The Effects of Tin Whisker Testing on Solder Connections

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Abstract:
The RoHS legislation in Europe has far reaching consequences, which necessitates a change in lead coating on component leads. Although some suppliers are using a tin finish, there is a tendency for pure tin plating to form whiskers over time which can cause failure of the circuit. To prevent the formation of whiskers different companies have designed different plating schemes and used different materials. Industry has yet to standardize on a lead finish to replace the Sn:Pb solder used in the past.

This paper examines several different lead materials before and after exposure to tin whisker promoting environments to determine the effects of those environments on the soldered connection. In addition to promoting the growth of tin whiskers, these stressful environments also age the solder connections. Based on components used in the telecom industry, solder connections are examined for the presence of tin whiskers, grain structure, intermetallic formation and cracking after being temperature cycled (-40°C to 85°C) and soaked at 50°C and 85% RH.

Introduction:
Tin (Sn) whiskers have been known to cause electrical problems since the 1940s. Satellites have been lost due to tin whisker formation[1,2]. Whiskers have forced the recall of pacemakers[3]. During the 1990s pure Sn coatings were banned from most space, military and high reliability equipment.

Manufacturers found that adding as little as 5% Pb to the Sn would suppress most whisker formation. Lead (Pb) and Sn have been used together for years to create mechanical and electrical connections in electronic equipment. Equipment has been protected from whiskering as well as electrically connected by the application of Pb along with the Sn.

Recently, some US states, Europe, Taiwan, Korea and China have mandated the removal of Pb from electrical equipment. The best known of these is the European Restriction of certain Hazardous Substances (RoHS)[4]. This removal of Pb from component termination coatings and solders is once again raising the specter of whiskers.

Various lead coatings have been supported by a number of manufacturers. Several manufacturers are using matte tin coatings and are post processing the plated components to form a uniform copper – tin intermetallic layer to prevent stress buildup in the coating[5]. Others are using an under-layer barrier layer of nickel (Ni) to reduce the diffusion of copper (Cu) into the Sn plating. Sn with small amounts of other metals such as copper (99.3Sn:0.7Cu) or a silver and copper (95.5Sn:4.0Ag:0.5Cu) plating are also being used[6]. And at least one supplier has moved away from Sn entirely and is using a nickel-palladium-gold or a nickel-palladium coat[7]. All manufacturers state that their coatings are whisker free coatings; i.e. they will not produce whiskers.

Pb-free solders have been in use in consumer electronics for several years. However, the life expectancy of consumer electronic products today is only one to two years. Advances in software and hardware make many consumer products sold today obsolete within a year. This planned obsolescence does not extrapolate well in the area of telecommunications where the life expectance is still greater than 10 years. The telecommunication's customers do not want to change out an entire system costing hundreds of thousands of dollars every two or three years. They may add some hardware to their system and change software to give the system added capabilities.

So many parts of the system will remain in operation for over ten years. This difference in life expectancy has to be taken into effect when considering a changeover to a Pb-free solder. The reliability of Pb-free solders has yet to be fully established for these long term investments.

Methodology:

During the introduction of RoHS compliant products into the marketplace, life acceleration tests were performed to determine differences in reliability between the Sn:Pb solder and the SAC solder. Extrapolations of lifetimes from accelerated conditions to use conditions could not be done directly because the activation energies for many reactions of SAC solders are not known. To compensate for this lack of data products with standard products manufactured with Sn:Pb solder were run side by side with SAC products. SAC305 (96.5Sn: 3.0Ag: 0.5Cu) was used in manufacturing the RoHS compliant products.

We used temperature cycling between -40°C and 85°C with a 15 minute soak at each extreme and a ramp rate as fast as our chamber would go to perform thermal cycling. The cycle rate was about 1.25 cycles per hour or 30 cycles per day. We cycled the products for 300 cycles.

The static environment was a thermal and humidity soak of 50°C and 85% RH. It has been suggested that a second copper intermetallic (Cu_3Sn) begins to form at temperatures greater than 60°C[8]. This second intermetallic forms a more uniform layer at the copper-solder interface and prevents further copper diffusion of copper into the tin. We did not want this to occur during the experiment and prevent whisker formation.

Results:

We can report only on three types of lead materials coating combinations. These are a bare copper leadframe dipped into molten tin, a nickel-iron leadframe plated with tin, and a copper leadframe plated with nickel and then tin. We also examined the endcaps of ceramic MLC capacitors use tin plating over nickel over silver. There was no palladium used in the lead coatings of any component utilized in the products we tested.

Products that had not been environmentally stressed were examined and compared to the stressed products. Several things were noted. The Cu_6Sn_5 intermetallic was present as small precipitates, not in large crystalline structures. The Cu_6Sn_5 intermetallic at the Cu-Sn interface was not as thick as that seen in the stressed samples. There were larger distances between hillocks that would allow copper diffusion. No differences were noted with respect to the nickel intermetallic layer.

There were no distinct morphological differences between the samples that had been temperature cycled and those which were held at a static temperature.

Morphology of Cu_6Sn_5:

During the reflow process Cu_6Sn_5 intermetallics are formed at copper – tin interfaces as well as with the copper incorporated within the solder. Initially the Cu within the solder forms small clusters of intermetallic within the solder matrix. These clusters may appear as strings of precipitates within the solder matrix. Figure 1 shows these precipitates within the solder matrix. The initial amount of Cu_6Sn_5 intermetallic in the solder exceeds the limited amount of copper in the SAC solder. Most of the copper comes from the copper pad or lead. Initially the Cu_6Sn_5 intermetallic was between 2 microns and 3 microns thick.

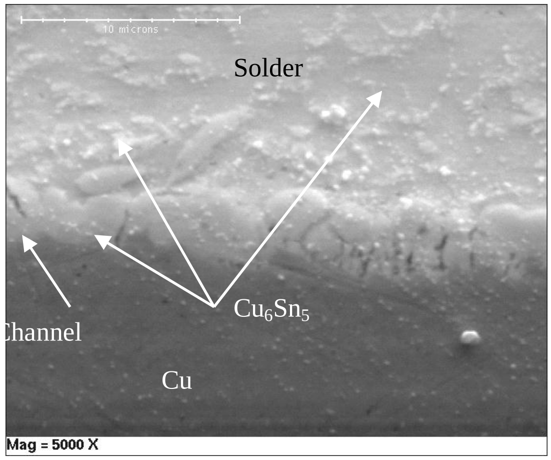

Figure 1 - After reflow. Note the amount of Cu_6Sn_5material within the solder matrix.

The Cu_6Sn_5 material does not form uniformly at the interface, but forms in scallops or hillocks along grain boundaries[9]. Long hexagonal crystals can form at the tops of these hillocks and break free becoming mixed with the molten solder. Figure 2 shows several hexagonal crystals of Cu_6Sn_5 within the solder matrix that is no longer connected to the hillock formation at the bottom of the image. There are often channels between the hillocks that allow the diffusion of additional Cu into the Sn matrix.

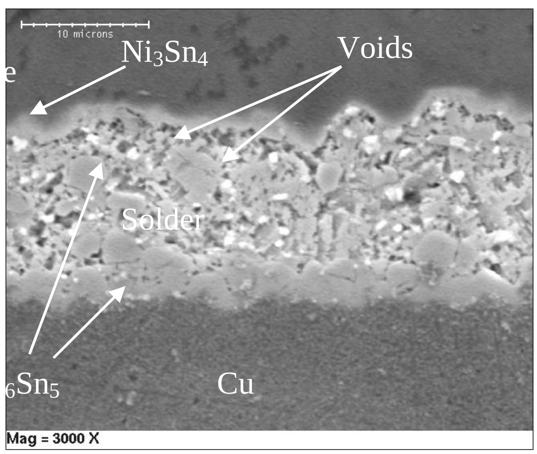

Figure 2 - Ni_3Sn_4 is thinner than Cu_6Sn_5. It does not have as many paths for metal to migrate into the solder. Sn has left voids at the Ni_3Sn_4 interface as the tin moved into the NiFe lead.

At room temperatures and above, Cu_6Sn_5 intermetallic continues to slowly form within the bulk solder and at the copper-tin interface. This formation is limited by the amount of copper available in the solder matrix. The intermetallic grows as a long hexagonal crystal. Cu_6Sn_5 intermetallics were found in hexagonal crystal forms throughout the solder matrix. See Figures 2 and 3.

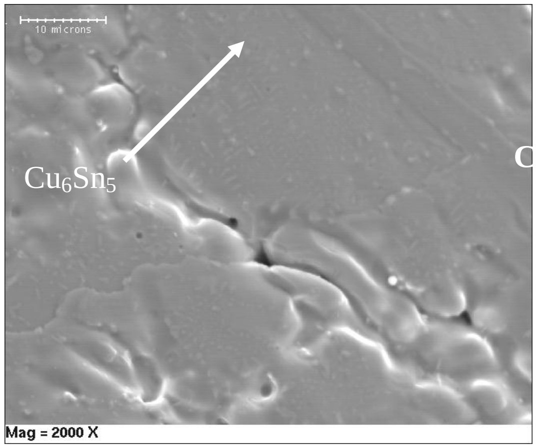

Figure 3 - A long Cu_6Sn_5 crystal embedded on the surface of the SAC solder is seen in this image.

Morphology of Ni_3Sn_4:

Figure 2 shows a nickel-iron lead soldered to a copper pad. The Ni_3Sn_4 intermetallic forms a dense barrier to further diffusion of the Sn into the nickel-iron. Figure 2 shows the voids in the solder at the nickel – tin interface as a result of the tin diffusion into the nickel-iron. It is possible that these voids will, in time, coalesce and form the basis of a solder failure. Similar voids were not seen on nickel plated copper.

Morphology of Ag_3Sn:

One Ag_3Sn crystal, longer than 40 microns, was found on the surface of the solder. No other large Ag_3Sn crystals were found on any sample. The remaining silver was spread throughout the solder in all samples. See Figures 4 and 5.

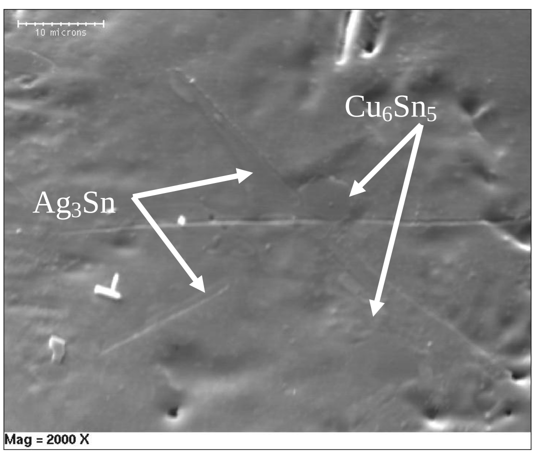

Figure 4 - Surface of solder after 300 hours of Heat and humidity. Both Silver –tin and copper – tin intermetallics are seen in this image.

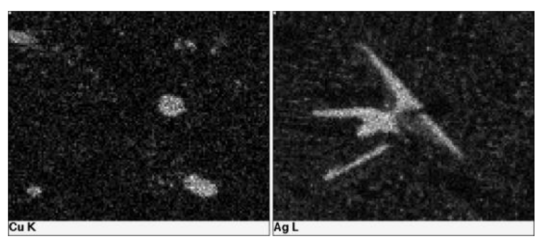

Figure 5 - Elemental maps for Figure 3. Copper is on the left, silver is on the right.

Watch out!

The space program was never able to totally eliminate pure tin coatings even though they clearly stated that pure tin was not acceptable. Despite all of the controls put in place to prevent mistakes and mixing of Pb-bearing and Pb-free components, some Pb-bearing components may at some time be used. Mistakes will happen.

Figure 6 shows one of these mistakes detected during our experimentation. One component with Sn:Pb solder coated leads slipped past all of the checks and Pb got into the product. The Pb will mix throughout the molten SAC solder during reflow and not be contained at the lead.

Some manufacturers dip the external portions of the leads after encapsulation into molten tin. This is performed to make a stress-free coating. However, places can be missed, and a dipped component may not have even coverage. Figure 7 shows a cross section of a tin dipped lead with areas of very thin coatings. Figure 8 shows some $CuSO_4$ "flowers" that were found during inspection due to some exposed copper from a lead and some sulfur in the water used to provide humidity in the chamber.

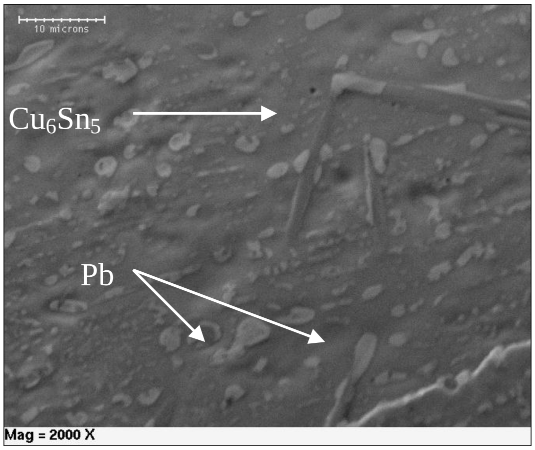

Figure 6 - Far end of the foot of the solder connection. Note the Pb mixed with the SAC solder. The Pb came from the lead coating.

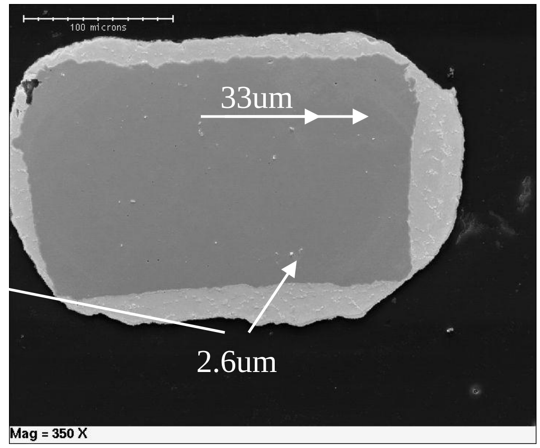

Figure 7 - Note the large differences in coating thickness. This is a dipped component, with Sn covering a NiFe lead. This could lead to corrosion of the NiFe and whisker growth where the Sn is thin.

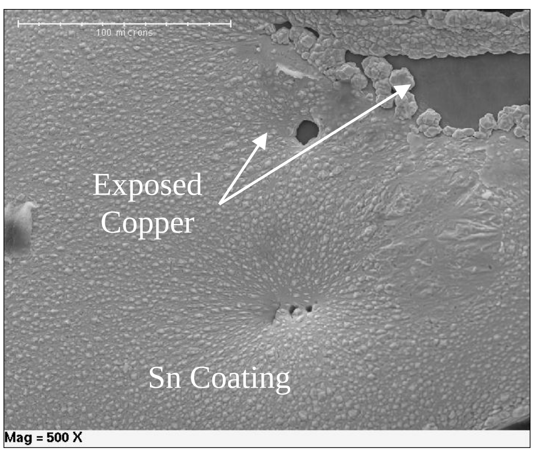

Figure 8 - Exposed copper after Tin dipping

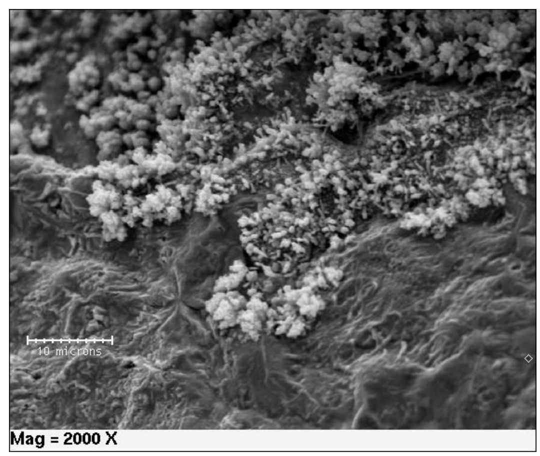

Figure 9 - CuSO4 "flowers" on exposed Cu lead after heat and humidity. Note the spread of the flowers onto the Sn.

Life Expectancy:
We used temperature cycling, and static heat and humidity based on a number of papers suggesting that the heat and humidity will induce tin whiskers to grow faster on copper lead frames due to copper diffusion and conversion to Cu_6Sn_5.[10] Temperature cycling is known to accelerate the formation of whiskers on nickel-ferrous alloys which are used in electronic components. The test conditions were modified to work with the available equipment and time constraints.

All products passed functional testing after being subjected to the stress conditions. The Sn:Pb "control" group included with each SAC "test" group showed that we were not stressing the products too harshly. Based on this data, the products using SAC solder did not show any differences in life expectancy than the Sn:Pb products.

Conclusions:
All units passed functional testing after being stressed. The stress criteria did not damage the products. In future experiments the values may be increased to determine the damage point and more quantitative data can be determined.

Examination of the components by optical microscopy and using a scanning electron microscope did not find any occurrences of tin whiskering on the leads or the solder. There are several things that might have contributed to this. We were not able to temperature cycle the products as fast as required. The temperature we used for the temperature & humidity environment may need to be optimized. There may be a longer delay before whiskering occurs that we did not detect. Or, perhaps the methods used to coat the leads are sufficient to protect from whiskering for a reasonable time.

Several differences between the morphology of the copper intermetallics between the virgin samples and the environmentally stressed samples were noted. The stressed samples had much more copper incorporated as intermetallics within the solder matrix than the virgin samples did. Also the stressed samples had intermetallics clearly visible on the surface of the solder connections. No large intermetallic pieces were seen on the virgin samples on the surface of the solder, nor within the solder matrix. The change in the amount of copper incorporated within the tin matrix was more than we would have expected to occur at the temperatures the products were stressed. It remains to be seen if this is a true change or if the difference was due to a manufacturing change. The virgin samples were drawn from a different lot than the stressed samples. We do not assemble the products ourselves and have no control over the reflow conditions. So a longer time over liquidus or a higher peak temperature may have contributed to this condition in the experimental products.

The silver intermetallic did not form as fast as we anticipated and only one crystal was noted during this investigation. Additional research may show that the silver does not form crystals as fast as the copper does, so any silver intermetallics will remain small and widely dispersed within the solder matrix unless the solder has been stressed by excessive temperatures or time above liquidus.

Tin plated Alloy-42 (58Iron:42Nickel) forms a nickel – tin intermetallic layer at the interface with the solder. This layer is contiguous and does not present pathways for migration between the grains. Tin moves into the nickel iron leaving voids behind at the interface. The voids were not noted on the nickel plated copper lead. Additional investigation should be done to verify the possibility that nickel iron lead frames will cause voiding weakening the solder connection or not.

Mistakes will occur. We had a component containing Pb on its leads get into our test products. This problem will occur sporadically until the supply of components containing Pb is depleted. Plating an entire leadframe followed by a high temperature bake to relieve stresses within the tin may be a better method of covering the leads than tin dipping a finished product. The plating can be better controlled for thickness and coverage. Two tin dipped leads were found that had exposed copper. This exposed copper produced corrosion on one of these leads during the high temperature and humidity test. Whiskers are known to be found at corrosion sites, and this may force growth.

References:

[1] NASA Advisory NA-044: "Tin Whiskers", October 23, 1998.
[2] NASA Advisory NA-044A: "Tin Whiskers", December 17, 1998
[3] Dept. of Health, Education, and Welfare Public Health Service Food and Drug Administration, 3/14/86 Number: 42
[4] The Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment Regulations 2005, ISBN 0110734165.
[5] Control of whisker growth in Tin alloy coatings, Application Note AN2035, ST Microelectronics, 2006 STMicroelectronics
[6] National Semiconductor http://www.national.com/packaging/leadfree/faqs.html#lfq14
[7] Evaluation of Nickel/Palladium/Gold-Finished Surface-mount Integrated Circuits, Romm, Lange, Abbot, Texas Instruments, Application Report SZZA026, July 2001
[8] Growth of eta Phase Scallops and Whiskers in Liquid Tin-Solid Copper Reaction Couples, Robert A. Gagliano and Morris E. Fine, JOM, June 2001, pp 33-38.
[9] Growth of eta Phase Scallops and Whiskers in Liquid Tin-Solid Copper Reaction Couples, Robert A. Gagliano and Morris E. Fine, JOM, June 2001, pp 33-38.
[10] Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes, JESD22A121, MAY 2005, JEDEC Solid State Technology Association

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Tin Whisker Failures

Satellite	Initial Failure	Final Failure
GALAXY VII	5.6 years	8.1years
GALAXY IV	N/A	4.9 years
SOLIDARIDAD	5.4 years	6.8 years
GALAXY IIIR	5.4 years	10.1 years
OPTUS B1	12.8 years	N/A
DBS-1	4.6 years	N/A

No Pure Tin

Aerospace

Military

Implanted Medical

High Reliability Equipment

RoHS banned Materials

Global Requirements

- **Pb**
- **Cr+6**
- **Cd**
- **Hg**
- **PPB**
- **PBDE**

Lead Coatings

- Sn over Cu
- Sn over Ni over Cu
- Sn -Ag over Cu
- Sn over NiFe
- Sn - Ag - Cu over Cu
- Au over Pd over Ni over Cu
- Ni over Pd over Cu

Pb-Free Solder in Consumer Market

- 1 – 2 Year Life
- Less expensive to manufacture
- Buy New in Two Years

- 10 – 20 Year Life
- Expensive to Manufacture
- Add to System as Needed
- Replace 20 Years

Methodology

- -40°C to 85 °C
- 300 Cycles
- Powered and Functioning

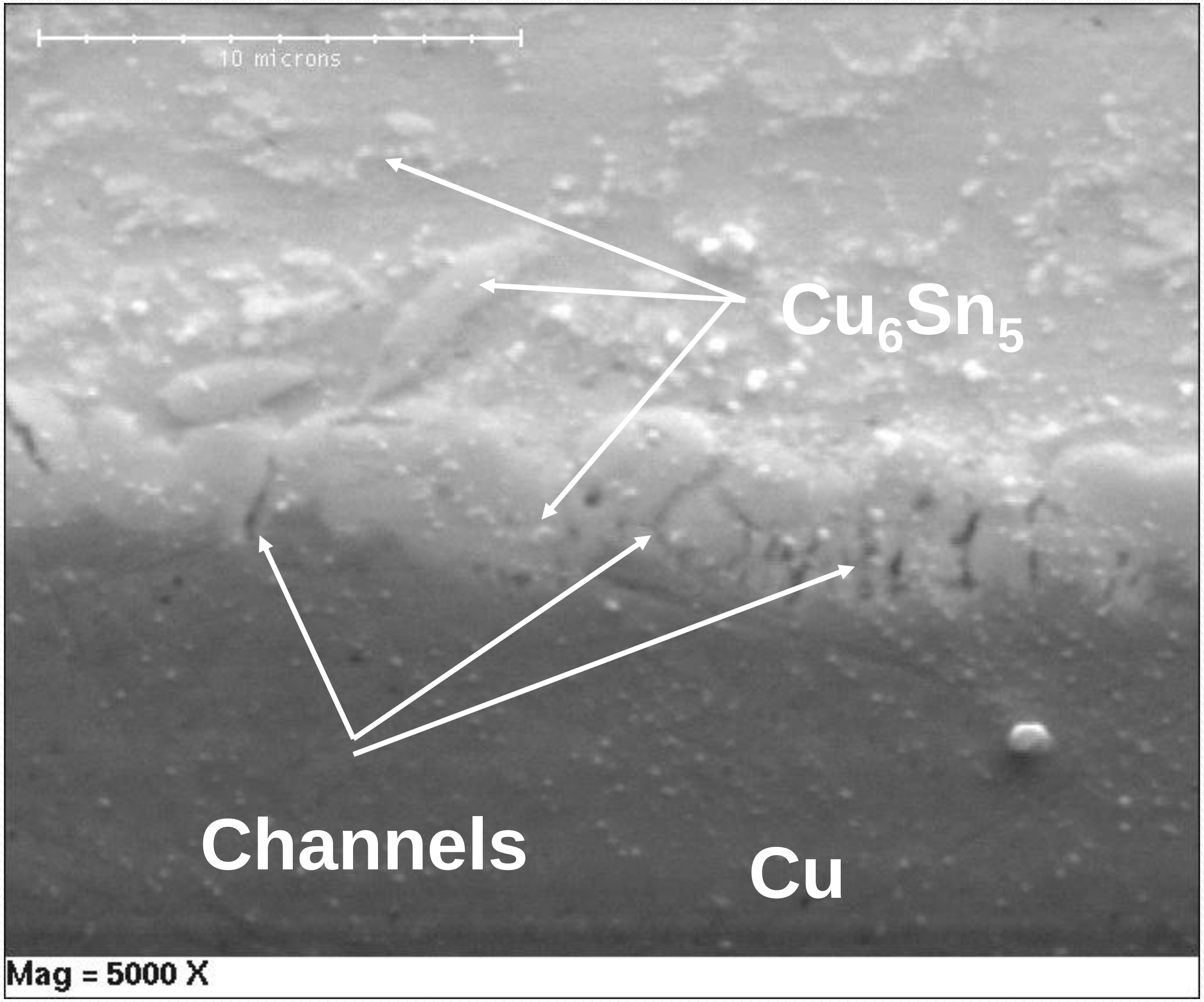
- 50°C and 85%RH
- 300 hours
- Powered and Functioning

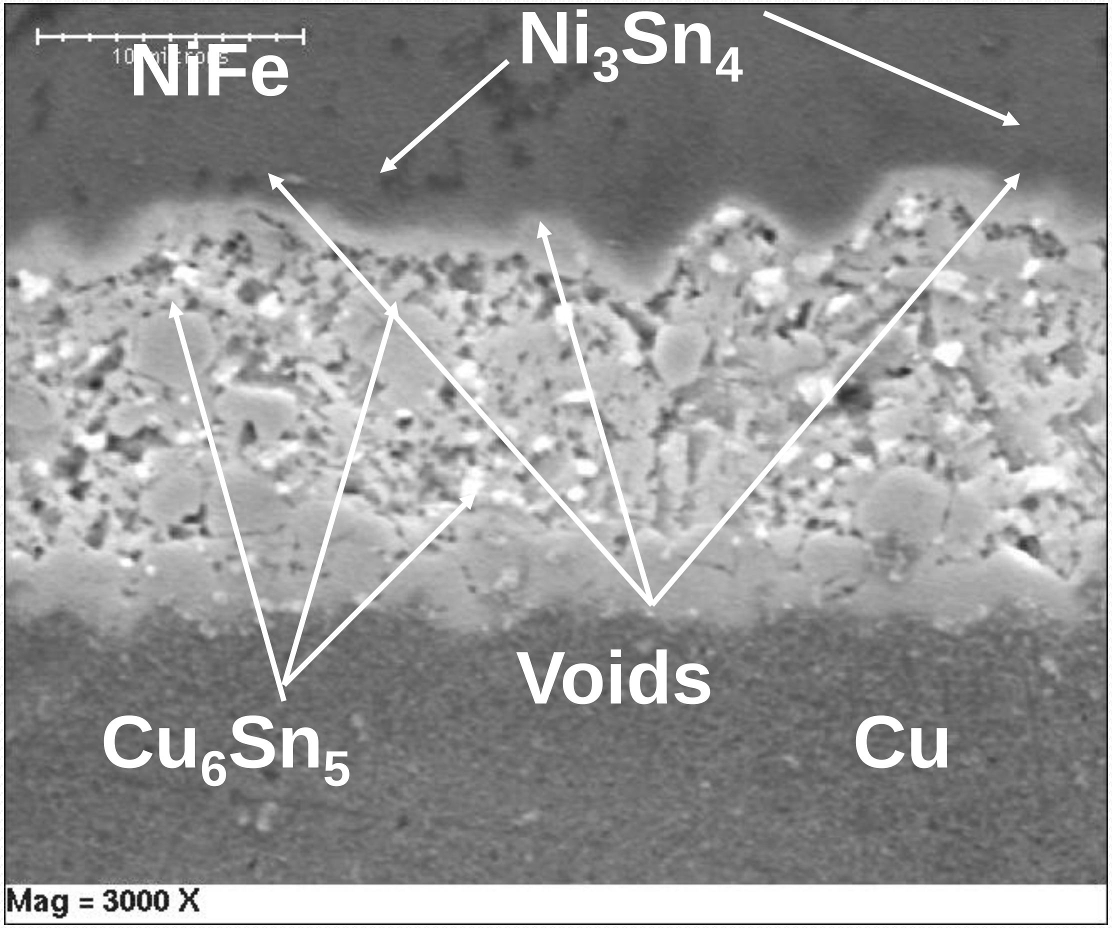
Lead Materials

- Tin dipped Copper Lead
- Tin Dipped NiFe Lead
- Tin Plated over Nickel over Copper
- Tin Plated over Nickel Over Silver (Caps)

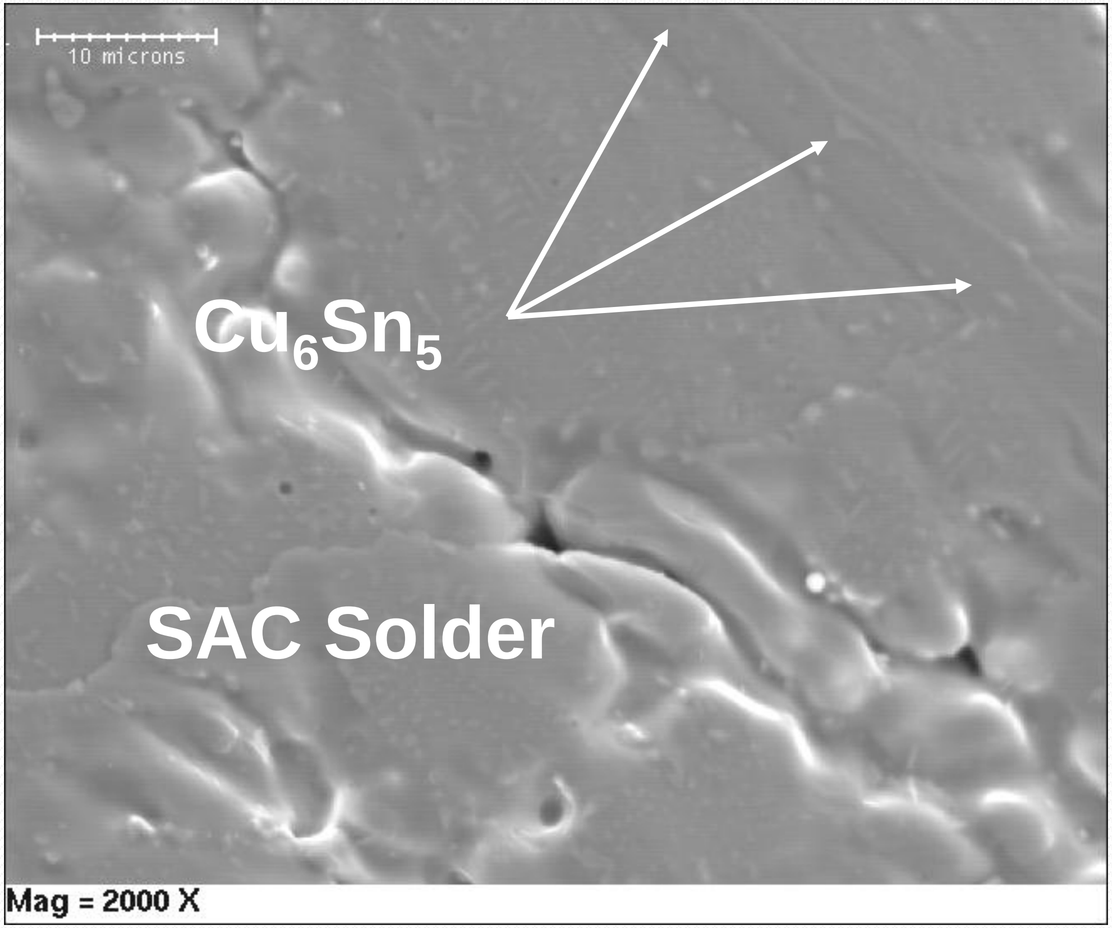
- No Pd used in the products tested

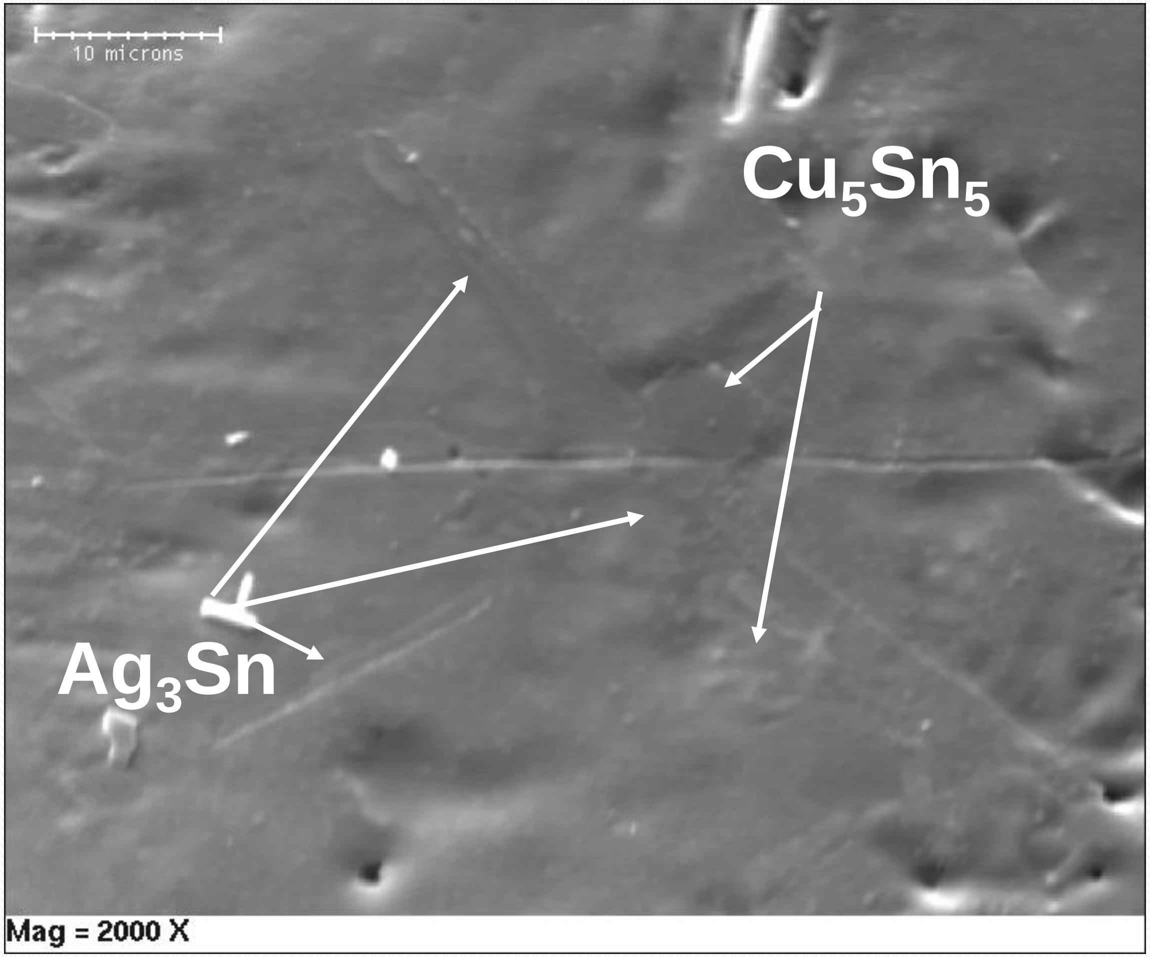
Initial Morphology



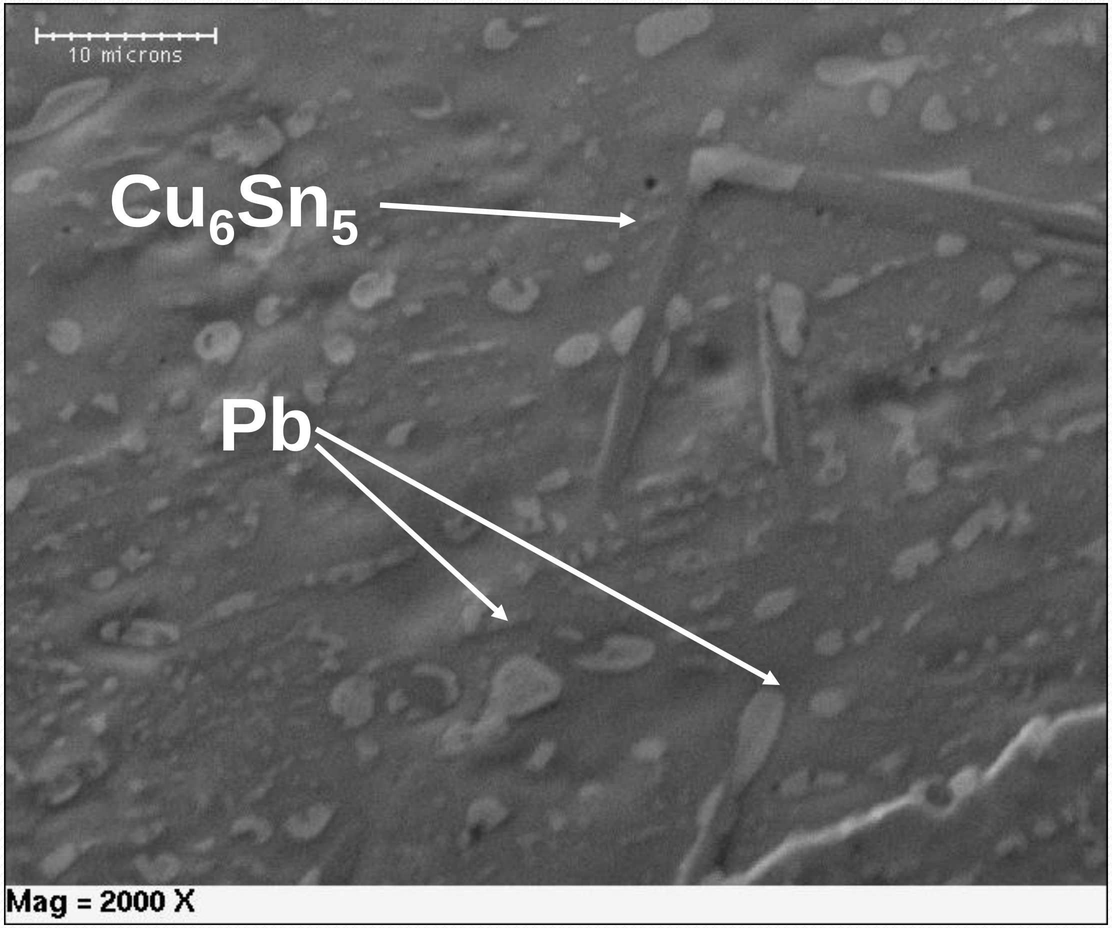


10 microns
NiFe
Ni_3Sn_4
Voids
Cu_6Sn_5
Cu
Mag = 3000 X


10 microns
Cu6Sn5
SAC Solder
Mag = 2000 X


10 microns
Cu5Sn5
Ag3Sn
Mag = 2000 X

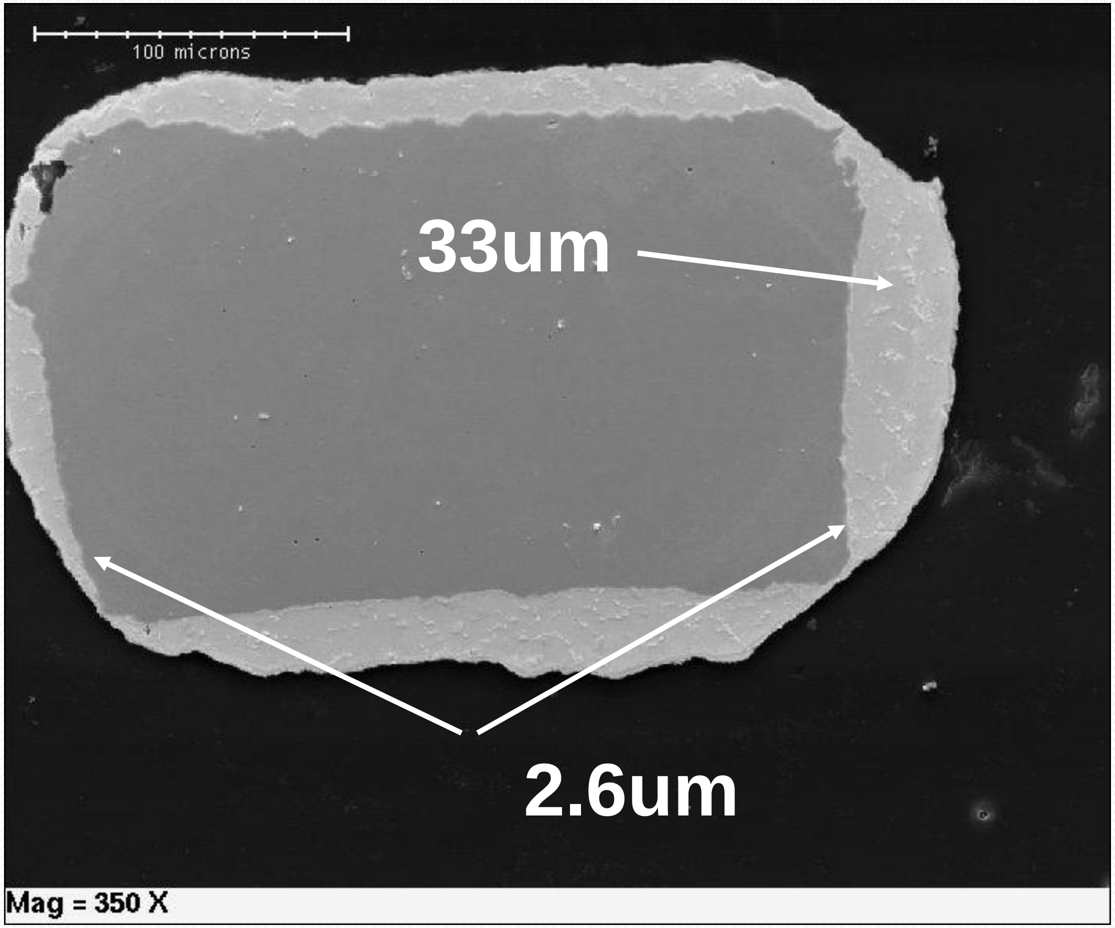
Pb coated components



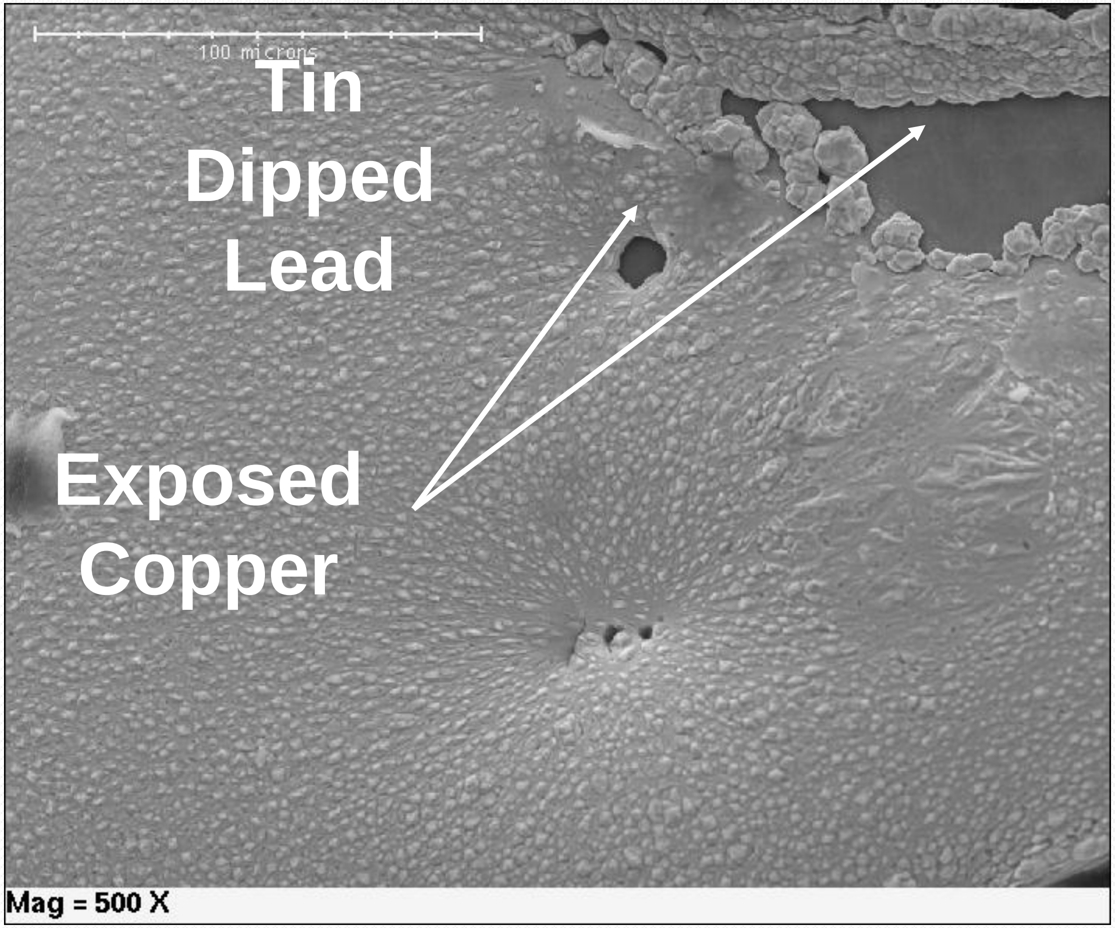
Caution!!!

- Tin Dipped Leads
- Pb Contamination
  - Components
  - Equipment
  - Operators
- Contaminants

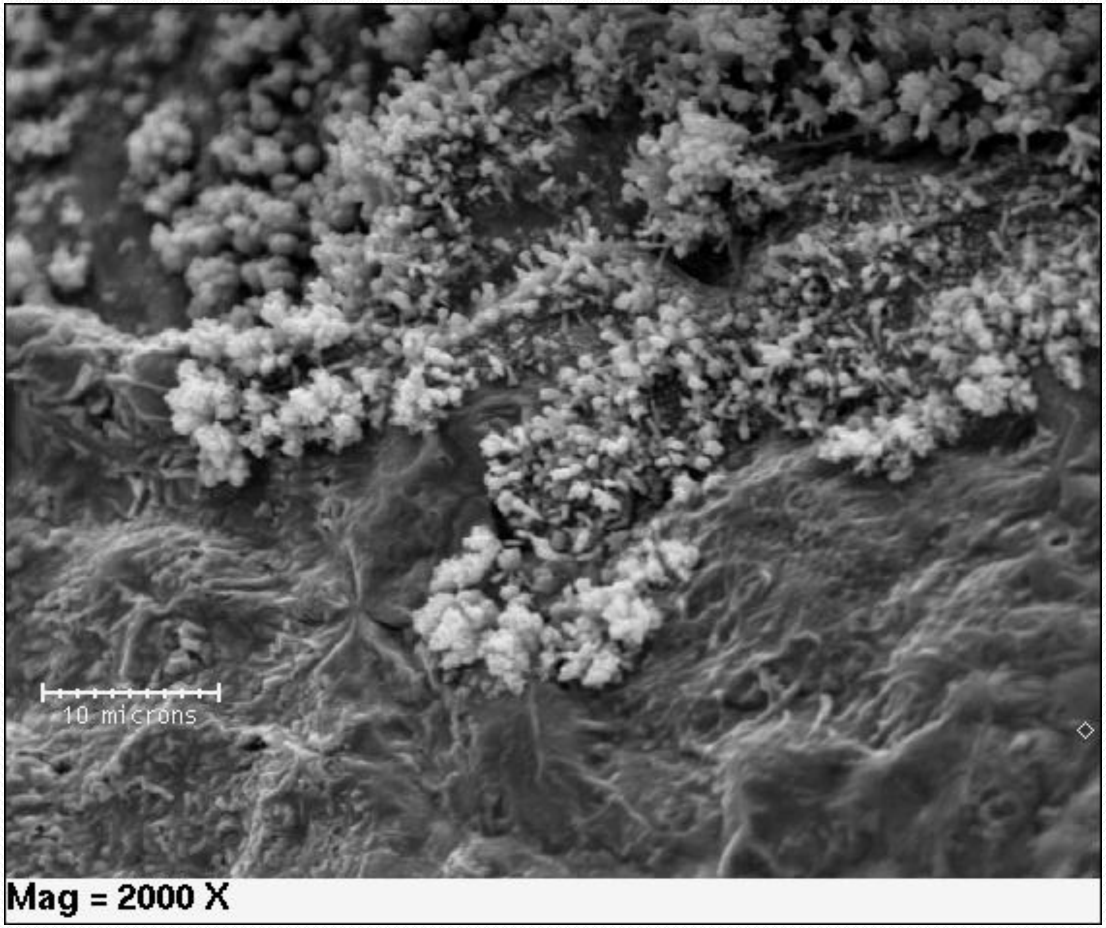
Solder Dipped Lead Issues



Tin Dipping Issues



Environmental Contaminants



Life Expectancy

- No Failures of SAC Solder Products
- No Failures of Pb Solder Products

- No Differences Detected Between Solder Compositions

Conclusions I

- Stress Can Be Increased
- No Whiskers Noted on Any Unit
- More Dispersed Intermetallics in Aged Samples
  - Due to Temperature and Time Above Liquidus?
- Silver Intermetallic Remains Dispersed

Conclusions II

- Copper Intermetallic Forms Large Crystals
  - At Copper – Solder Interfaces
  - Mixed within Solder Matrix
- NiFe Leads May Form Voids at Solder Interface and May Cause Reliability Issues
- Mistakes Will Occur
  - Pb in Products
  - Incomplete Lead Coverage & Corrosion