or roughness protrusions in the solder joints are visible in cross-sections (Fig. 5c, 9b, 10 a, c – diamond arrows). The voids are often related to the rough interface as it shown in Figure 13.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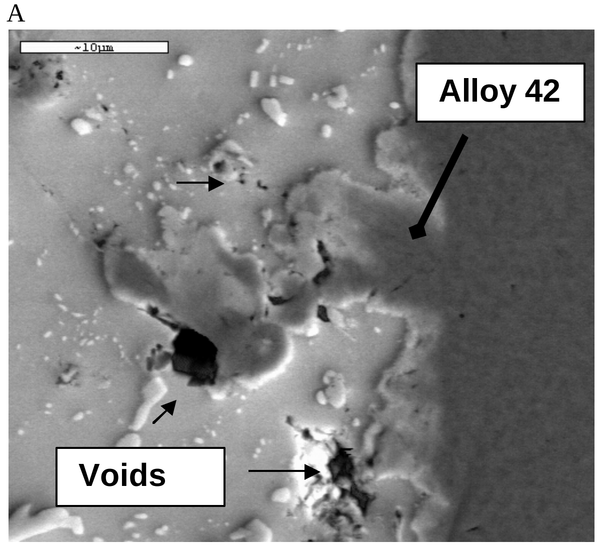

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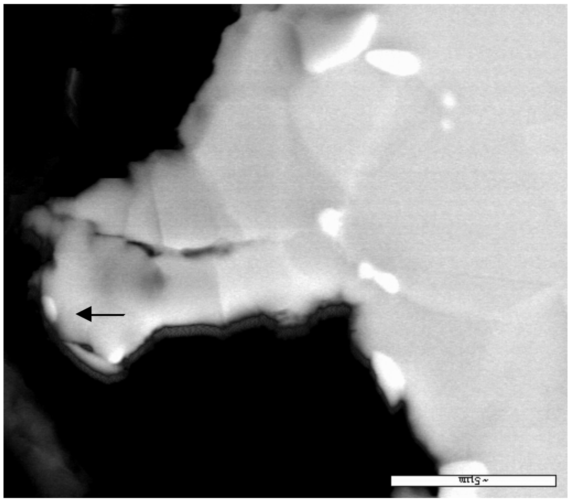
Figure 13. Area 3 from Figure 9 a, SEM: a – 450X, b – 3,000X

<u>Details on Protrusions with Irregular Shape, Striations, and Cracks</u>

Some of the observed whiskers consisted of two connected rods often separated at the top (Figure 2a). The cross-section of one of such whiskers is shown in Figure 13 a, b. All the details of the microstructure described before are present in this cross-section as well. The whisker rod is growing from recrystallized solder depleted of Ag and Cu and containing much less intermetallic particles than the bulk solder. The corrosion path consisted of many small voids in the interdendritic space connecting recrystallized solder with larger outgassing voids formed on Alloy 42 protrusions.

The SEM image at high magnification of this rod whisker is shown in Figure 14a. Two separated parts of the rod whisker have recrystallized pure Sn structure. An intermetallic particle is situated at the top of one of the rod parts. The EDX analysis identified it as Cu_6Sn_5 type (Fig. 14 b). In general, the rod whiskers (shorter and thicker than filament whiskers) have features similar to the hillocks.



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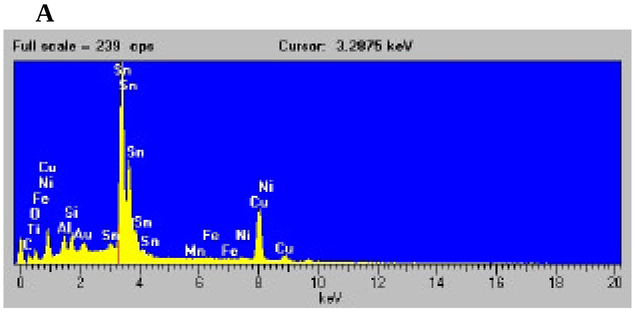

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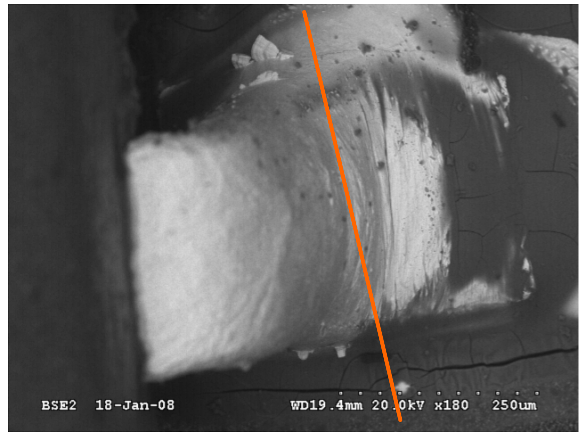
Figure 14. Enlarged image of area 3, Fig.9 a and EDX on the intermetallic particle: a – 7,000X; b – EDX on intermetallic particle, shown by arrow, 20 keV

To analyze the shell-like protrusions, perpendicular cross-sectioning with progressive polishing of the lead shown in Figure 15a was done. The sequence of the cross-sectioning and polishing as well as images after polishing are depicted in Figure 15. The details of the microstructure are shown in Figure 16. The shells have a similar microstructure to the rod whiskers and hillocks, that is, a Sn matrix with very few Ag_3Sn and/or Cu_6Sn_5 particles. In cross-section, the two-dimensional striations clearly visible on the surface of the shells, are evident as a surface roughness at the edges of the protrusion and stripes in the parallel direction. In some cross-sections, it they be seen as black lines or wrinkles (Fig.17a, b).

The crack in the first section looks like a separation between the grains (Fig. 16a). It is interesting that in the third polishing, Fig. 16c, a line appeared instead of this crack. This line looks white under the scanning electron microscope. Elemental analysis on this line was attempted but the results were inconclusive because the layer was very thin, and the main analyzed solder volume was Sn. The EDX scan contained a small peak of Cu. Also, N was detected in this location (Fig. 18)



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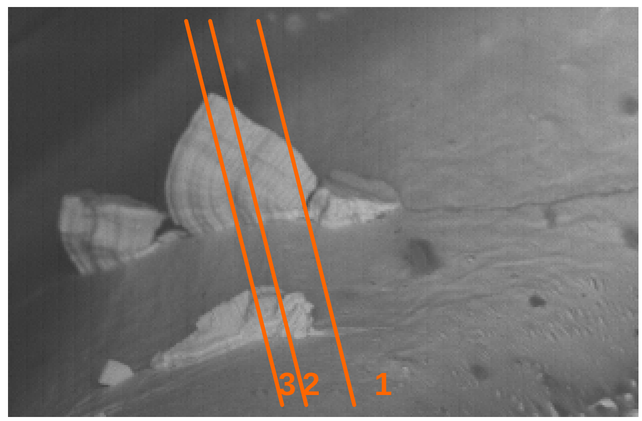

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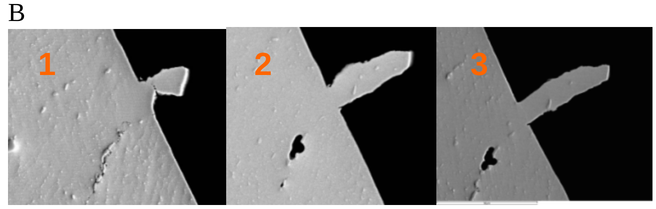
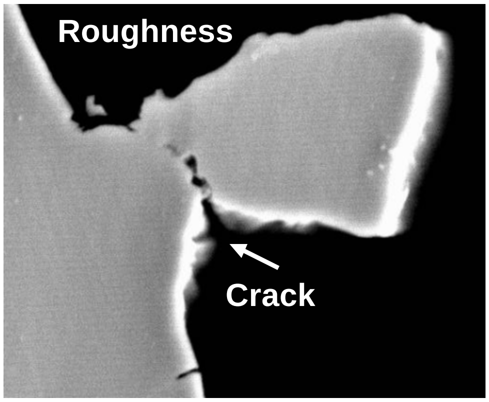


C D E

Figure 15. Sequence of cross-sectioning (a) and progressive polishing (b) and images after polishing (c – e) of shell-like protrusions, SEM: a – 180X; b – 450X x 2.5; c, d, and e – 1,800X

<u>Nitrogen in Solder</u>

More systematic analyses of solder composition showed that N is present in corroded interdendritic spaces (Fig. 11) and in the Sn matrix as well (Fig. 17c, expand to 200% to view online). N is found in the bulk solder and in hillocks and whiskers. The EDX study using both Hitachi S-3000N and Hitachi S-4500 SEM with three different software packages identified the N peak. It was more pronounced using lower voltage (Fig 19), but still detectable under 20 keV as well (Fig. 17, 18).



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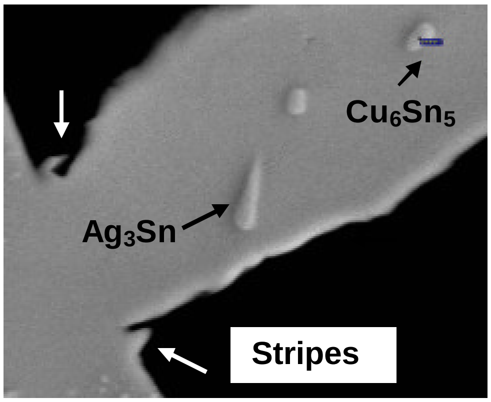

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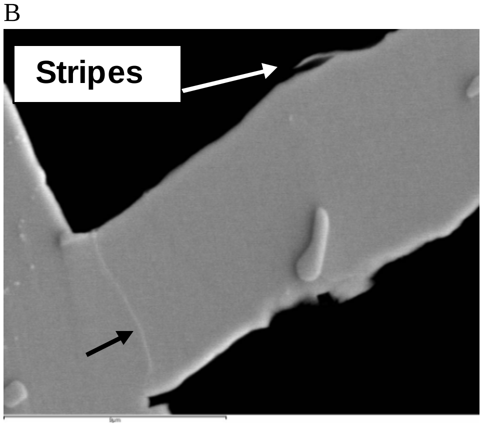

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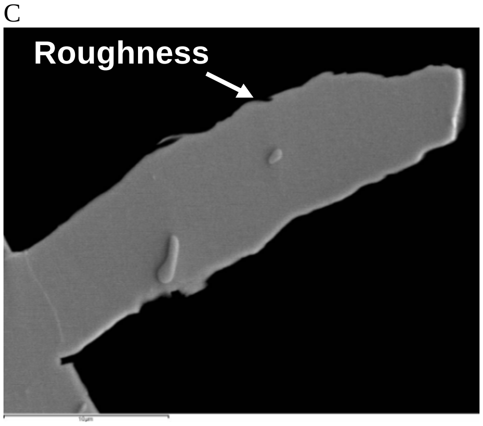

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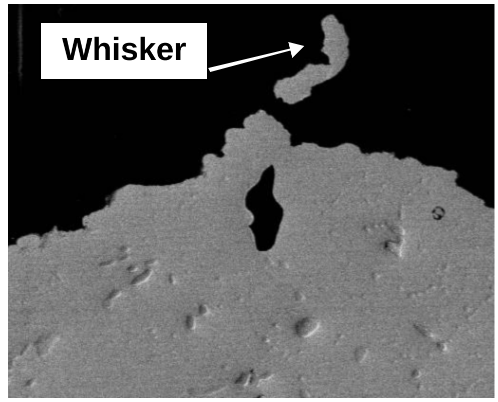
Figure 16. Details of shell-like protrusion microstructure, SEM: a – 1 polishing, 6,000X; b – 2 polishings, 6,000X; c - 3 polishings, 6,000X; d - 3 polishings, 4,000X



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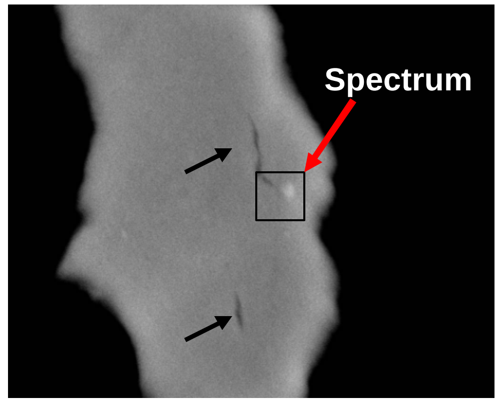

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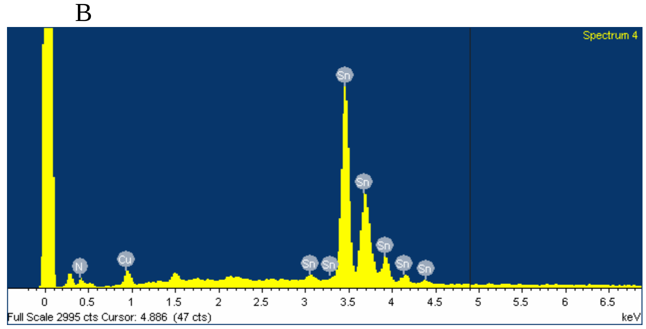


C

Figure 17. a) Whisker in a perpendicular cross-section at 1,800X b) enlarged image with wrinkles at 18,000X c) EDX on the white particle boxed in 17b, 20 keV

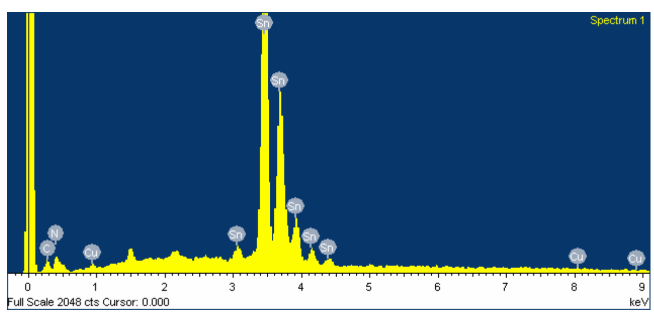


Figure 18. EDX on white line area of Figures 16c & d, at 20 keV

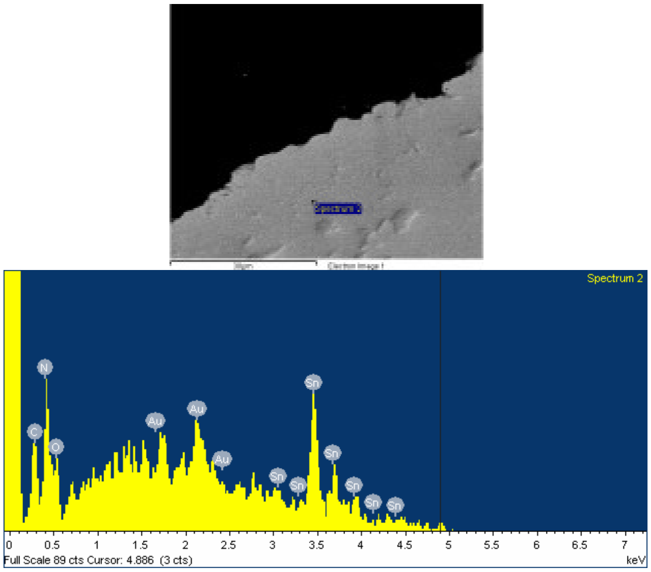


Figure 19. Microstructure and EDX on bulk solder, showing a distinctive N peak, 5 keV

Virgin Components

Because this study showed that the hillocks and whiskers related to corrosion paths from the solder surface to the component leads with rough interfaces, and also because the source of N is not known, the virgin devices were examined. The devices with the Alloy 42 lead-frame material used in solder joints that created whiskers ("bad") were compared to similar devices in the same assembly that did not grow whiskers ("good").

Contamination

The ion chromatography results are shown in Tables 1 and 2. Nitrite, bromide, lithium and magnesium ions were not detected. The detected anions and cations are shown in Table 1 and Table 2, respectively.

Table 1. Ion Chromatography Data for Virgin Components, Anion Concentration, all in µg/in^2

ID	F^-	Cl^-	NO_3	SO_4^{-2}	Total
Bad	1.7	5.1	0.6	1.8	**9.3**
Good	0.5	1.0	0.9	1.5	**3.9**

Table 2. Ion Chromatography Data for Virgin Components, Cation Concentration, all in µg/in^2

ID	Na^+	NH_4^+	K^+	Ca^{2+}	Total
Bad RT	2.7	0.0	2.8	2.7	**8.2**
Good RT	2.8	0.0	2.0	2.9	**7.7**
Bad 80°C	6.9	0.3	6.8	2.1	**16.1**
Good 80°C	2.2	0.3	3.9	0.9	**7.3**

The components on which whiskers were found – Bad – are more contaminated than their counterparts – Good. For room temperature extraction, the difference is insignificant. After 40 min extraction at 80°C, the levels of chloride and fluoride in the Bad sample exceed those in the Good sample by more than 5X and 3X, respectively. The cation content is also much higher in the Bad sample: Sodium is 3x the level as in the good sample, calcium is 2x, and potassium is almost 2x. There is no significant difference in nitrate and ammonium content.

Considering the total level of anions and cations, Bad components are 2.3x more contaminated than Good parts: 25.4 µg/in^2 and 11.2 µg/in^2, respectively. Good components are close to the industry accepted limit of contamination of 10.75 µg/in^2. Therefore, the virgin components of the types where whiskers and hillocks were found after assembly, have ionic contamination above acceptable levels.

Plating Quality and Composition

The SEM photos of leads of two types of components with the Alloy 42 lead-frame material are shown in Figure 20. It is easy to see the difference in plating shape. The troubled components have a double layer structure (Fig. 20 b, d). The top layer is shorter than the bottom. It produces a step that is round in shape. A close look at the lead surface allows one to conclude that the cleaning after plating was done differently. The good part has pronounced mechanically produced grooves, but the surface of the bad part is smooth, showing that cleaning was more likely done chemically.

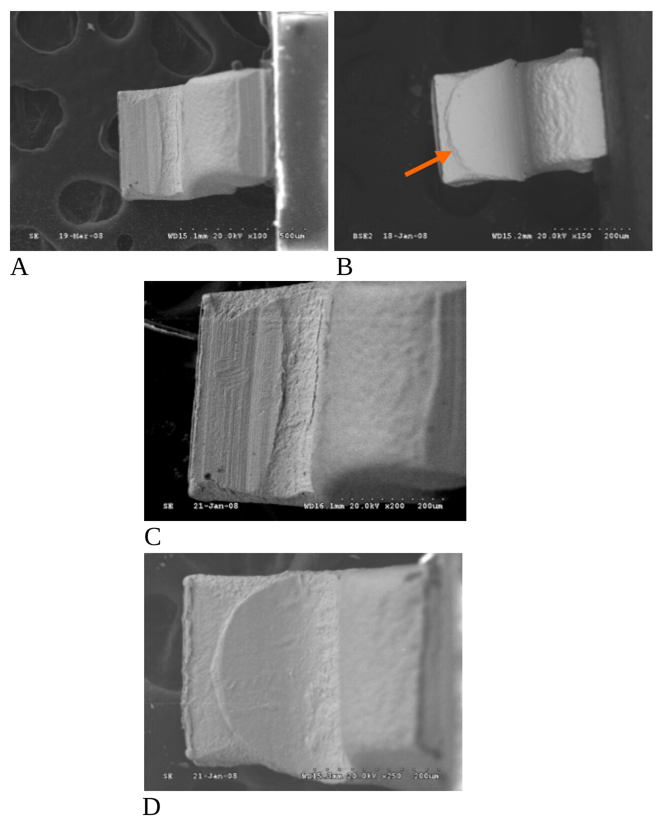


Figure 20. SEM images of two types of components with the Alloy 42 lead-frame material: a – Good, 100X; b – Bad, 150X; c– Good, 200X; d – Bad, 250X

Cross-sectioning confirmed the non-uniform thickness of the leads in the devices used in solder joints that created whiskers and hillocks (Fig. 21). In some of the areas where the step is visible, the thickness of the Sn plating may be greater than 30µm. The thickness varied from lead to lead. The average thickness of the Sn layer in lead 1 (Fig. 21 b) is about 24µm and in lead 6 (Fig.21 a) is 15µm.

The interface between the leads made of Alloy 42 and the bulk solder is rough (Fig 21 b, e, and f) as shown in the solder joint cross-sections. The most severe roughness was found on lead 1.

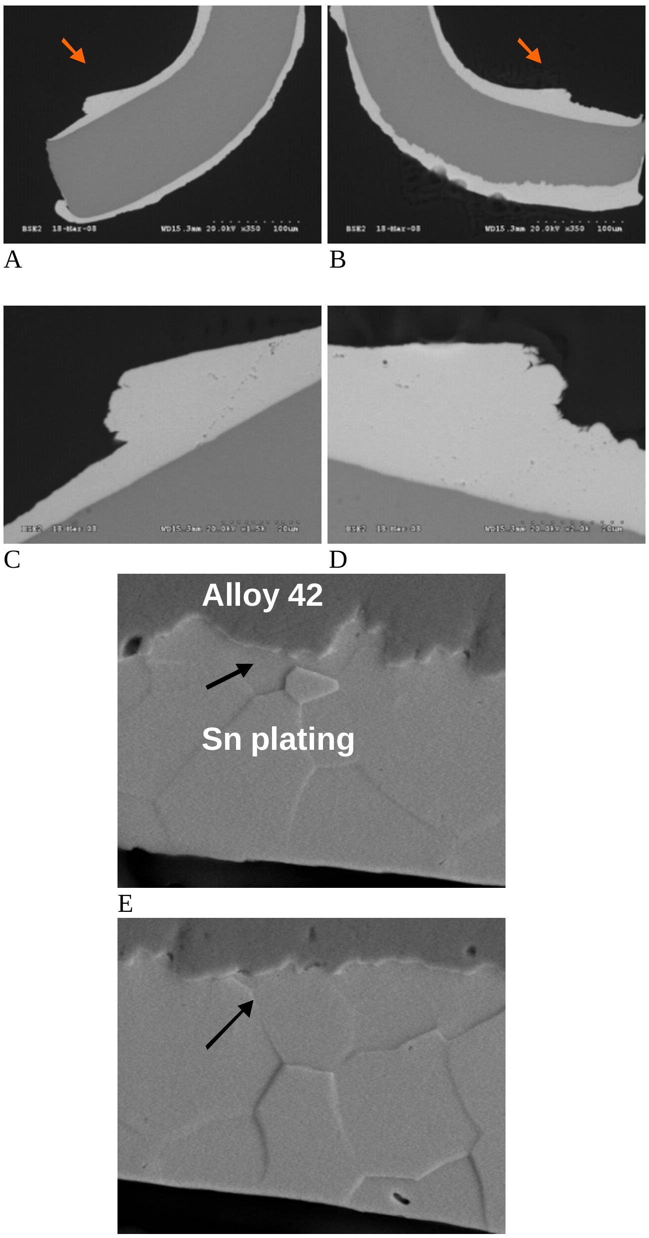


Figure 21. Cross-section of a virgin component with the Alloy 42 lead-frame material, SEM: a – lead 6, 350X; b – lead 1, 350X; c– lead 6, 2,000X; d – lead 1, 2,000X; e, f – lead 1, 6,000X

Such an interfacial roughness is not normally seen and may be a characteristic of a surface preparation before Sn plating.

The composition of the Sn plating was analyzed before and after cross-sectioning. N is present in both Bad and Good component plating. There is no significant difference between them in the N content (Fig. 22 and 23). Any area of the leads covered with electrolytic Sn contains N. The lowest detected concentration was 32 At % (10.3 Wt. %) and the highest was 43 At % (22.9 Wt. %).

The component bodies do not contain N. The N was not detected in any other materials of the components (Fig. 24).

The cross-sections of the virgin components were also examined using EDX. N was found in the Sn plating, and was not detected in the Alloy 42 lead-frame (Fig. 25).

It is well known that an electroplating bath for depositing Sn or a tin alloy may contain citric acid or its salt, and an ammonium salt. It is not clear yet in what form N is present in the electroplated Sn layer analyzed here, but the relationship between the plating and solder composition is evident. The thicker the Sn layer, the more nitrogen the solder inherits due to the higher gross amount present.

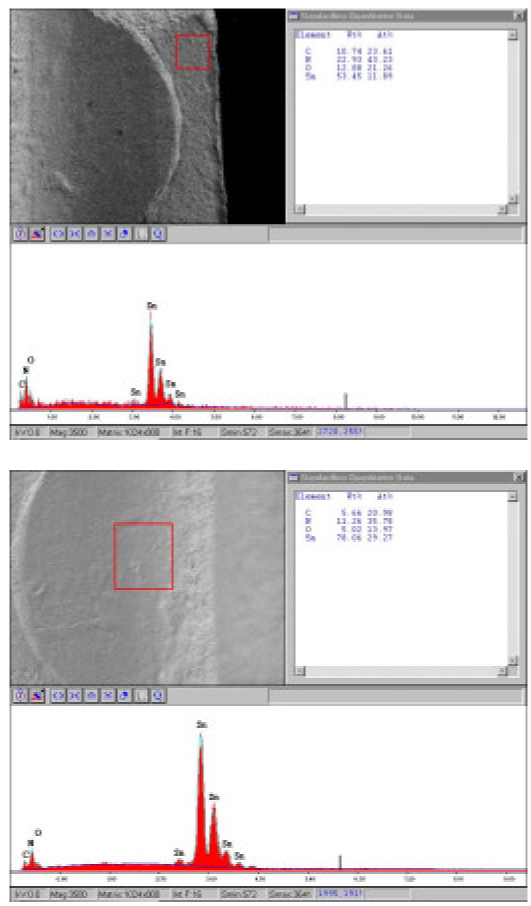


Figure 22. EDX spectrums and semi-quantitative analysis of Bad part

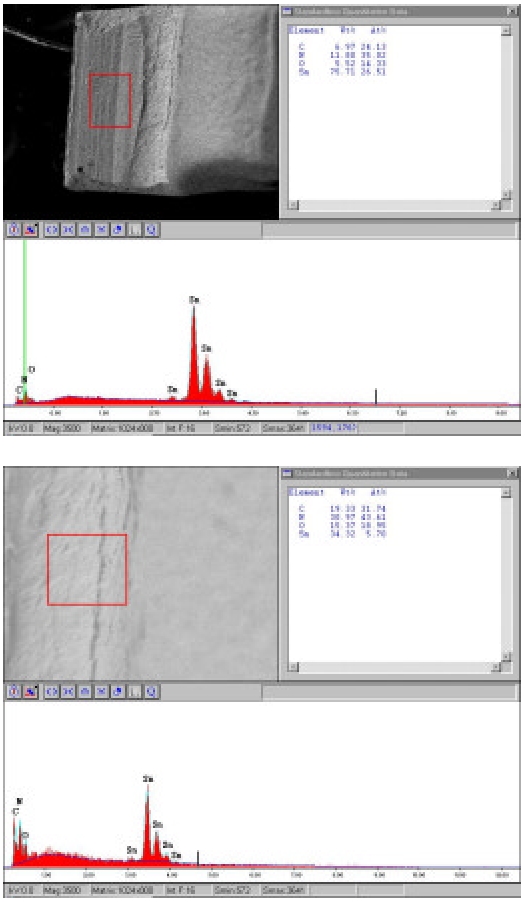


Figure 23. EDX spectrums and semi-quantitative analysis of Good part

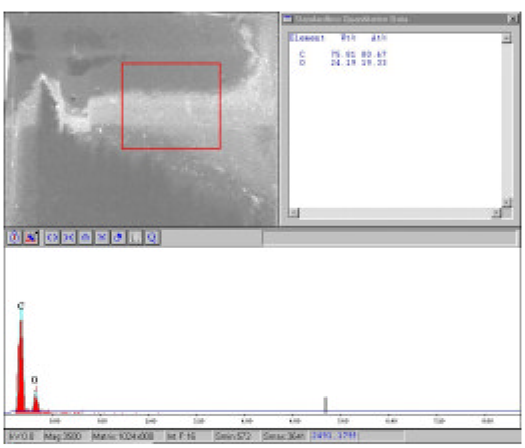
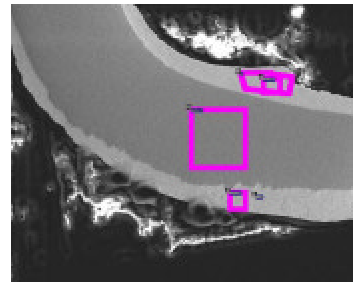
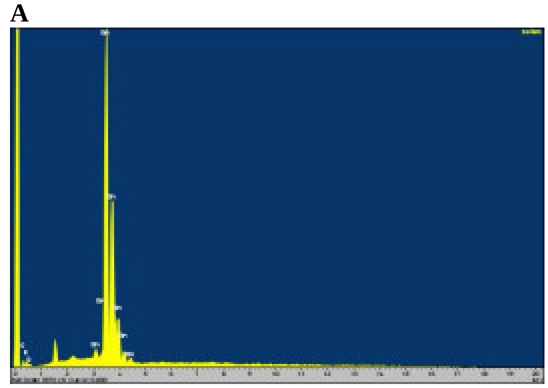


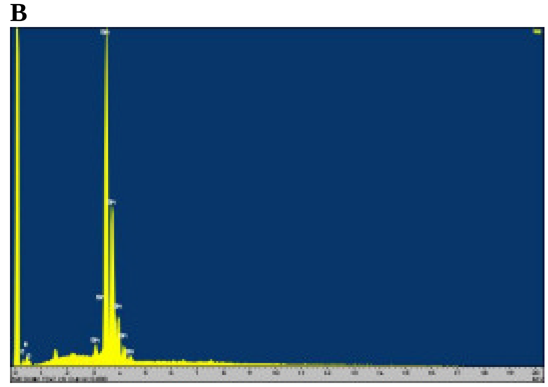
Figure 24. EDX spectrums and semi-quantitative analysis on component bodies



A



B



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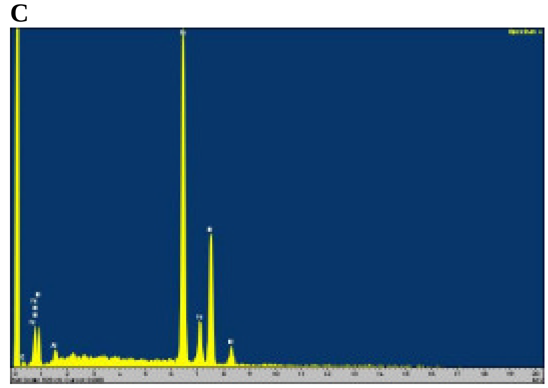

D

Figure 25. EDX analyses on cross-sectioned sample: a – lead image; b – Sn plating, top box, c – Sn plating, bottom box; d – lead material

CONCLUSIONS

Precise cross-sectioning with progressive polishing combined with detailed SEM and EDX analyses before and after cross-sectioning and ion chromatography testing done in this study allow one to draw the following conclusions:

- Whiskers growing from SAC305 solder in solder joints of leaded components with the Alloy 42 lead frame material were found and characterized.

- The whiskers and hillocks grow on both sides of the leads – the toe side that is expected to be under compressive stresses, and on the heel side, which may experience tensile stresses.

- Thin long filaments, thicker and shorter rods, hillocks that do not have an obvious preferable size in any of three dimensions, and thin shell-like protrusions are found in this work.

- Whiskers, especially rods, and shells have a striated surface. The striations are parallel to the long side of the whiskers and have a two dimensional pattern with a 90 degree angle in the shells. The striations form ledges or projections on the surface.

- The rod whiskers, hillocks and shell-like protrusions are composed of mostly Sn with a few Ag_3Sn and Cu_6Sn_5 particles. Only Sn was detected in long filaments.

- Whiskers mostly grow from hillocks, and hillocks emerge from solder depleted of Ag and Cu. This solder has a recrystallized structure with smaller grains at the base of the hillock and a few, or even one, large grains inside the hillock. It looks like a result of abnormal recrystallization.

- The hillock locations connect to the corroded spaces between the Sn dendrite arms occupied by $Sn+Ag_3Sn+Cu_6Sn_5$ eutectic. The corroded paths relate to large outgassing voids and a rough interface between component leads made of Alloy 42 and bulk solder, which may be a result of poor quality virgin devices.

- The virgin devices defined as having poor lead finish quality, exhibited the following attributes:
  - The rough Alloy 42 lead-frame surface was found on virgin components before soldering.
  - A poor quality of plating with a thick non-uniform electrolytic Sn layer was detected.
  - The virgin devices were heavily contaminated. The level of anions and cations in whiskering components was 2.3x higher than for good components which did not whisker after assembly. The main contaminants were chloride, fluoride, sodium and calcium.
  - High content of N was found in the electrolytic Sn plating.

- There is not enough data to draw conclusions on the mechanism of whisker formation from lead-free solder yet, but it could be said that the origin is corrosion related. Corrosion propagates through the eutectic regions in the interdendritic spaces of the solder and is accompanied by intensive diffusion in the bulk solder that causes solder depletion of Ag and Cu. The depleted solder area may experience compressive stresses from the rest of the solder. Compressive stresses may result in abnormal recrystallization and hillock and whisker formation

- The root cause of the corrosion is not yet understood as well. As an extension of the work done in this study on the virgin components, more work should be done on all chemicals involved in assembly and also on board quality.

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