Celestica

Solid partners.
Flexible solutions.

Whisker Growth on SAC Solder Joints: Microstructure Analysis

Polina Snugovsky, Zohreh Bagheri, Marianne Romansky

SMTA Toronto, May 15th, 2008

Whisker growth from lead-free solder

- It is believed that whiskers are specific to Tin plating and in general do not grow from solder

- Several publications discussing whisker growth from solder
  - Sn whiskers in Sn3Ag0.5Cu0.5Ce solder joints
    - T-H Chuang and S-F Yen, JEM, 2006
    - Ball grid array packages
    - After storage at room temperature
    - The high propensity to whiskering attributed to the oxidation of $CeSn_3$
  - SnPb whisker in Sn-Pb solder
    - T. Lensniewski, APEX2008
    - TTSOP dipped
    - -40°C to 85°C, 1000 cycling

Whisker growth from lead-free solder (cont.)

- ”Can Whiskers Grow on Bulk Lead-Free Solder?” - No
  - J. A. Nychka, Y. Li, F. Yang, and R. Chen, JEM, 2008
  - Sn3.5Ag
  - Localized residual stress do not result in formation of whiskers in bulk Sn3.5Ag solder
  - No stress relaxation via spontaneous whisker growth, but instead the stress is relaxed through creep
  - Thin-film geometry is required for whisker growth.

- At the Celestica Laboratories, since the widespread introduction of lead-free solder, there have been several observations of spikes growing from the bulk solder of leaded and ball grid array joints.
- This paper is focused on the metallurgical analysis of leaded components that demonstrated whisker and hillock formation

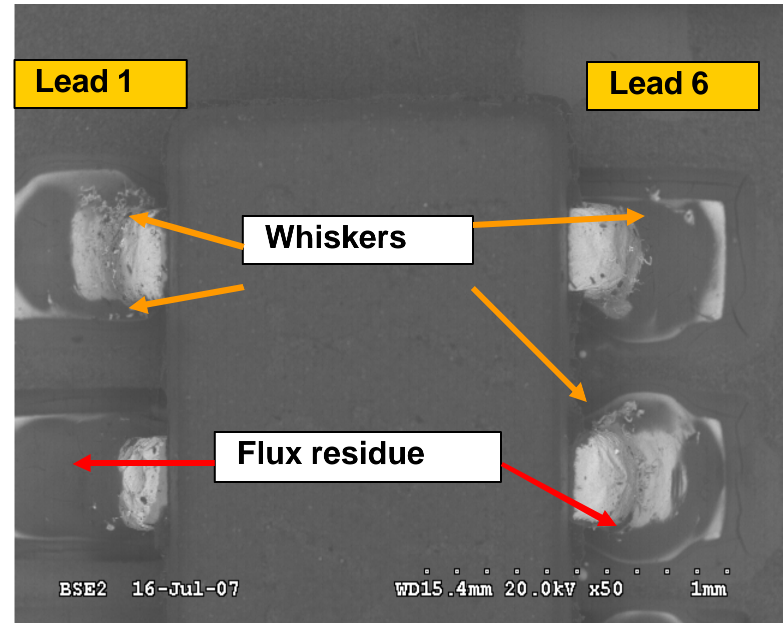
History of the Examined Samples

- Whiskers were observed on leaded components with low stand-offs
- Assembled using both SAC405 and SAC305 solder pastes
- Alloy 42 -the lead-frame material
- Electroplated matte Sn finish
- Life testing for 10 days at 60°C and 20-30% RH with voltage cycling
- High level of contamination on the assembled devices
  - Chloride
  - Sulfate
  - Ammonia

Visual and SEM Inspection of Solder Joints before Cross-Section

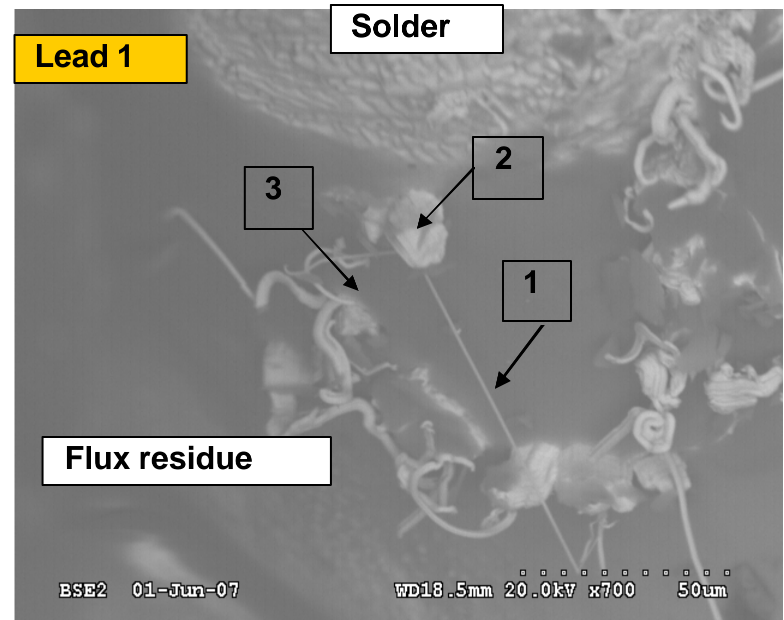
- Many whiskers and hillocks
  - Protruding through flux residue, and
  - Growing from solder without flux residue

SEM, 50X



- The whiskers and hillocks with different sizes
  - Thin long filaments (1),
  - Thicker and shorter rods (2), and
  - Hillocks with no preferable size in any of three dimension (3)

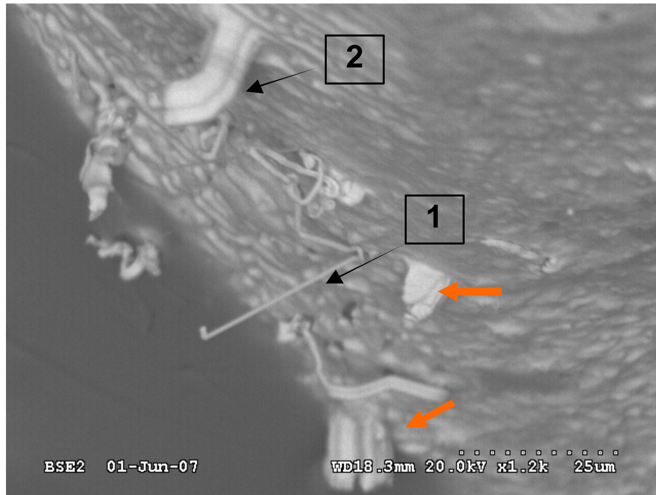
SEM, 700X



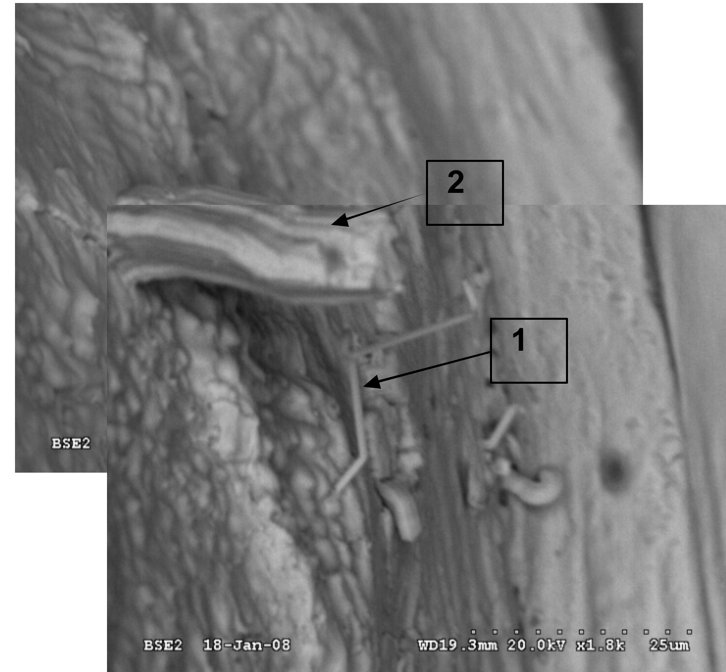
Visual and SEM Inspection of Solder Joints before Cross-Section (cont.)

- Whisker shape:
  - Straight, kinked or hooked
  - Some consist of two connected rods often separated at the top
  - A spiral shape found
- The length of thin filaments varied
  - Short - 10 to 20 μm
  - Long - up to 140 μm
- The typical thickness
  - About 1.5 to 2.0 μm
- It appeared that thin whiskers often grew from hillocks
- Thicker rods usually had a striated surface which was not obviously visible on thin whiskers

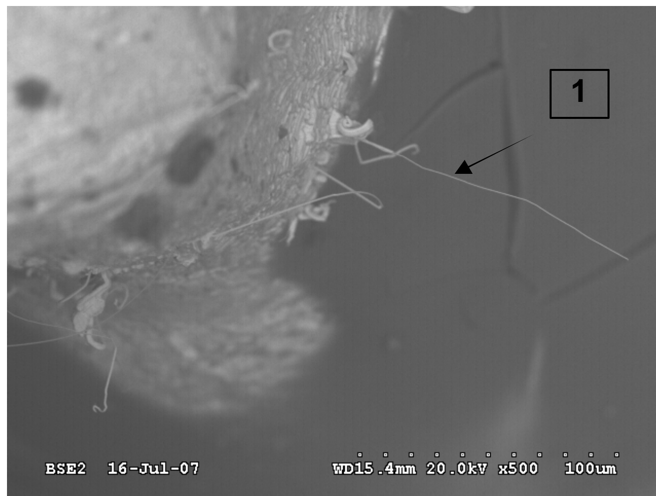
Visual and SEM Inspection of Solder Joints before Cross-Section (con.)



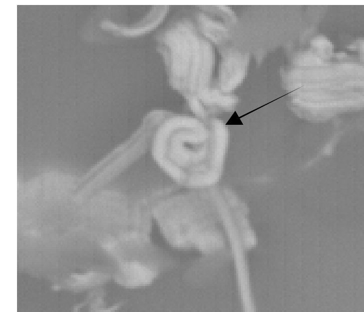
SEM, 1,200X



SEM, 1,800X



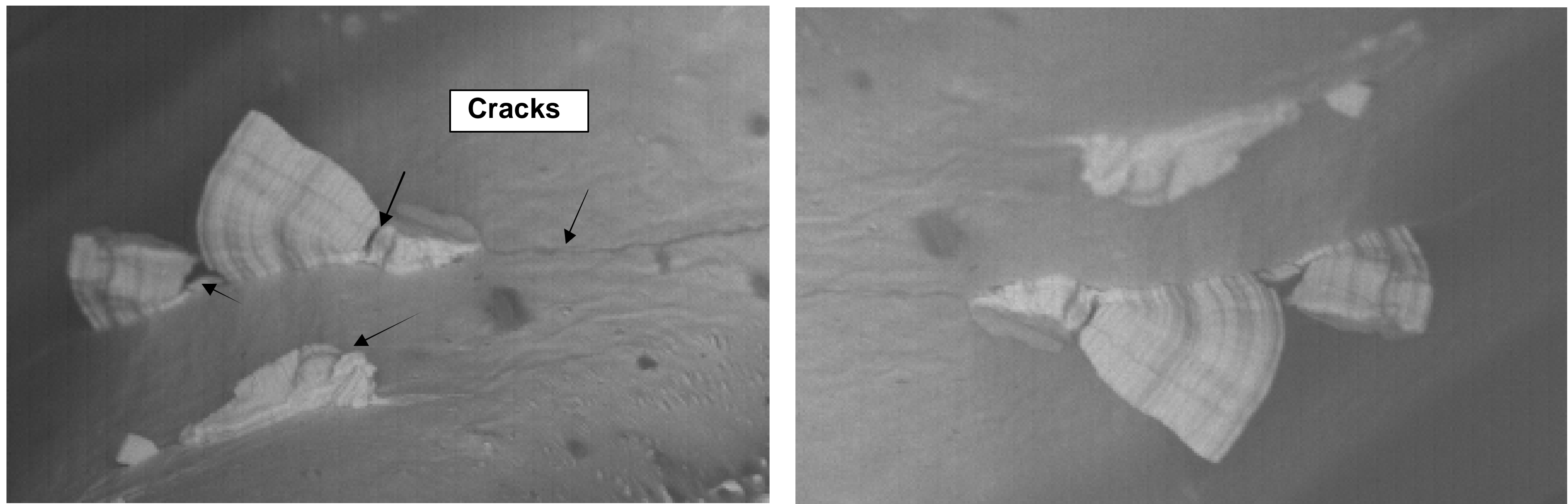
SEM, 500X



SEM, 700X

Visual and SEM Inspection of Solder Joints before Cross-Section (con.)

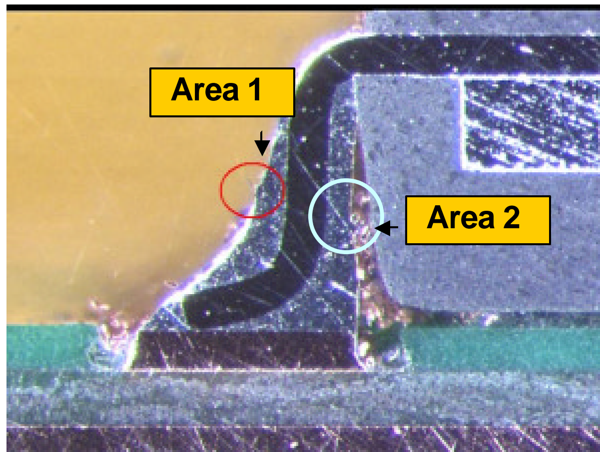
- Protrusions looking like thin shells
- Grow from a crack in the surface layer that may be an oxide or crystallized flux film
- Clearly visible striations in two directions
  - The stripes parallel to the edges of the shells
- Cracks in protrusions following the vertical striations



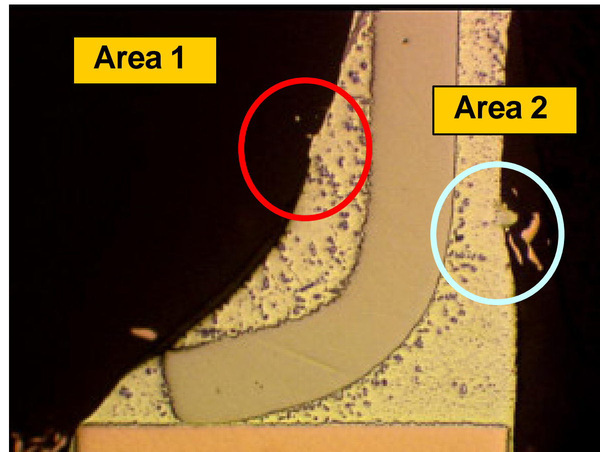
SEM, 450X

Cross-section Analyses of Solder Joints

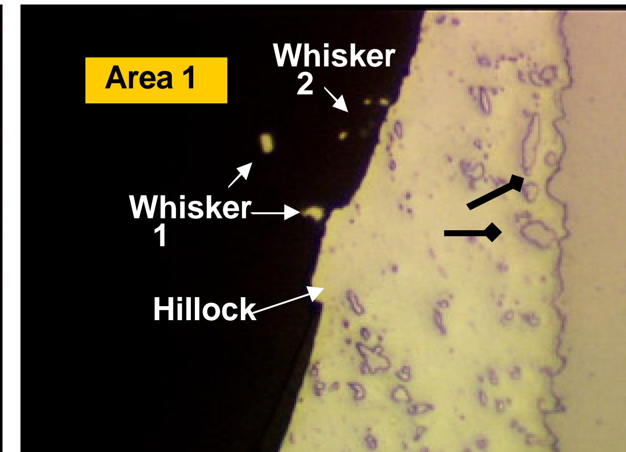
- Cross-section of selected locations with whiskers following by progressive polishing
  - Longitudinally and perpendicular to the leads
- The locations from which whiskers or hillocks started growing were targeted
  - In each polishing step, a layer 1 to 2 μm was removed
- Whiskers and hillocks were found at both toe and heel sides of the cross-sectioned lead



30X

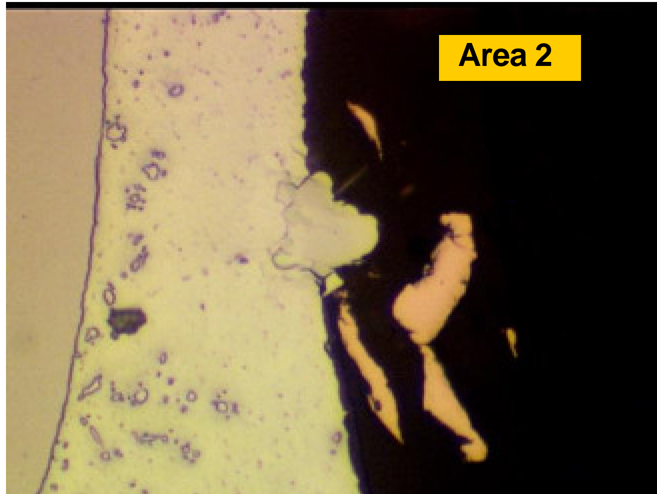


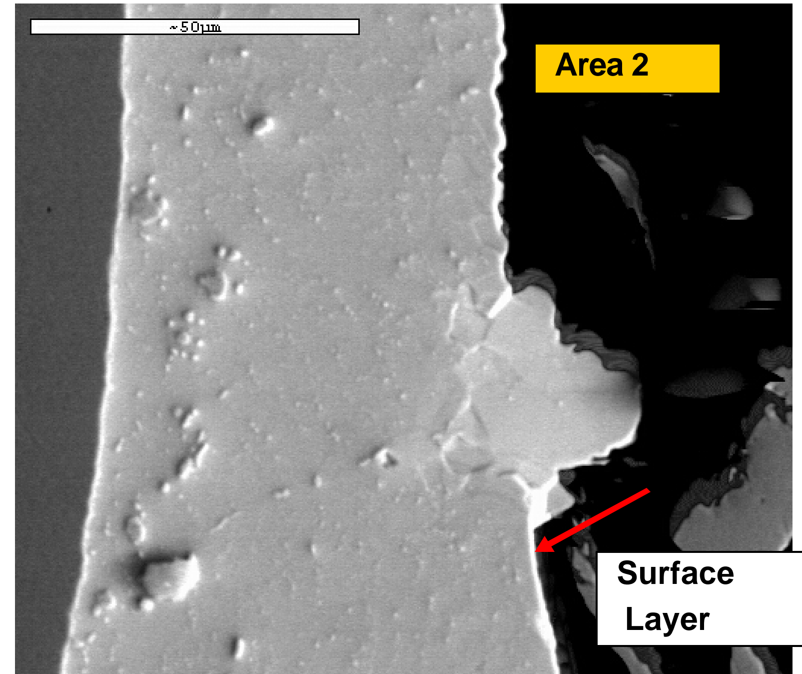
100X



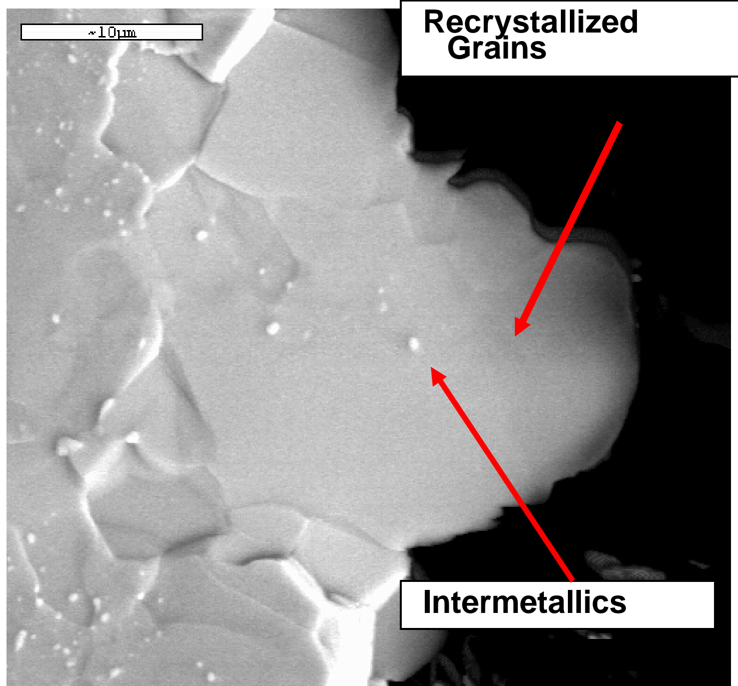
400X

Hillock Microstructure

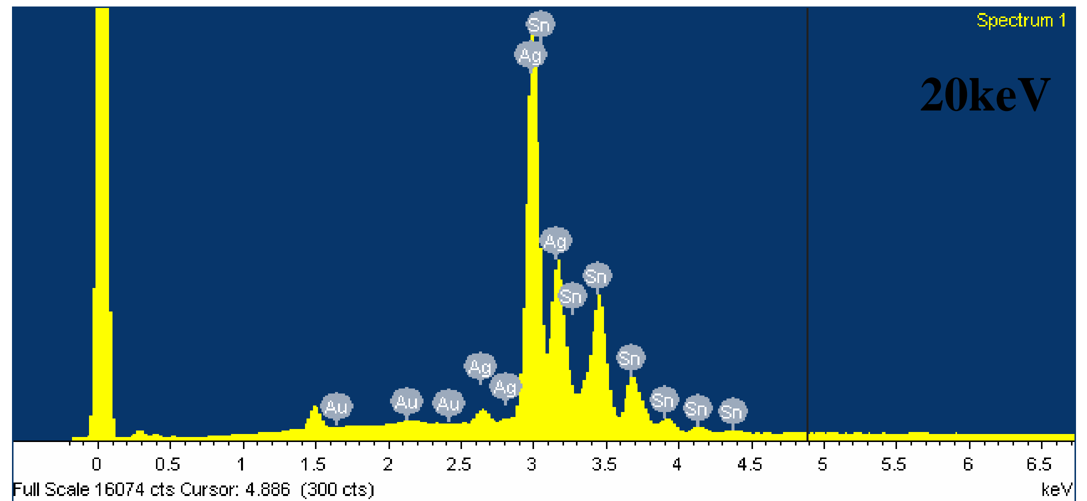




SEM, 1,000X



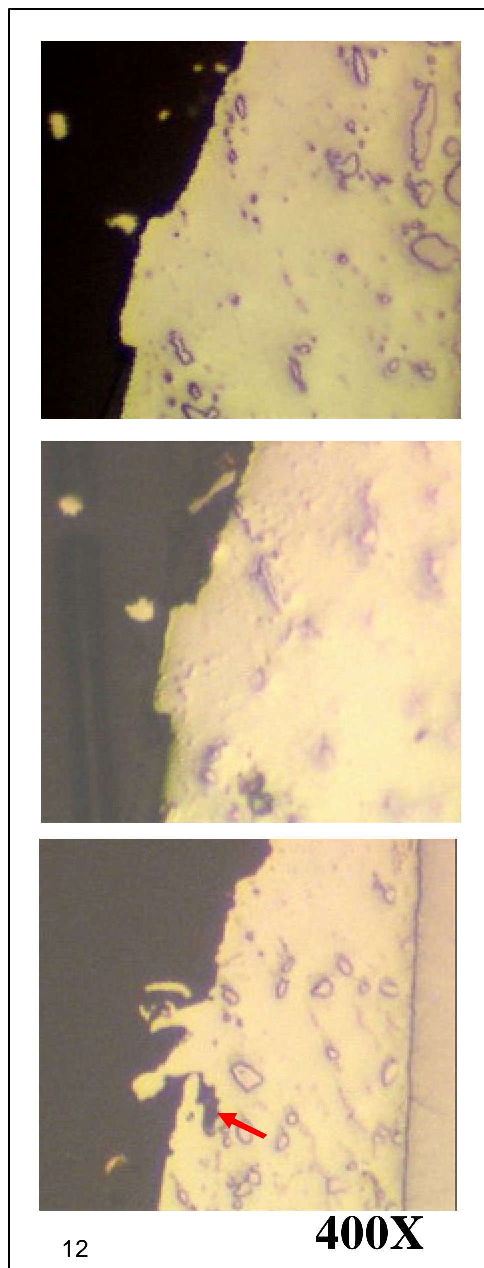
SEM, 3,000X



Hillock Microstructure (cont.)

- Different from the bulk solder microstructure
- 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
- The intermetallic particles are distributed non-uniformly and located only in the centre of the hillock
- The intermetallic particles contain either Ag or Cu in addition to Sn
- 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

Hillock Shape Evaluation and Connection with Whiskers



400X

Lead 1

Whisker

Hillock

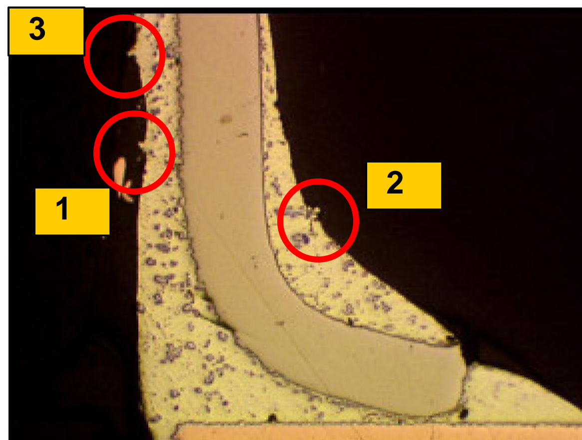
Whisker

Hillock

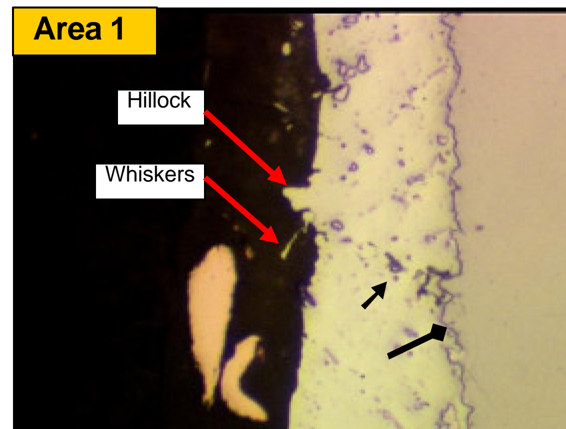
SEM, 450X

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

- Co-existence of voids with hillocks and whiskers
  - The corrosion channels are traceable to large outgassing voids
  - The voids are often related to the rough interface
- Corrosion channels near the rod whiskers or hillocks
  - 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



100X

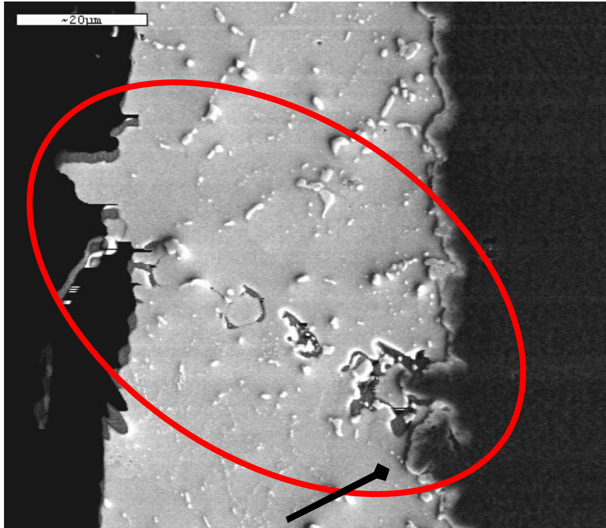


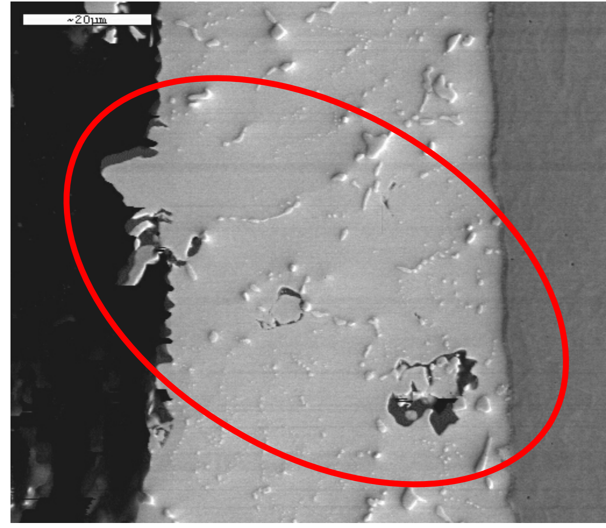
400X

400X

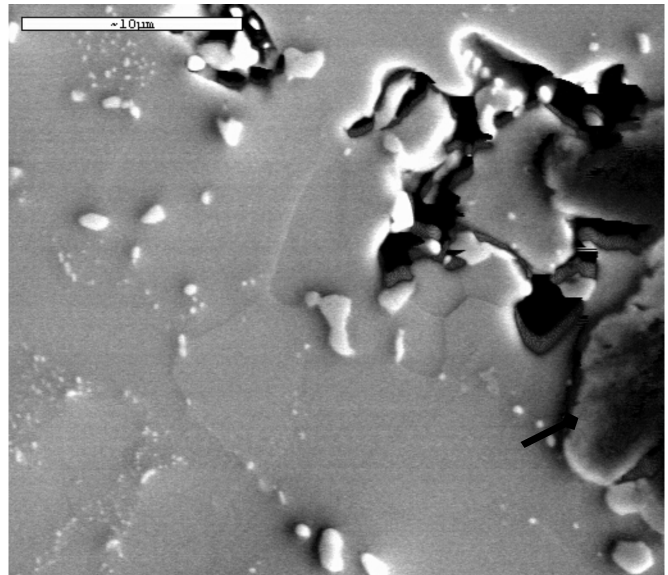
Inter-granular Corrosion and Lead/Solder Interface Roughness in Connection with Whisker and Hillock Growth (cont.)

Area 1



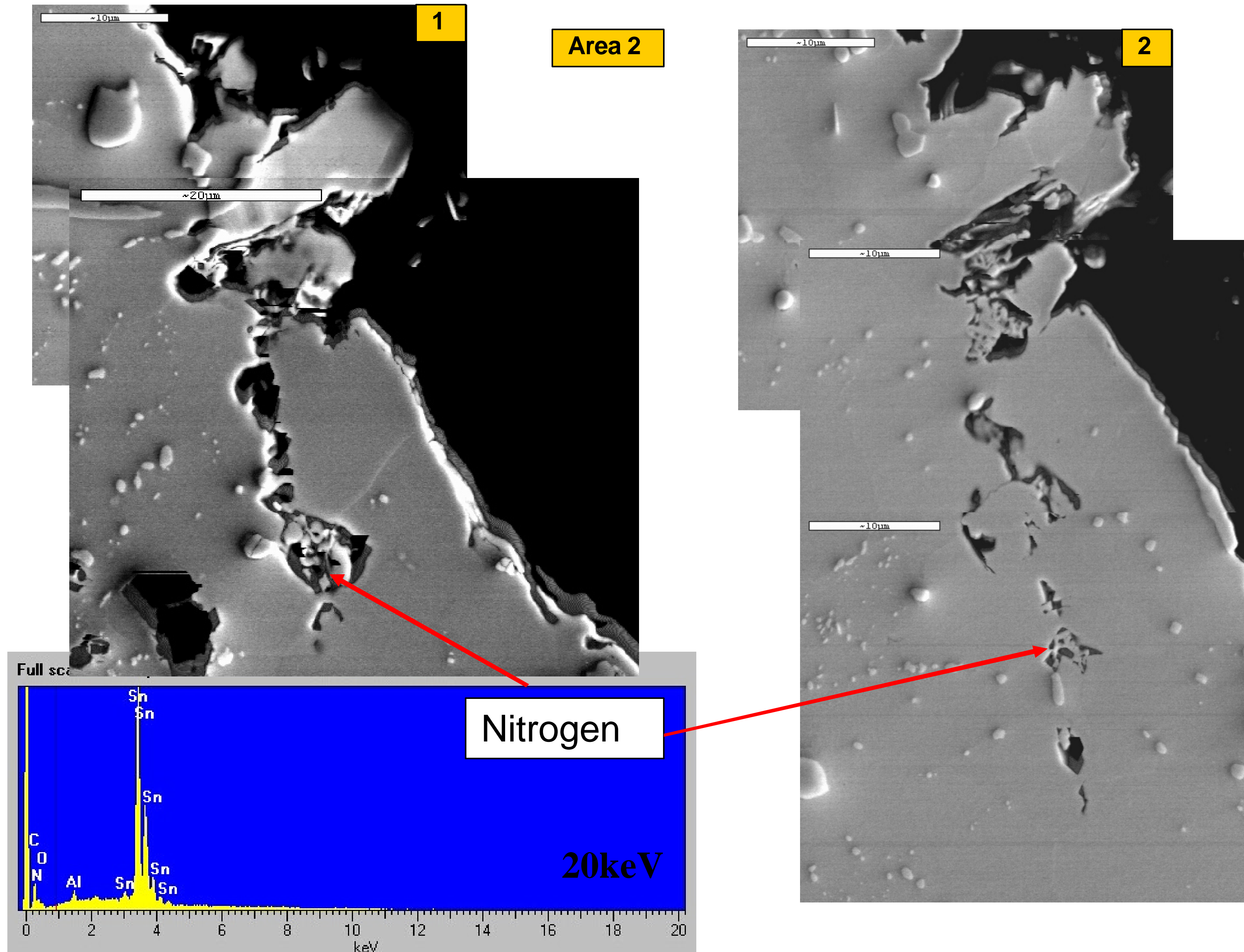


SEM, 1,300X

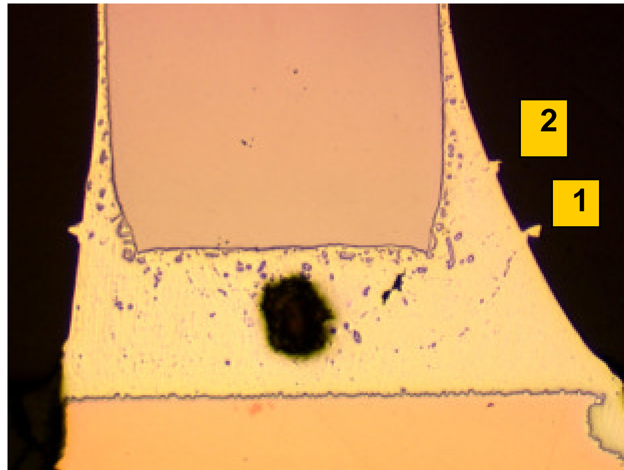


SEM, 4,000X

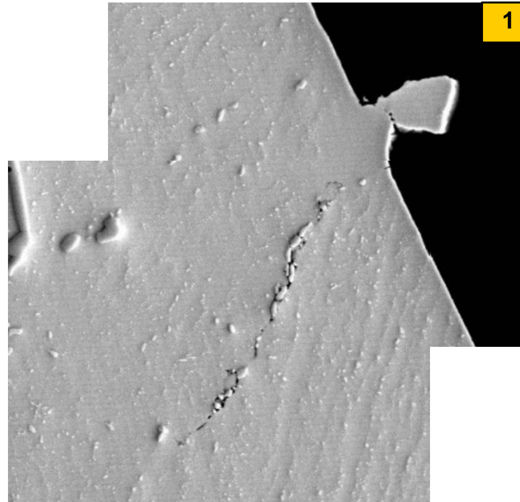
Inter-granular Corrosion and Lead/Solder Interface Roughness in Connection with Whisker and Hillock Growth (cont.)



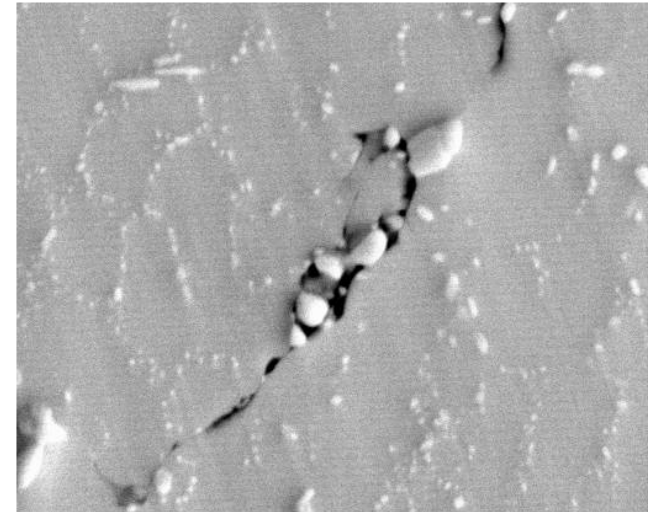
Inter-granular Corrosion and Lead/Solder Interface Roughness in Connection with Whisker and Hillock Growth (cont)



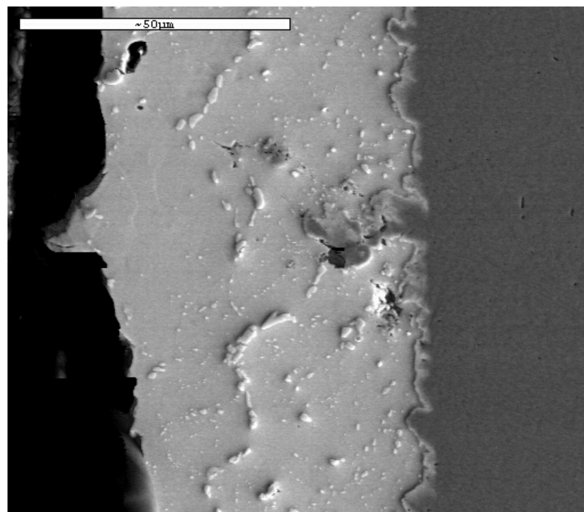
200X



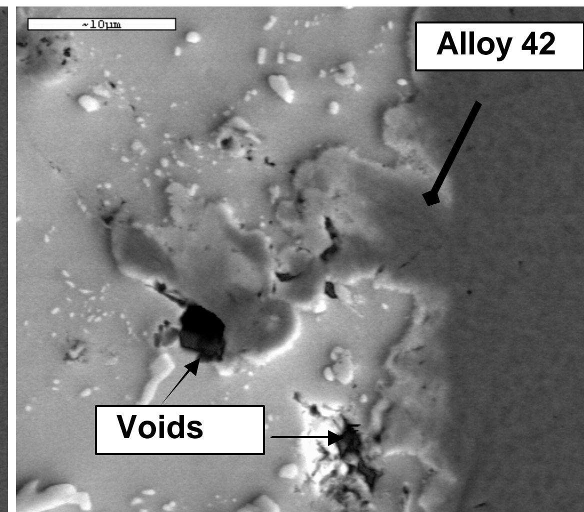
SEM, 1,800X



SEM, 6,000X



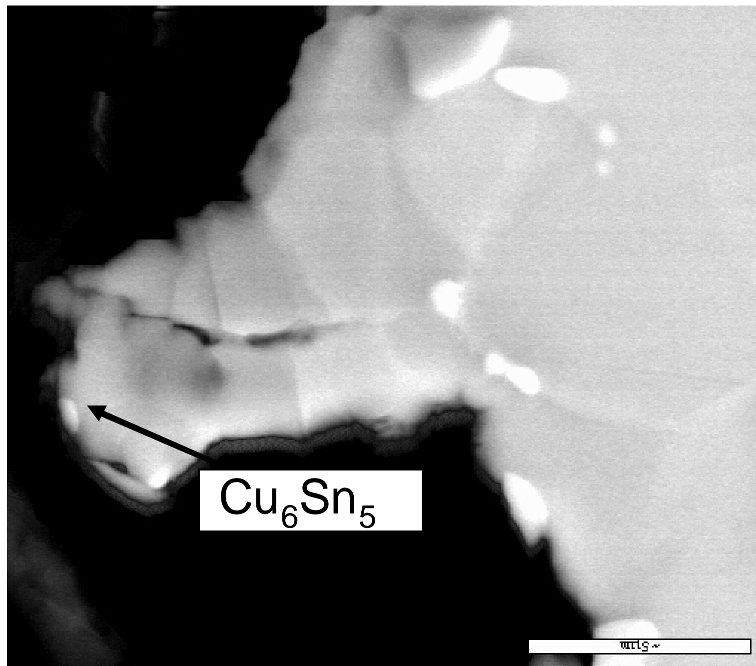
SEM, 450X

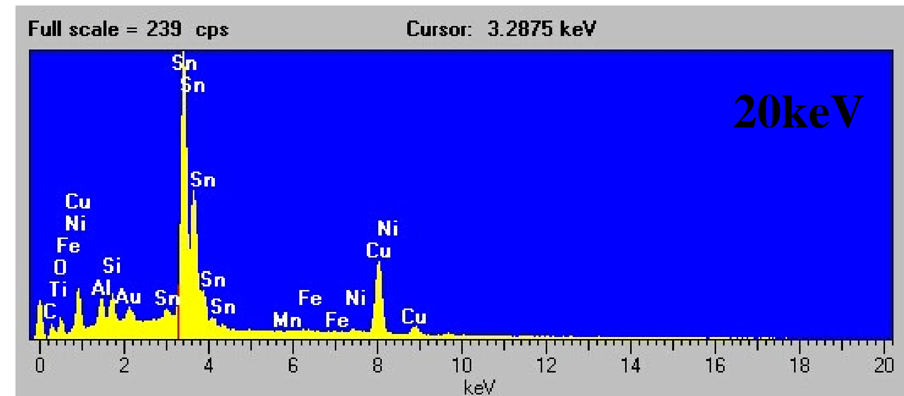


SEM, 3,000X

Details on Protrusions with Irregular Shape, Striations, and Cracks

- The rod whiskers have features similar to the hillocks
- Grow from recrystallized solder
  - Depleted of Ag and Cu and
  - Containing much less intermetallic particles than the bulk solder
- Have recrystallized pure Sn structure
- May contain Cu_6Sn_5 and/or Ag_3Sn particles



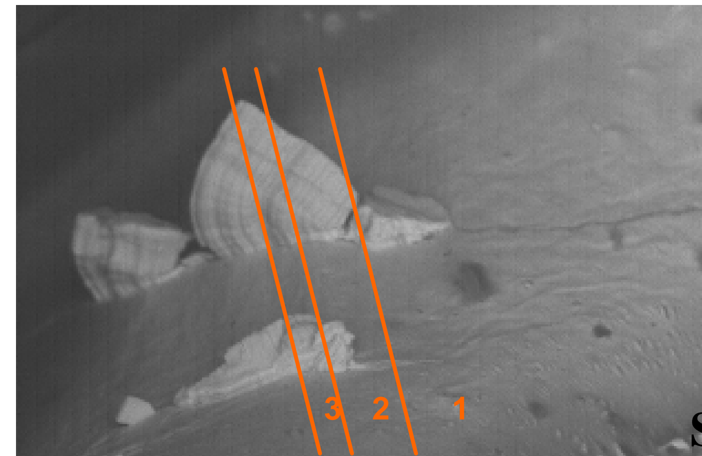


SEM, 7,000X

Details on Protrusions with Irregular Shape, Striations, and Cracks (cont.)

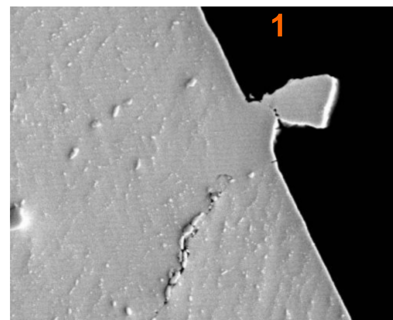
- The shell-like protrusions have a similar microstructure to the hillocks
  - Sn matrix with very few Cu_6Sn_5 and/or Ag_3Sn particles
- The two-dimensional striations are evident as
  - A surface roughness at the edges of the protrusion and
  - Stripes in the parallel direction
  - Black lines or wrinkles
- The cracks look like a separation between the grains

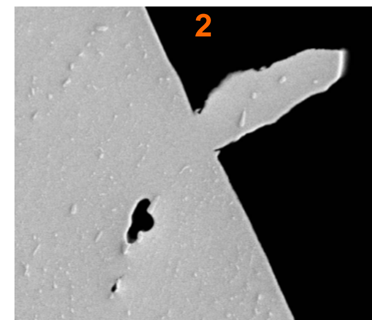
SEM, 180X

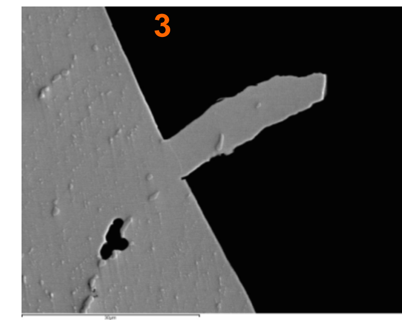


SEM, 450X

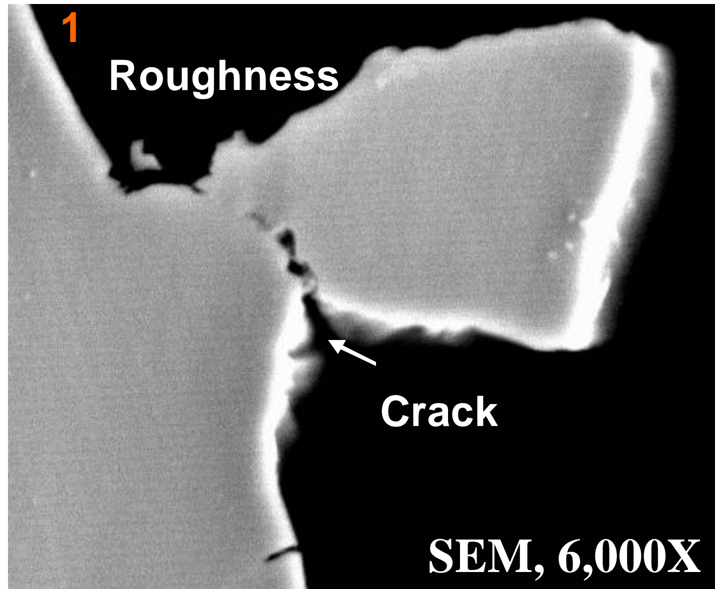
SEM, 1,800X

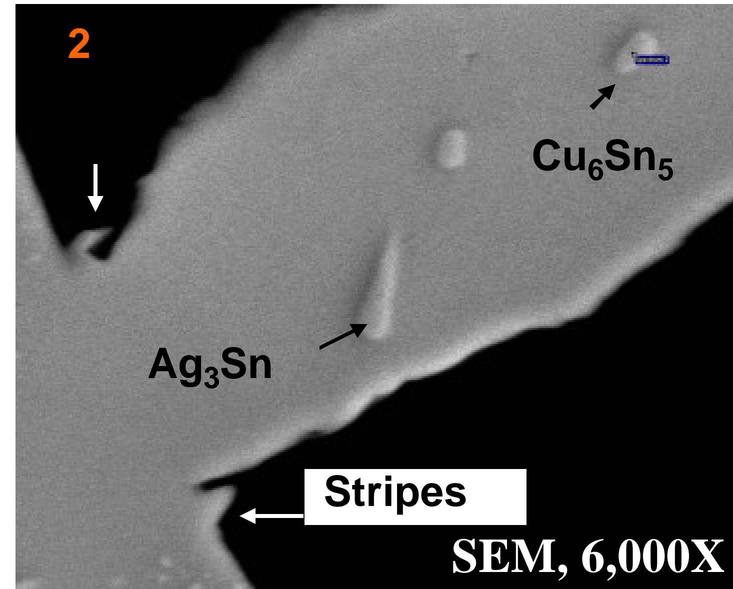


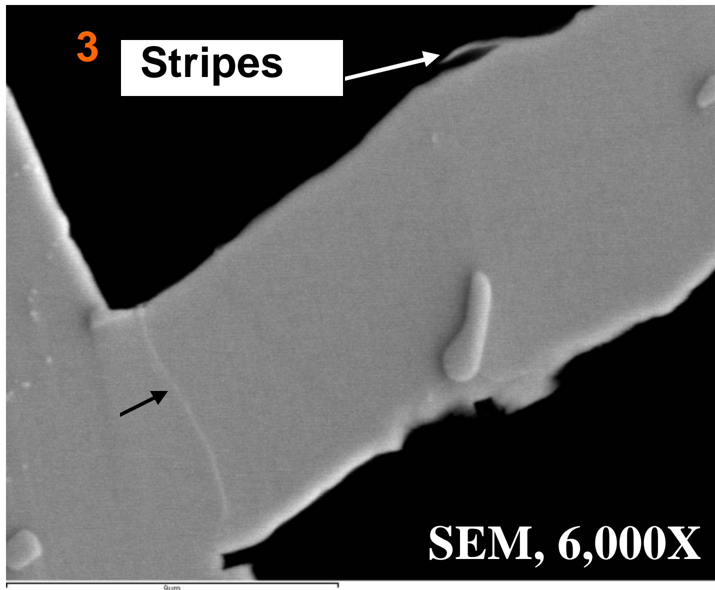


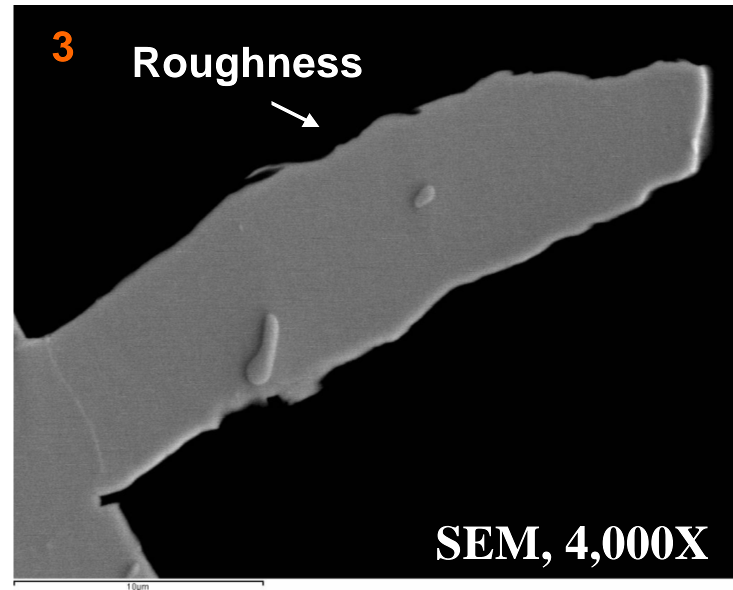


Details on Protrusions with Irregular Shape, Striations, and Cracks (cont)



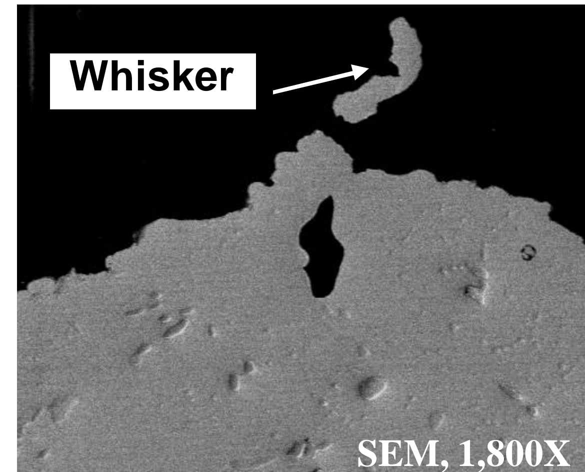


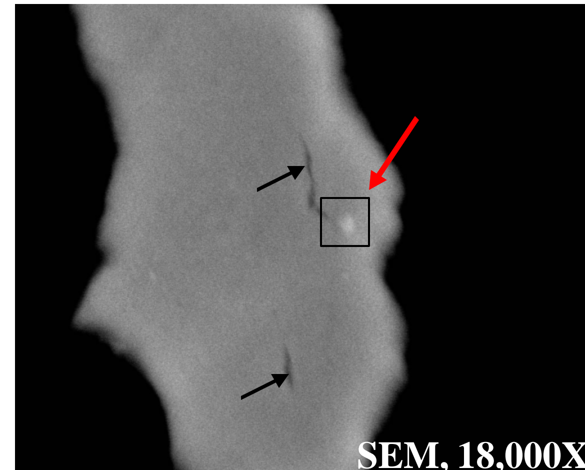


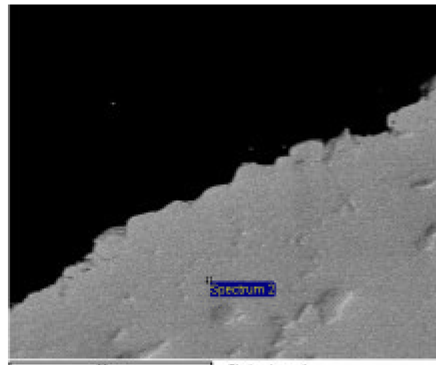


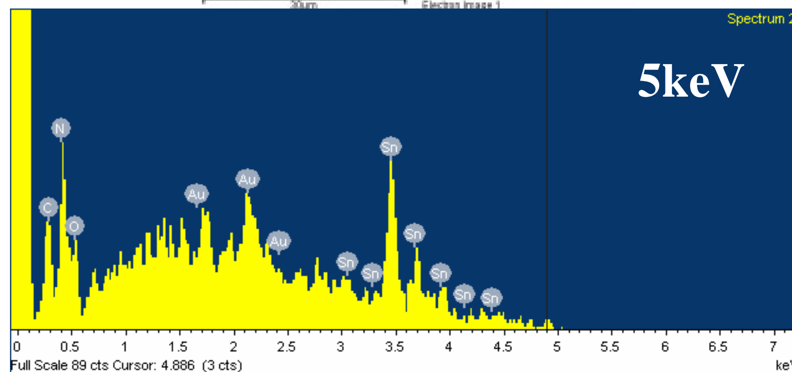
Nitrogen in Solder

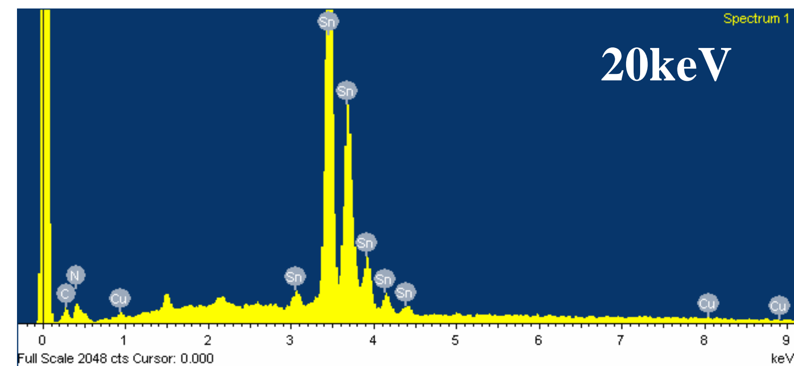
- N is present in
  - Corroded interdendritic spaces and
  - In the Sn matrix as well
    - Bulk solder and
    - Hillocks and whiskers
- The N peak is more pronounced using lower voltage, but still detectable under 20 keV











Virgin Components, Ion Chromatography

- Virgin devices with the Alloy 42 lead-frame material
  - Created whiskers - "bad"
  - Did not grow whiskers - "good"
- Bad – are more contaminated than their counterparts – Good
  - Chloride - 5X; Fluoride - 3X; Sodium - 3x; Calcium - 2x; Potassium - ~ 2x
  - No significant difference in nitrate and ammonium

Anion Concentration, µg/in2

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**

The total level of anions and cations:

Bad - 25.4 µg/in2
above acceptable levels

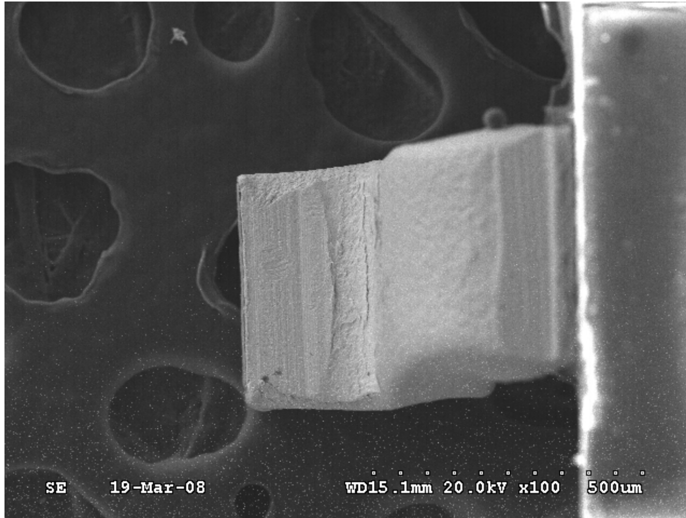
Good - 11.2 µg/in2
close to accepted limit

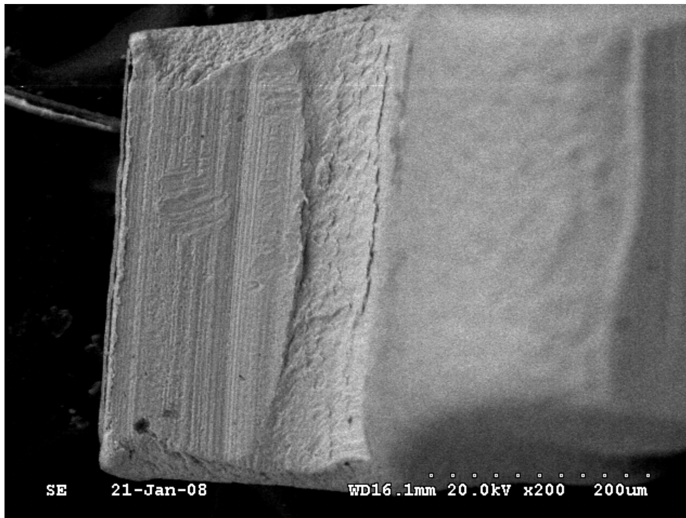
Cation Concentration, µg/in2

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**

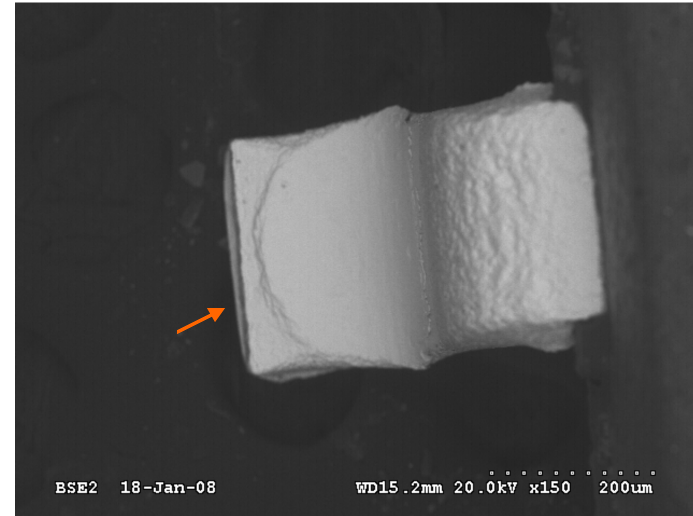
Virgin Components, Plating Quality

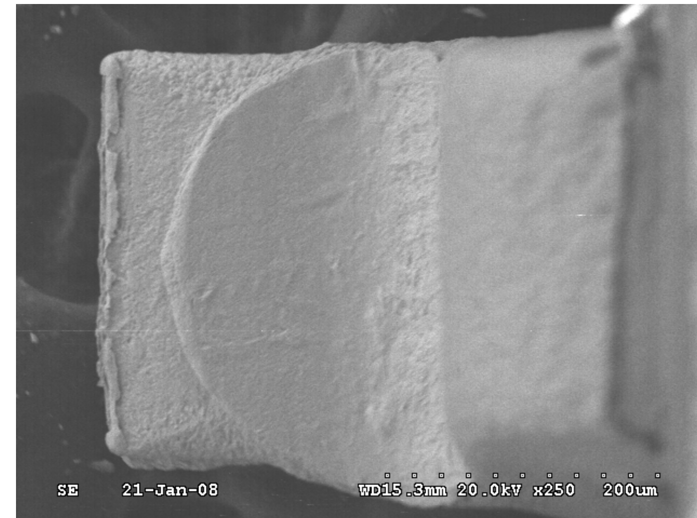
- Difference in plating shape: Bad components have a double layer structure





Good

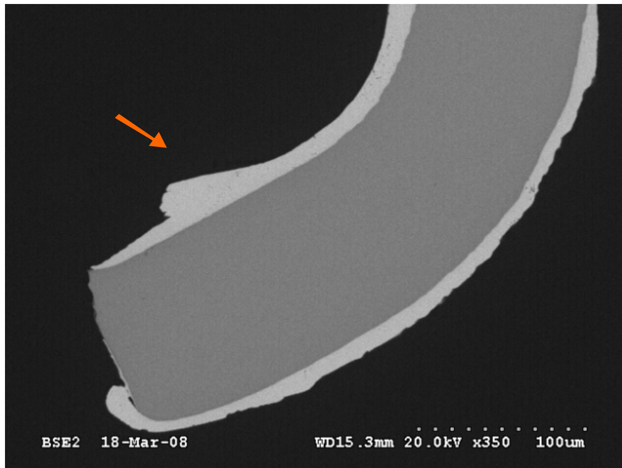


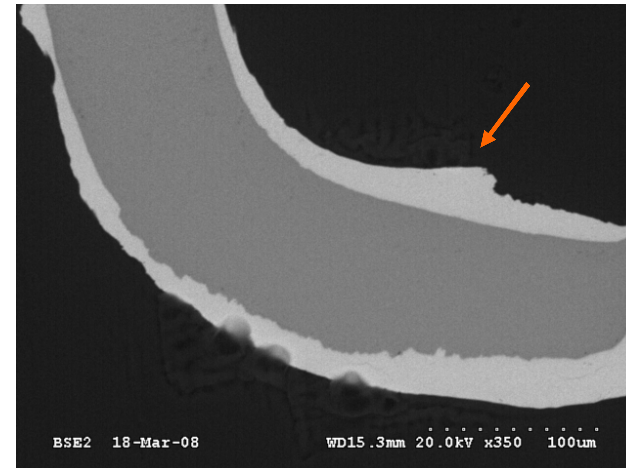


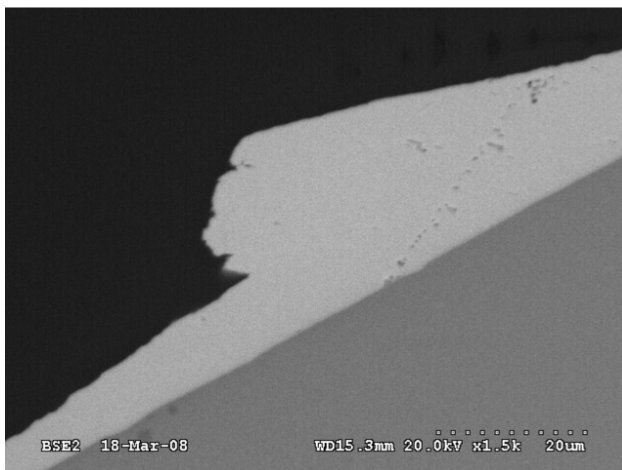
Bad

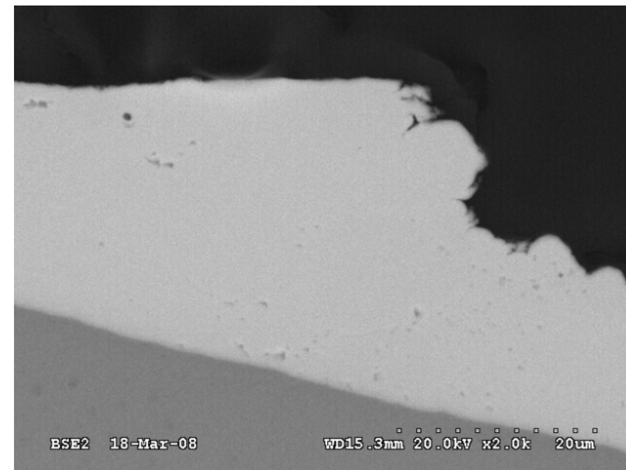
Virgin Components, Plating Quality (cont.)

- Cross-sectioning confirmed the non-uniform thickness of the leads in Bad devices
- The thickness of the Sn layer varied from lead to lead
  - Average - 15µm to 24µm



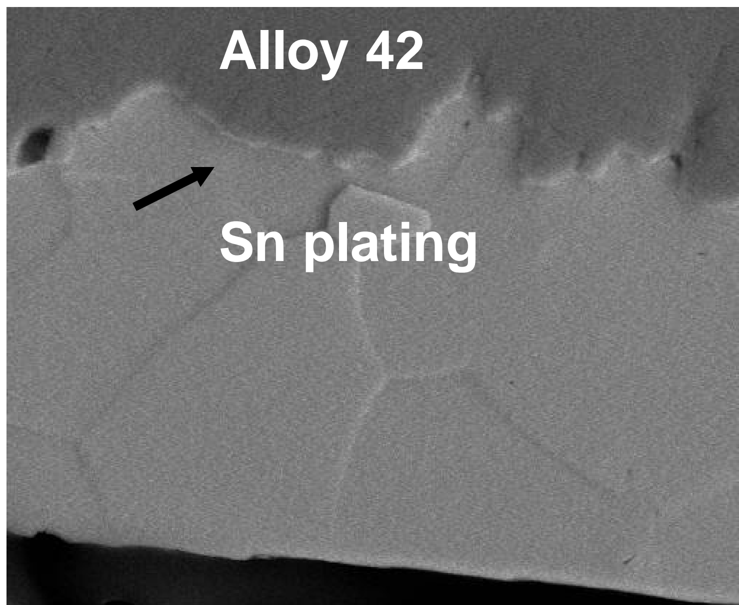


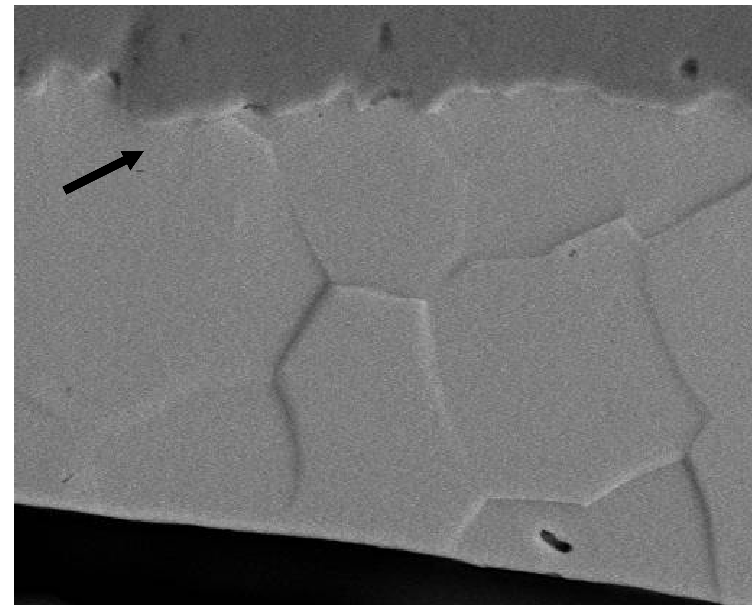




Virgin Components, Plating Quality (cont.)

- The interface between the leads made of Alloy 42 and the bulk solder is rough
- Such an interfacial roughness is not normally seen
- May be a characteristic of a surface preparation before Sn plating

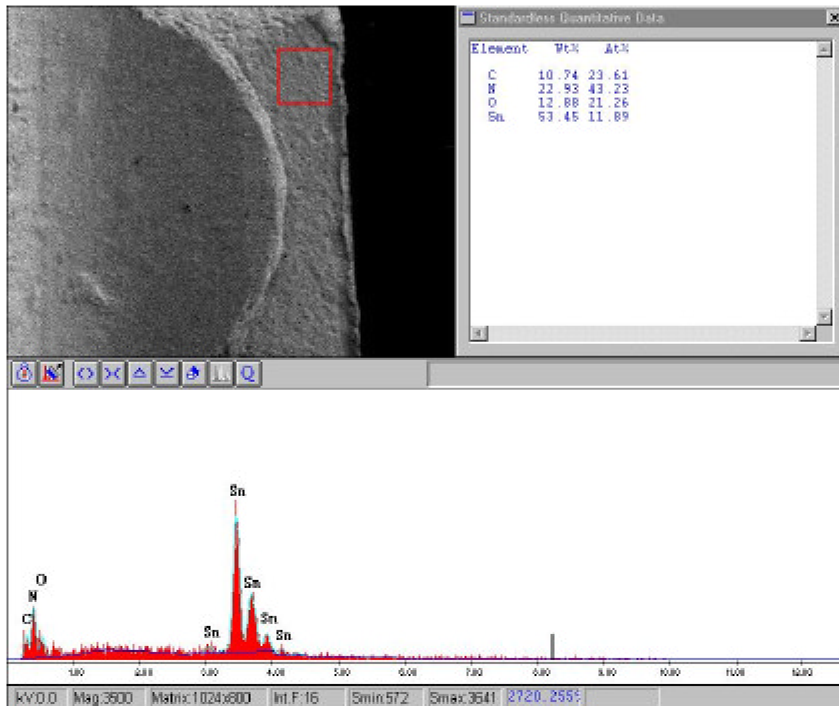




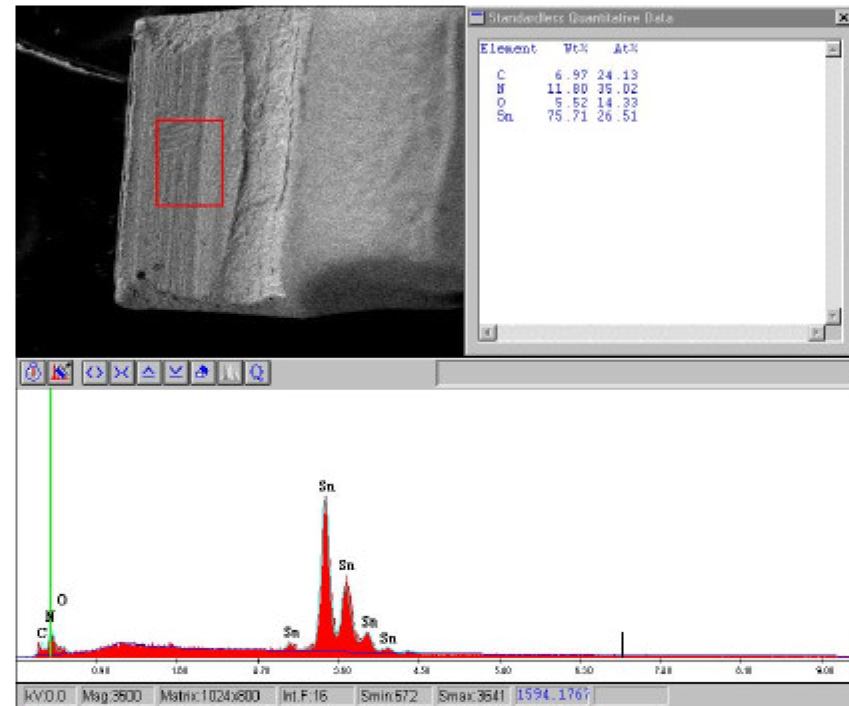
SEM, 6,000X

Virgin Components, Composition

- Any area of the leads covered with electrolytic Sn contains N
- The lowest concentration - 32 At % (10.3 Wt. %)
- The highest content - 43 At % (22.9 Wt. %)
- The component bodies do not contain N



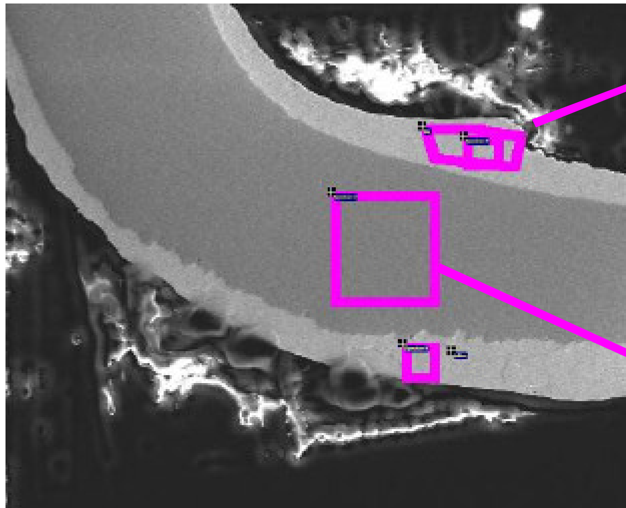
Bad

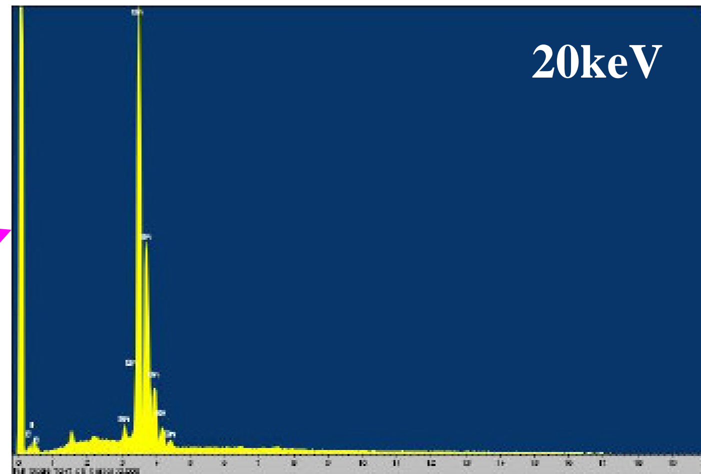


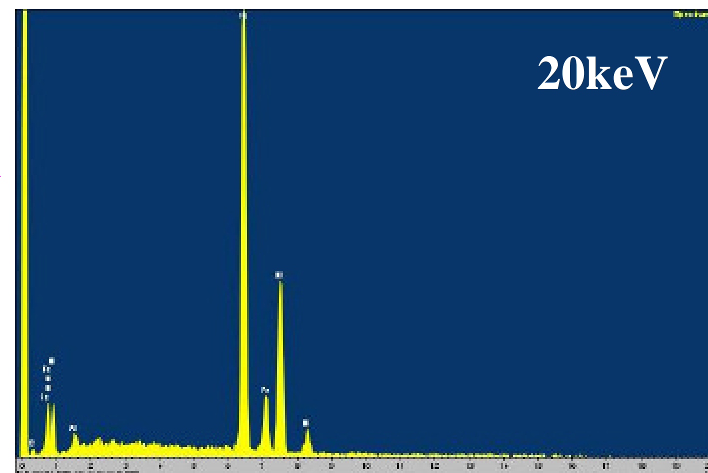
Good

Virgin Components, Composition (cont.)

- In cross-sections of the virgin components,
  - N was found in the Sn plating
  - No N in the Alloy 42 lead-frame
- The thicker the Sn layer, the more nitrogen the solder inherits due to the higher gross amount present







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.

Conclusions (cont.)

- 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.

Conclusions (cont.)

- 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.

Acknowledgements

The authors thank the following individuals:

Pooneh Vaziri and Prakash Kapadia for ion chromatography analysis and

Thilo Sack for the manuscript review and technical discussions.

Thank you

Celestica™

Solid partners. Flexible solutions.