Long-Term Tin Whisker Risk Mitigation using a Conformal Coating

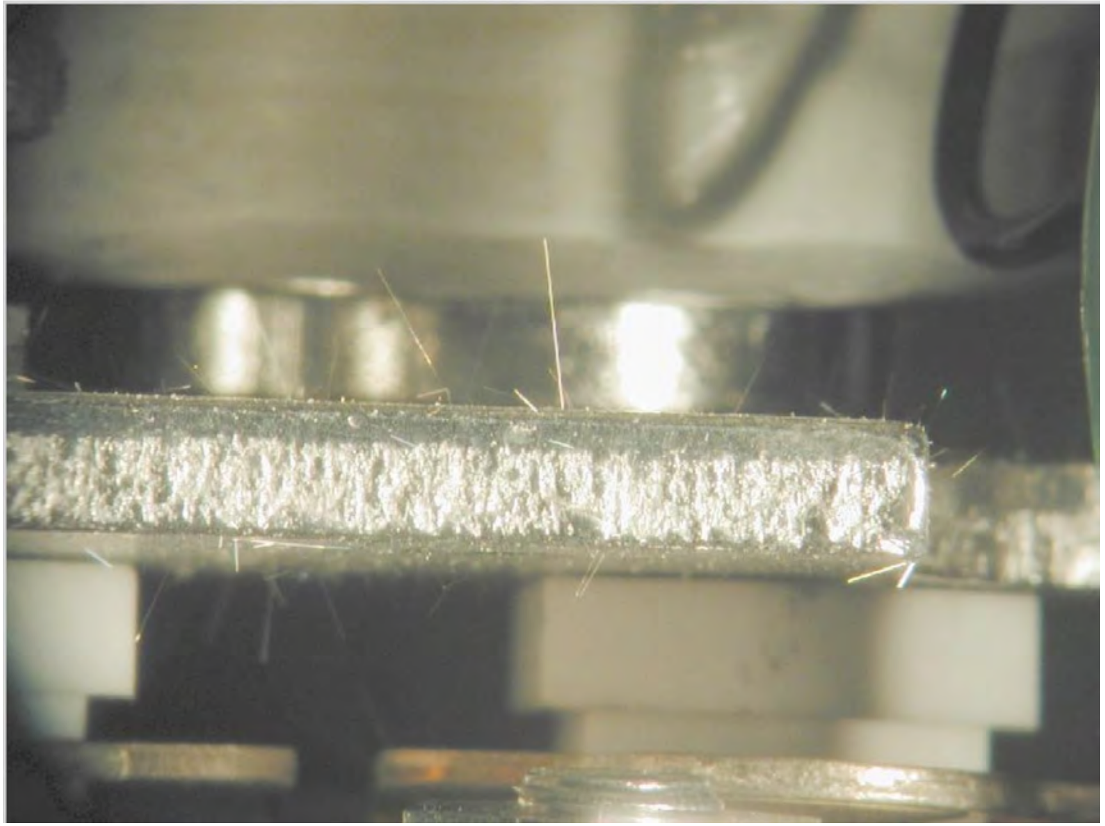

Figure: Whisker growing on a relay armature. [1]

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[1] H. Leidecker, J. Brusse, "Tin Whiskers: A History of Documented Electrical System Failures", Technical Presentation to Space Shuttle Program Office, April 2006.

Acronyms

ARC – Aircraft Radio Corporation

BSE – Backscattered Electrons

COTS – Commercial off the shelf

EEE – Electrical, Electronic and Electro-mechanical

ESA – European Space Agency

ETW – Electronics Technology Workshop

FOD – Foreign Object Debris

JEDEC – Joint Electronics Device Council

MEMS – Microelectromechanical systems

NEPP – NASA Electronics Parts and Packaging

NASA – National Aeronautics and Space Administration

Pb – Lead

SE – Secondary Electron

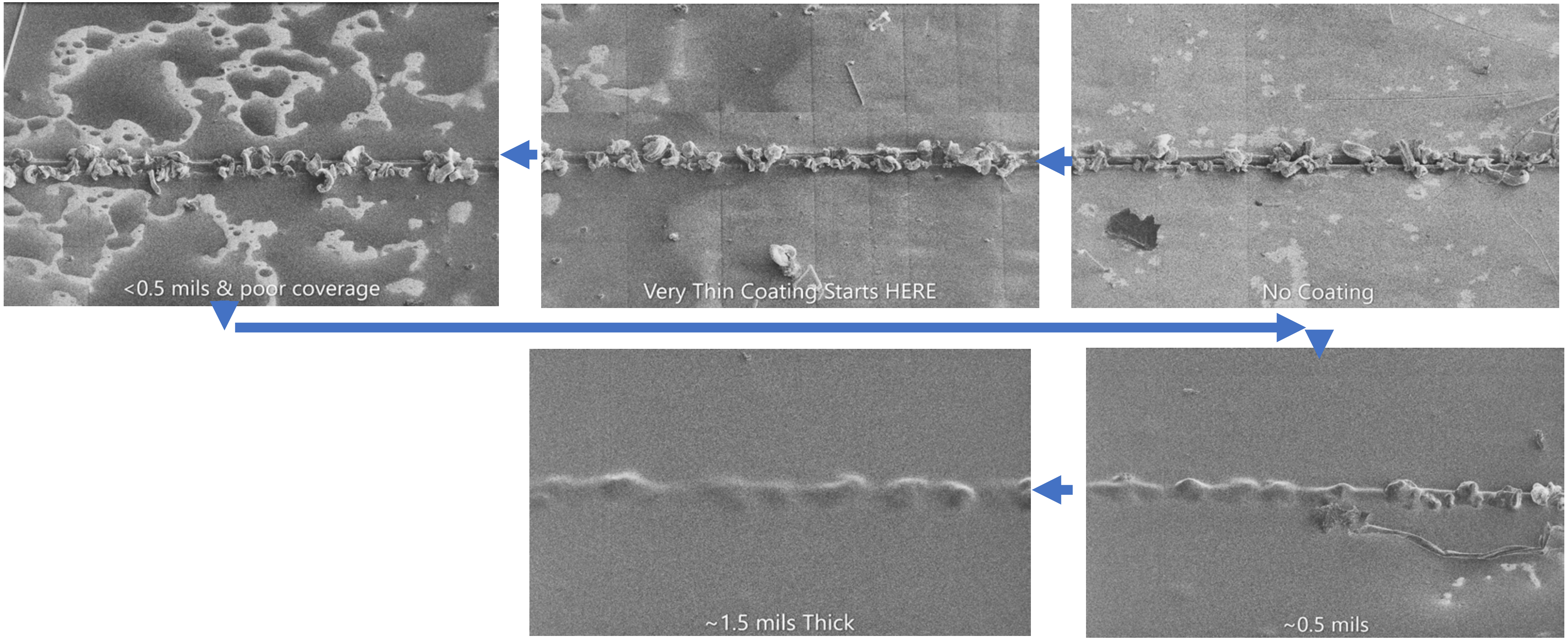
SEM – Scanning Electron Microscope

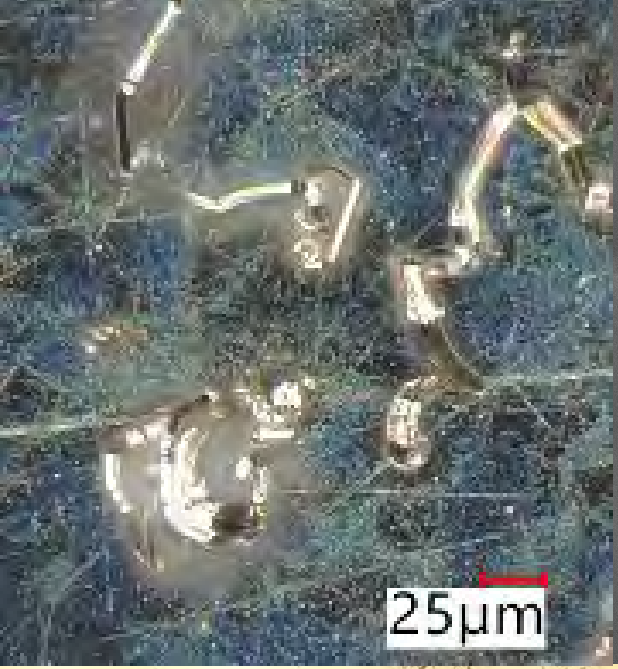
Sn – Tin

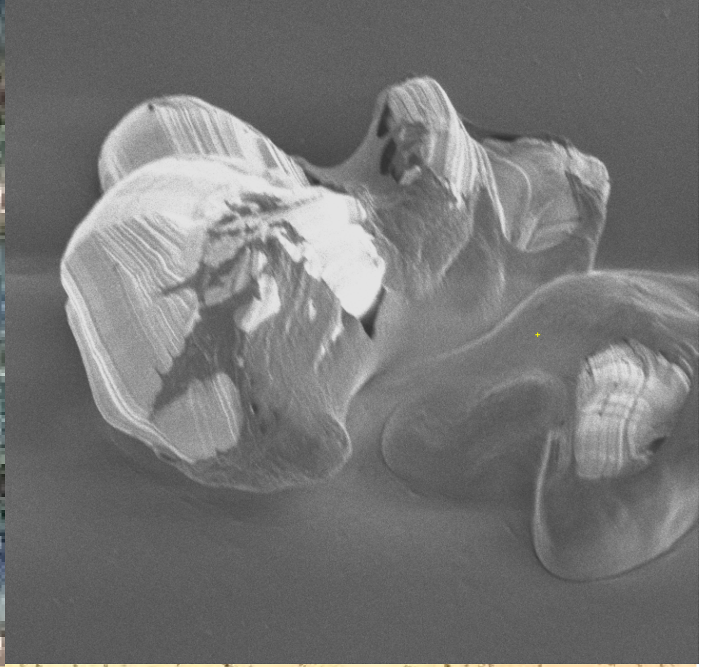
UV – Ultraviolet

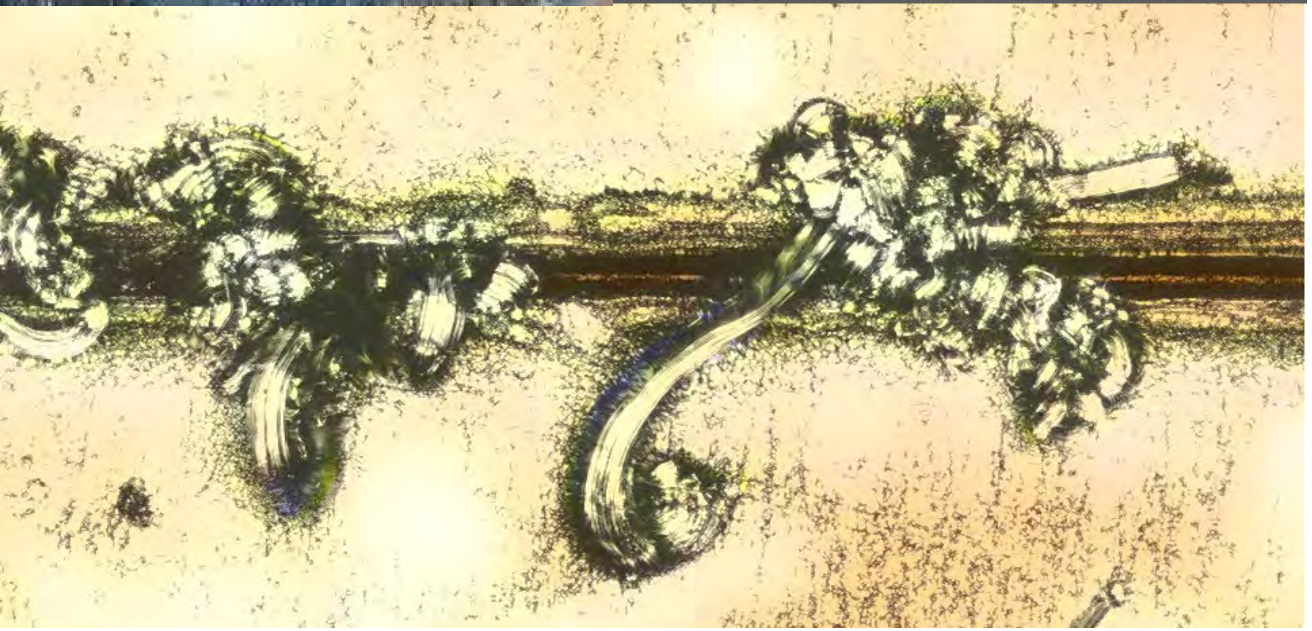
Importance of 2-mils Thickness – Coating Transition

- Samples transition gradually from no coating to 2-mils thickness.
- Whiskers have penetrated the coating in this thinned region illustrating the importance of 2-mils or greater thickness.









What are Metal Whiskers?

- Microscopic, hair-like structures that can grow from bulk tin and tin-plate/films. Generally, they are a single crystal but not always.

JEDEC definition [1]:

  - *A tin growth feature is classified as a whisker if it has an aspect ratio greater than 2.*
  - *Of significance for electrical failure risk if its length is greater than 10 µm.*

- Coatings of Tin, Zinc, and Cadmium are particularly susceptible to whisker growth.
- Tin whisker Characteristics:
  - Most whiskers are under 1 mm in length but occasionally they grow as long as 1 cm to 2 cm.
  - Thickness between a fraction of a micron to several tens of microns (typically between 1 & 10 microns)
  - Electrically conducting through the bulk of the whisker material.
  - A thin electrically insulative layer (e.g. tin oxide) forms on the whisker surface.
- Cause electrical failure by bridging adjacent circuitry.
- Can mechanically jam small structures such as in MEMS devices.

[1] “Environmental Acceptance Requirements for Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes,” JESD201A, JEDEC, Sep. 2008.

A Brief History of Metal Whiskers

- Electronic failure due to Whiskering was first reported by Aircraft Radio Corporation (ARC) in 1946 (“Cadmium Whiskers”).
- Bell Telephone saw failures in telephone line equipment in late 1940s reported on pure Tin and Zinc plated coils in tuning filters.
- By the mid 1960s, the industry had figured out that at least 1% lead content in tin (by weight) mitigates tin whisker growth to a large extent. [1]
- This solution (3% lead by weight for wiggle room) incorporated into most military standards 1970s to present for EEE parts materials enabling use of tin finishes in high reliability applications.
- Even so, inadvertent and sometimes intentional use of pure tin continues, and occasionally tin whisker induced failures have followed. These include but are not limited to [2]:
  - Space Shuttle program affected (flight control system)
  - Commercial satellites complete & Partial Loss (Galaxy IV, Galaxy VII, OPTUS B1, etc)
  - Heart Pacemaker
  - F-15 Radar
  - Relay failure and other electromechanical part failures
  - Many, many more examples

[1] S.M. Arnold, "Repressing the Growth of Tin Whiskers," Plating, vol. 53, pp. 96-99, 1966.
[2] The NASA Electronic Parts and Packaging Program, “*"Publicly" Reported Failure References.” Whisker Failures.* https://nepp.nasa.gov/whisker/failures/index.htm *(accessed June 6, 2023).*

Types of Whisker Failure - Electrical System Risks[1]

Stable short circuits in low voltage, high impedance circuits

- Whiskers can extend between adjacent contacts permanently if the circuit current is limited to below the fusing current of the whisker.

Intermittent short circuits

- Oxide coatings present on the surface of tin can cause a whisker to present as a variable resistance short circuit. Long, thin whiskers may move in and out of electrical/mechanical contact depending on forces on the whisker (vibration, , etc).

Transient short circuits

- A whisker bridge in a circuit that is not current limited will vaporize the whisker causing a momentary short circuit.

Metal Vapor Arcing

- Under certain conditions, whisker vaporization can initiate plasma arcing. Once initiated, arcing is **very destructive** and is only limited by the **power available**, the **circuit protection** or the **available material** needed to self sustain. Atmosphere can act as a quenching agent compared to the vacuum of space. Arcs can carry HUNDREDS OF AMPS resulting in CATASTOPHIC DAMAGE!

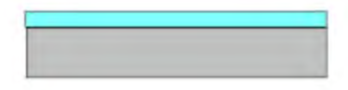
Debris and Contamination

- Whiskers may break loose, bridge isolated conductors, interfere with optical surfaces, or jam mechanisms.

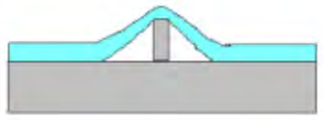
[1] The NASA Electronic Parts and Packaging Program, "Basic Information Regarding Tin Whiskers." Basic Info on Tin Whiskers. https://nepp.nasa.gov/whisker/background/index.htm#q3 (accessed June 6, 2023).

How can Conformal Coat Help

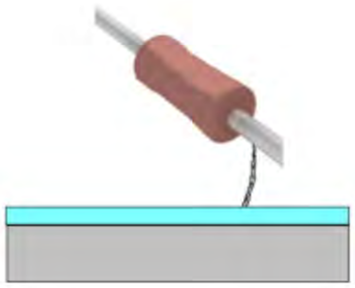
1. Will conformal coat inhibit nucleation of whiskers?



2. Will conformal coat inhibit outward escape of whiskers?



3. Will conformal coat inhibit inward penetration of whiskers



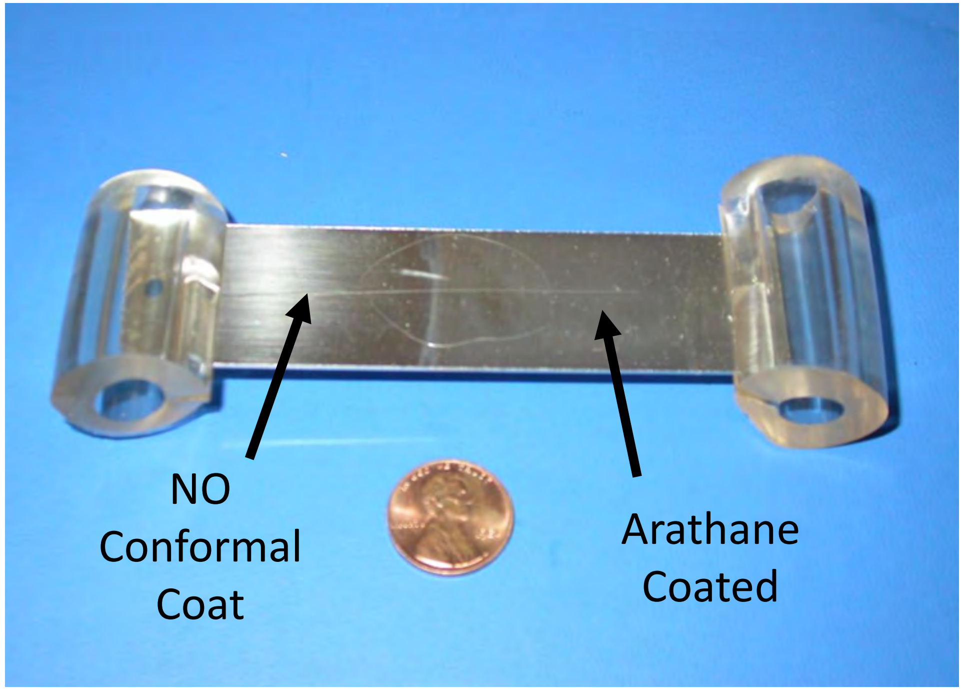
4. Will conformal coat protect against loose (i.e. detached) whisker debris?

NASA GSFC Conformal Coating Experiment

- Samples made Originally in Dec. of 1998.
- Objective:
  - Evaluate the effectiveness of Arathane 5750 (formerly Uralane 5750) conformal coating as a whisker mitigation strategy
  - Arathane 5750 is a conformal coating commonly used in aerospace applications due to a variety of desirable properties
- Approach:
  1. To obtain samples that are prone to grow whiskers
  2. Apply conformal coat
  3. Store in ambient conditions
  4. Monitor whisker nucleation and penetration through coating

Whisker Samples Under Study

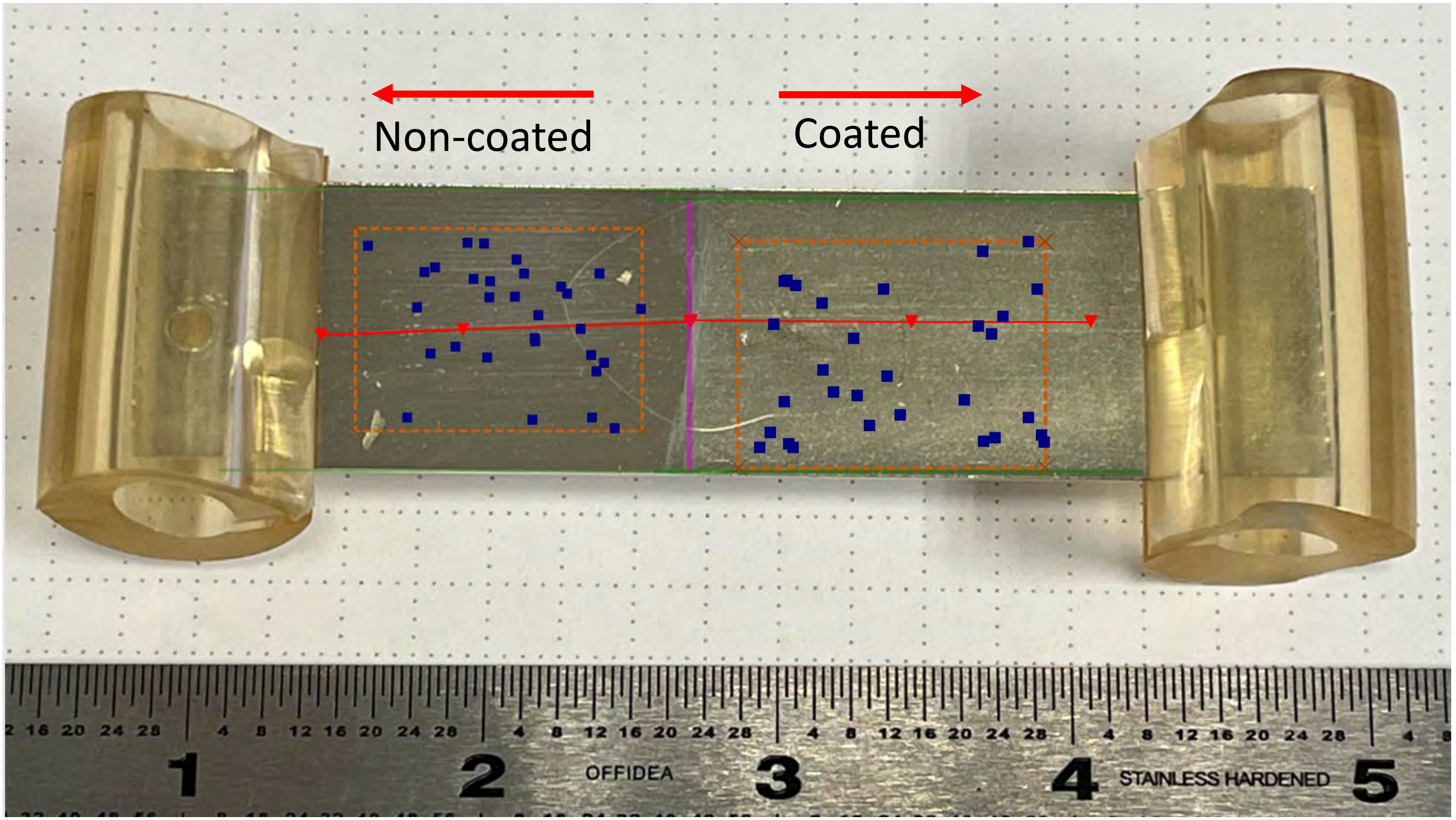
- Specimens: (14 total, 2 re-examined herein)
  - 1"x 4"x 1/16"Brass 260 base material (70 % Cu, 30% Zn)
  - Tin-Plate 200 microinches thick (5.08 µm)
  - Intentional scratches created after plating to induce localized whisker growth
- Half conformally coated:
  - Arathane 5750
  - Nominal Thickness ~ 2 mils (measured to be 47 µm)
- Storage Conditions:
  - Ambient office
  - 23 years old



**Arathane™ 5750 was previously known as Uralane™ 5750*

Sample 6 – Inspection Locations

- Two (2) samples were investigated at 30 Inspection locations on both the non-coated and coated.
  - Chosen at random by using a random number generator.
- **Same** inspection locations from previous years study.
- Last coated side inspection performed in 2011.
- Last non-coated side inspection performed in 2015.
- Looking for
  - Whisker Growth as a comparison from year to year.
  - Whisker Density estimation.
  - Inspecting for breaches of the conformal coating.

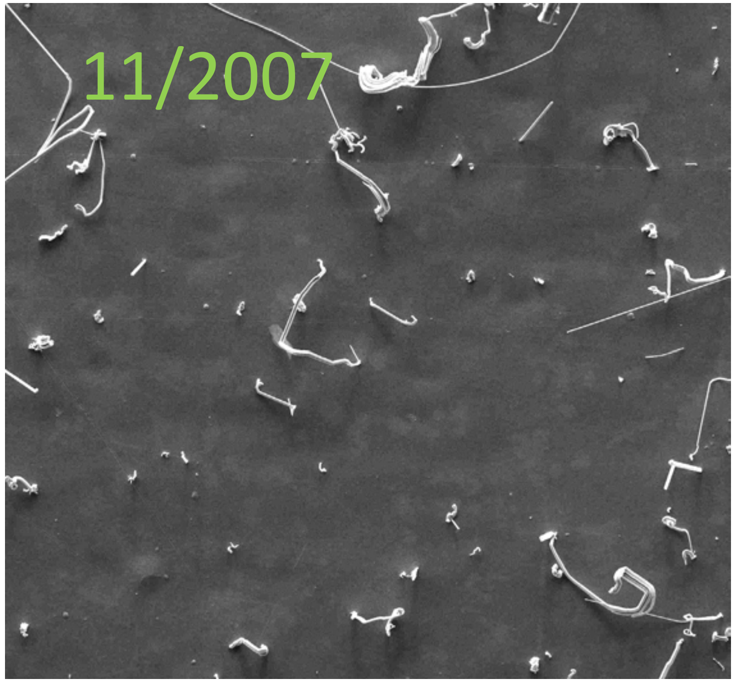


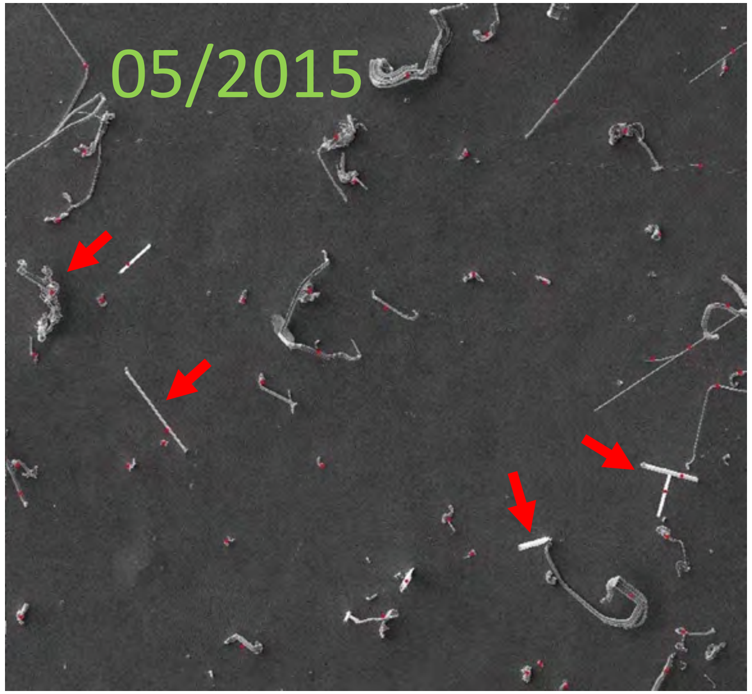
Sample 6 inspection locations. Blue dots represent the inspection locations. Red line is the location of an intentional cut.

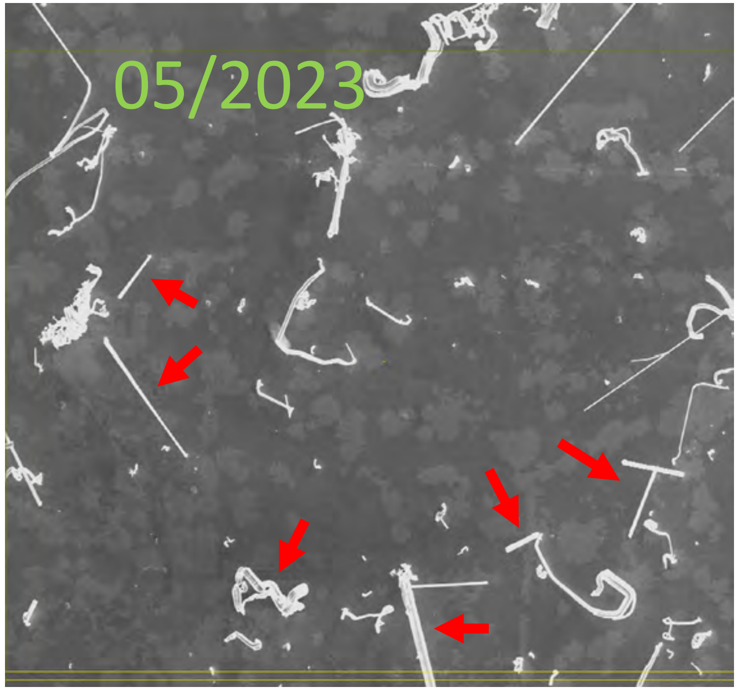
Non-Coated Whisker Growth Comparison

Sample 6 Location 18

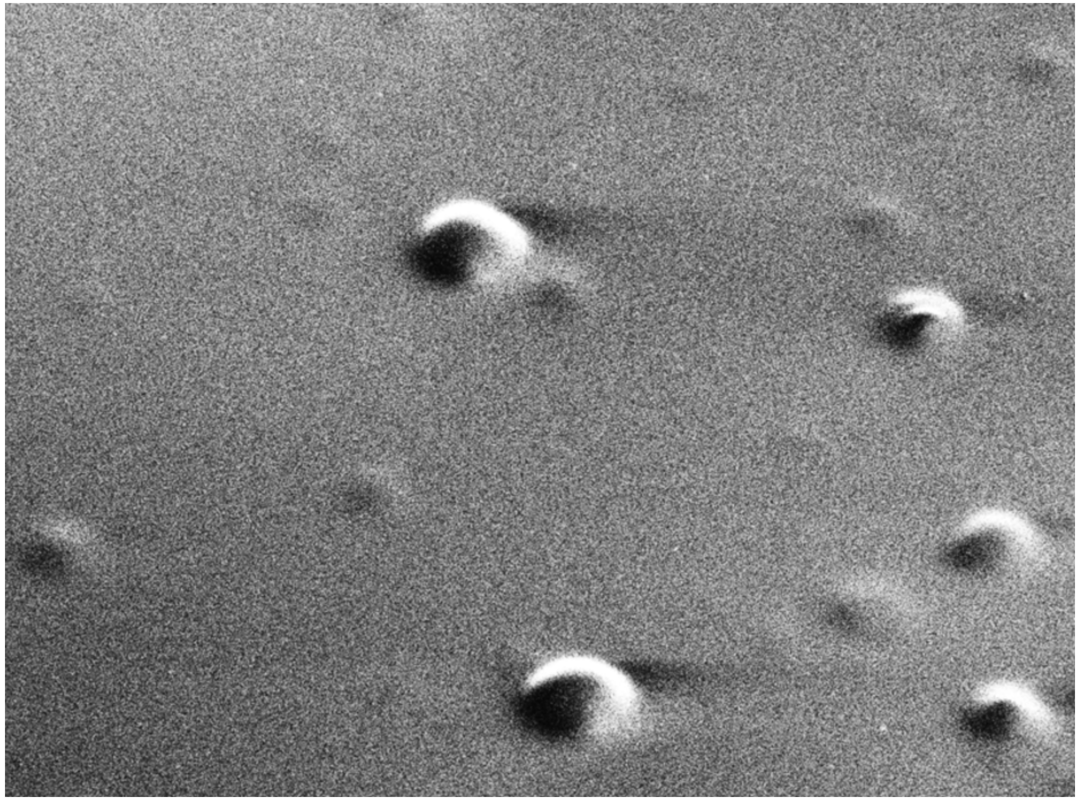
- 1st photo is from 11/2007 inspection, 2nd from 05/2015, and 3rd from 05/2023

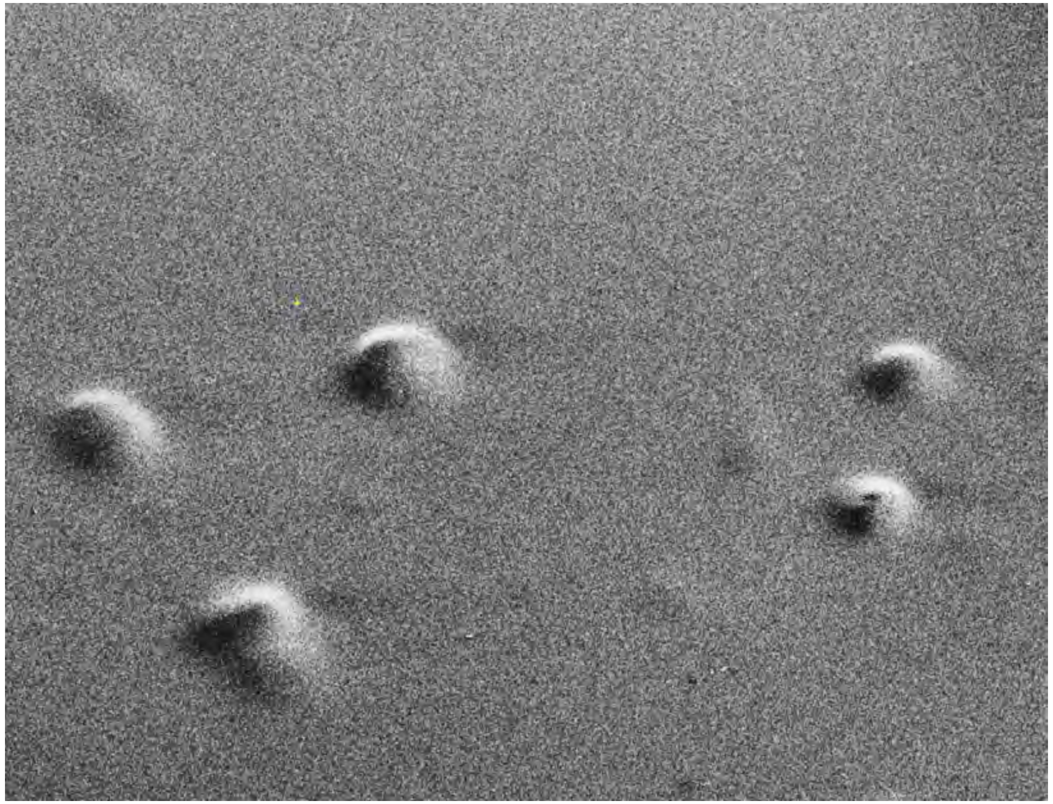






No whiskers have Breached the Coating in 2-mil Thick Regions

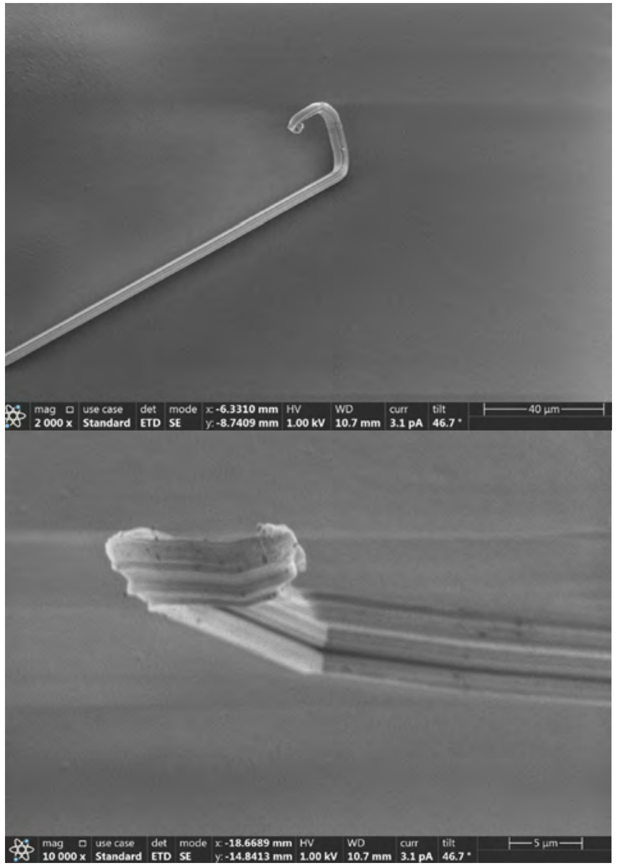




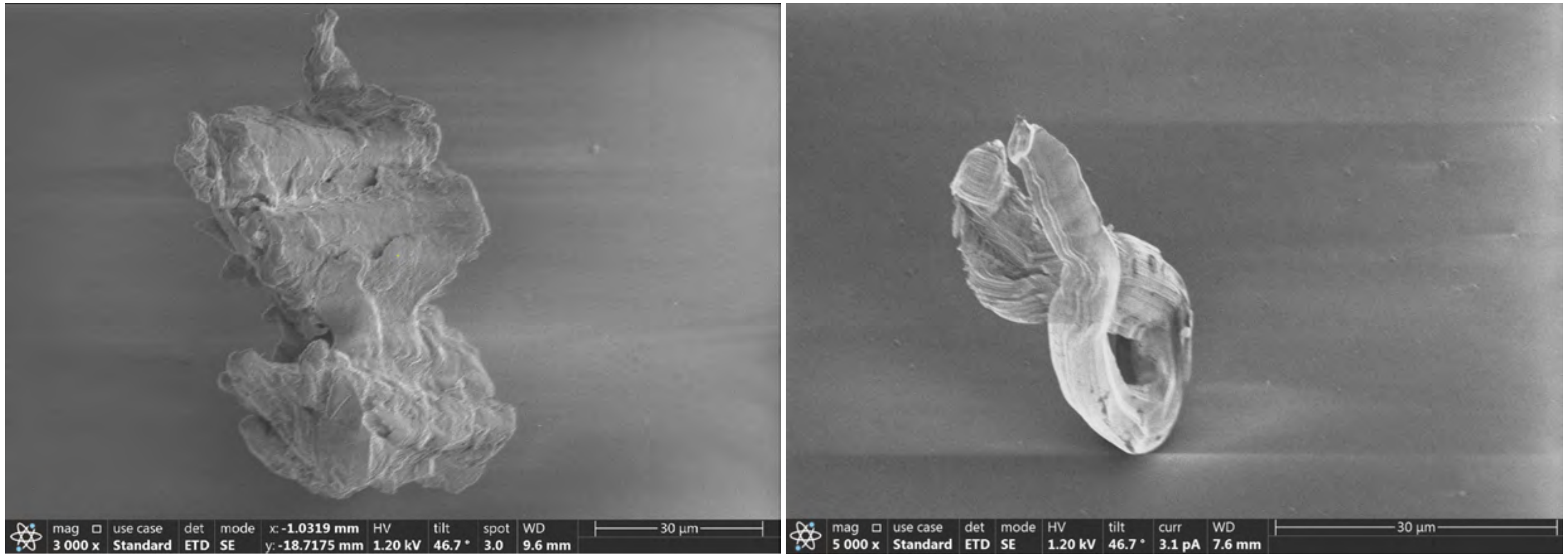
SEM photos of conformal coating inspection locations. Hillocks are captured whiskers.

Surface Contamination

- Some whisker are found on the coating surface, but they did not come through the coating.
    - These whiskers are mechanically detached from the non-coated region of the sample.
- Other debris also found on the surface.
- Contamination was investigated in the SEM at high magnification.
- Sample rotation/viewing angle was adjusted as necessary to confirm that particles were on top of the coating.



SEM photos of a whisker lying on the coating surface.



SEM photos of [Left] a surface particle that is not a whisker, [Right] a whisker lying on the coating surface.

Whisker Density, Coated Versus Non-Coated

Non-Coated:

- Whiskers are present on non-coated side of the sample as a control for conformally coated side.
- Whisker formations that branched in multiple directions from the same root were counted as separate whiskers.
- Compared Secondary Electron (SE) and Backscattered electron (BSE) SEM imagery for each inspection area to make determinations.

Conformally Coated:

- Tin whiskers formed under conformal coating
- No tin whiskers penetrated to 2mil or thicker conformal coating after 23 years.
- Whisker hillocks were counted for density calculation.
- Density of whisker hillocks on the conformal coated sides are less than density of whiskers on the uncoated sides.

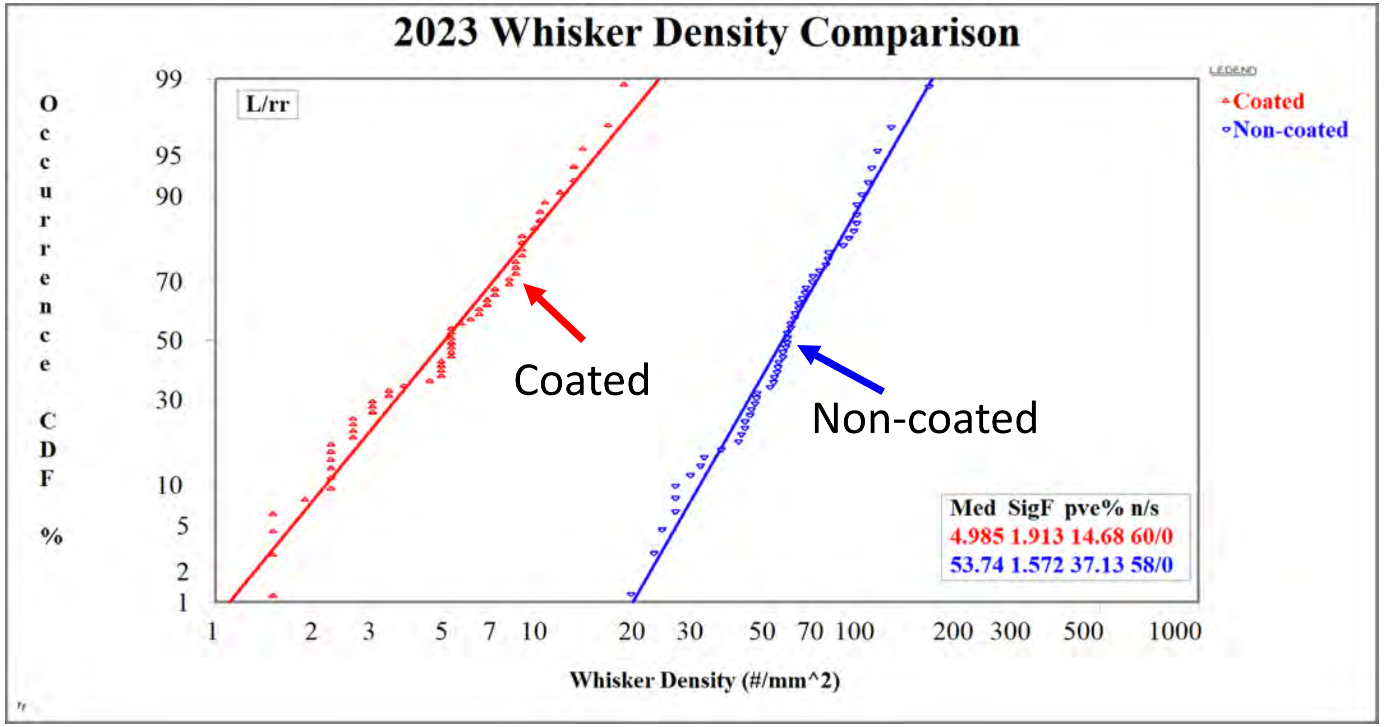


Figure: Lognormal fit to whisker density estimates.

Non-Coated Whisker Density Change Over Time

- While individual whiskers have grown in size, overall whisker density has not changed much.

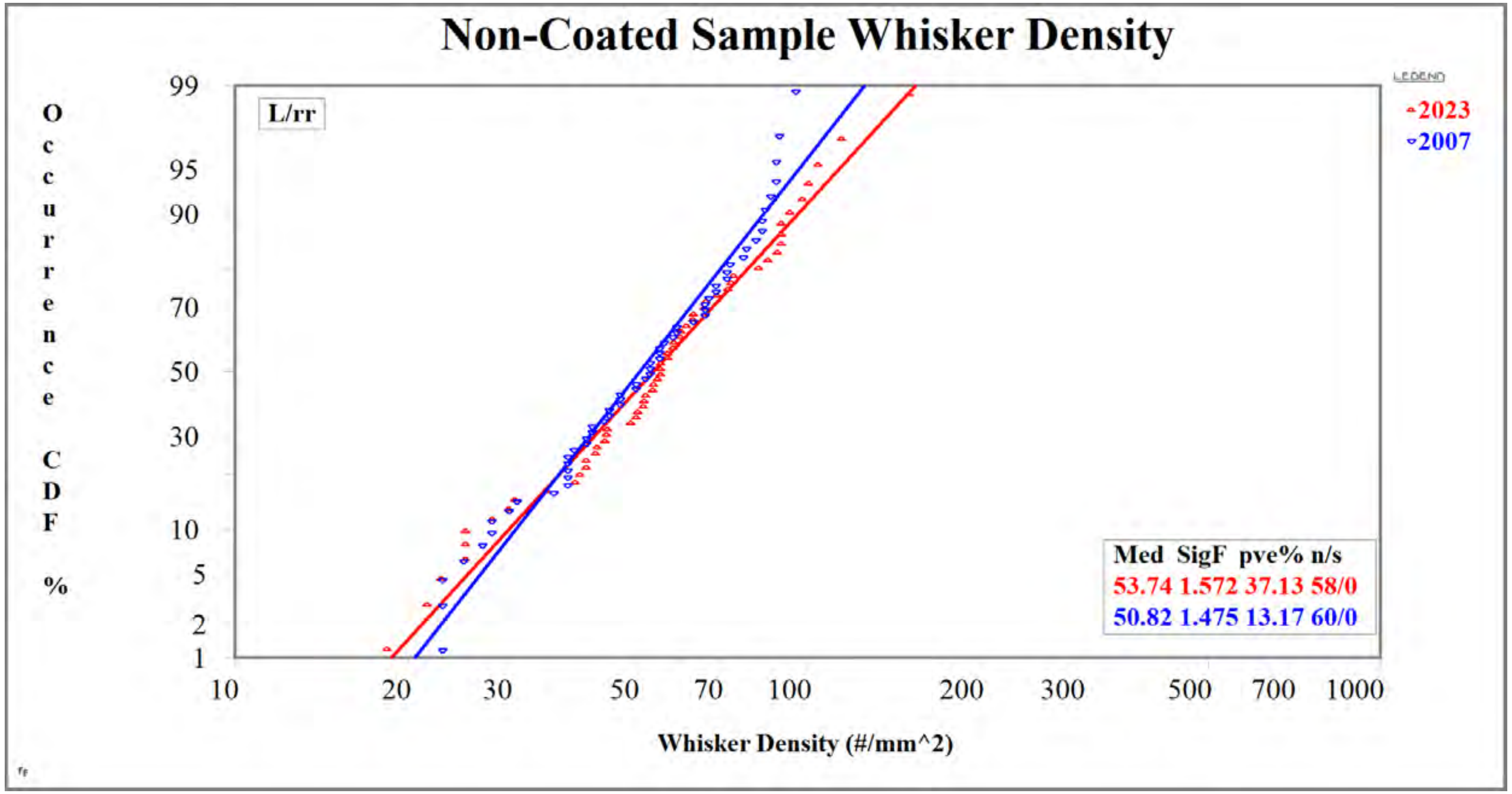
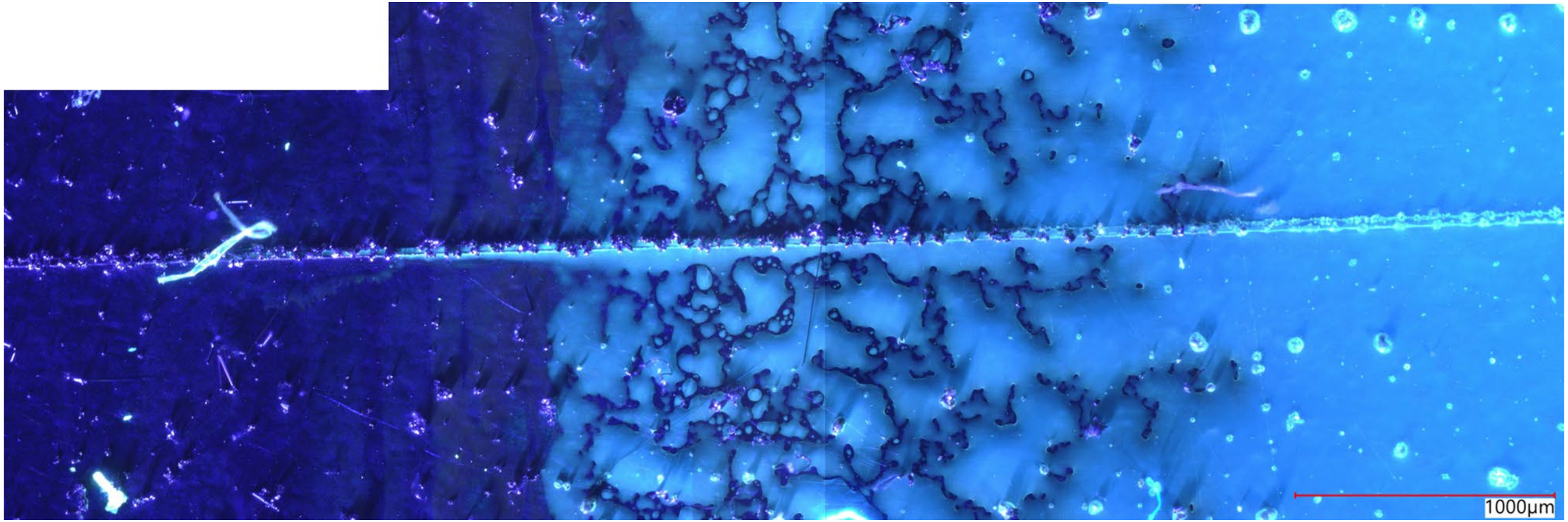


Figure: Lognormal fit to whisker density estimates on the non-coated Side.

UV Coating Coverage Inspection

- Arathane is Fluorescent under UV.
- Use a **BRIGHT** Ultraviolet (UV) light and a microscope that allows for a long shutter duration.
- Perform inspection with room light (visible spectrum) dimmed or off.

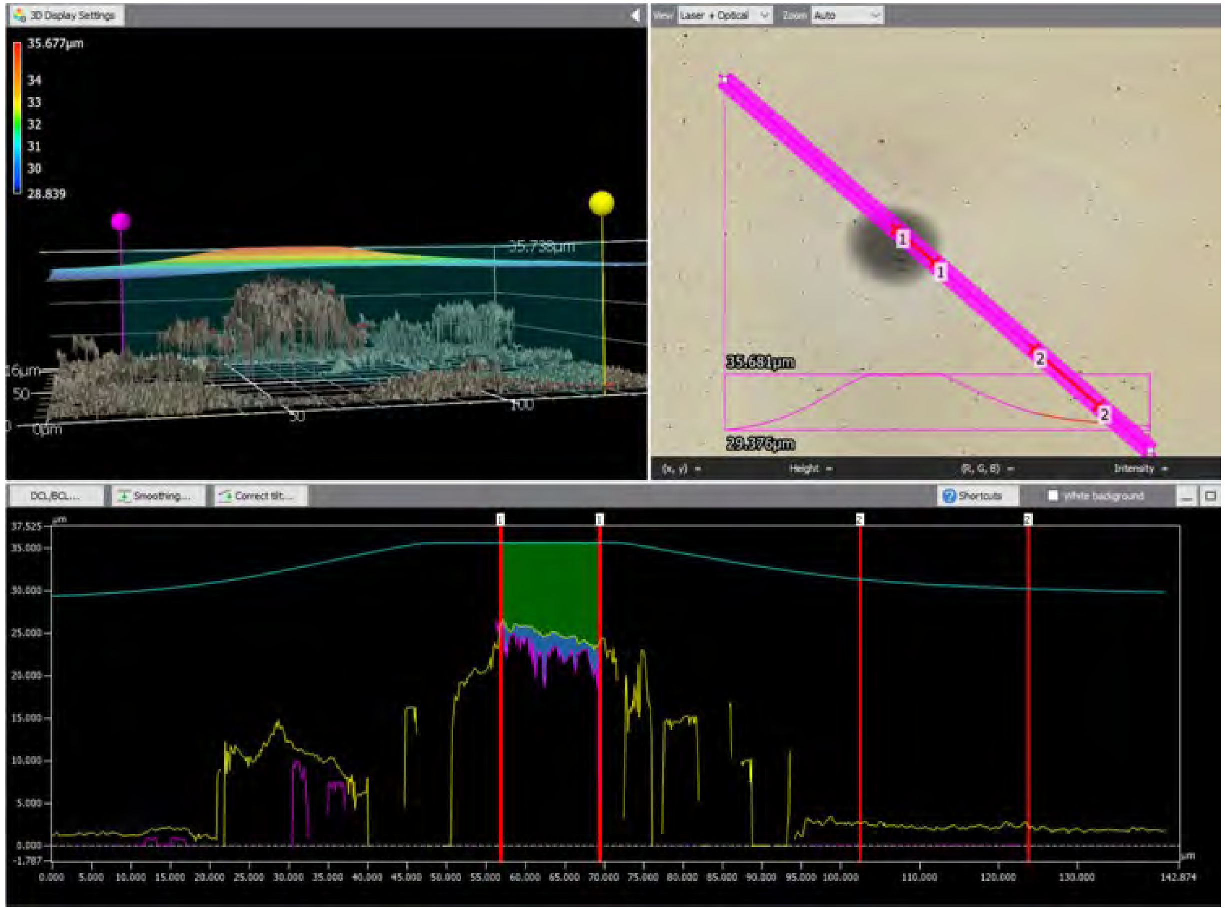


Non-coated

Coated

Confocal Microscope results of a Hillock Inspection

- A confocal microscope can easily focus on the top surface of the coating where standard optical microscope has difficulty.
- Differences in focal depth can be used to make measurements.
- Distances within the material must be corrected using the index of refraction.
- Arathane index of refraction = 1.6.
- The trapped whisker shown has the following characteristics:
  - ➢ Coating left above whisker: 17.2 µm
  - ➢ Coating top surface Lift: 6.3 µm
  - ➢ Overall nearby Coating Thickness: 45.4 µm
  - ➢ Trapped Whisker Height: 34.5 µm

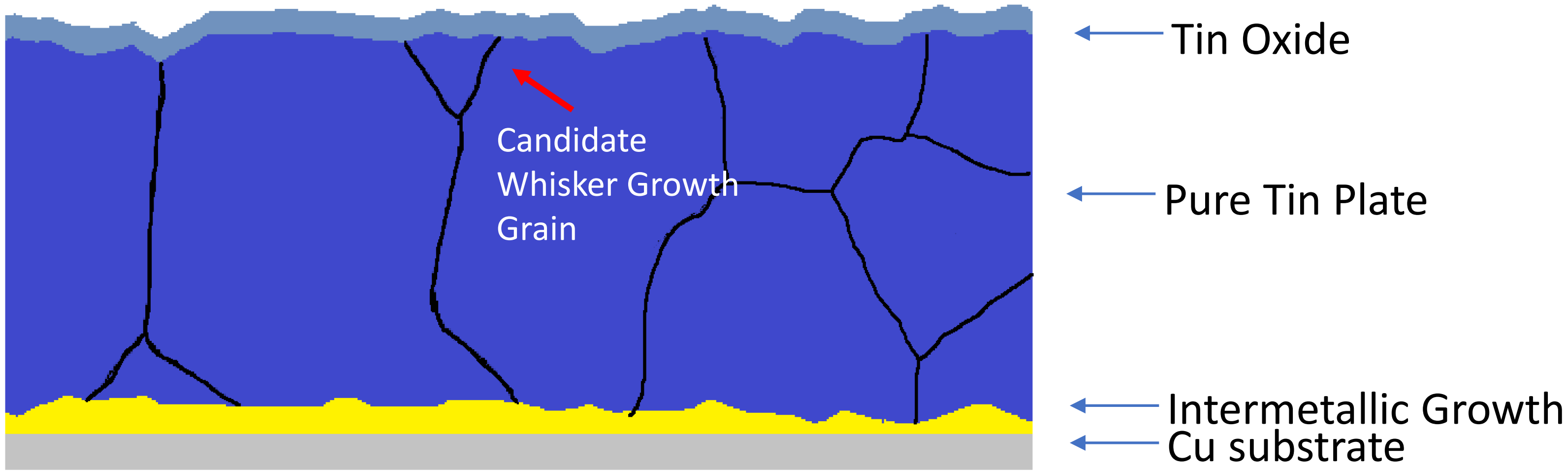


Conclusions

- A 2-mil thick Arathane 5750 conformal coating is effective at preventing long-term (23 years) whisker escape.
- Conformal coating prevents Foreign Object Debris (FOD) from affecting underlying electrical components. Even thinner coating regions are effective for blocking electrical contact of FOD.
- On non-coated regions, whisker growth has continued over the course of 23 years but at a decreased rate.
- Whisker nucleation does occur under the coating but at a decreased rate.

Growth Mechanism (not well understood)

- Compressive stress (within tin film) is thought to be fundamental to whisker formation.
- Cu_6Sn_5 intermetallic formation causes compressive stress. [1]
- Stresses can propagate to the surface via grain boundary diffusion. [2]
- Bulk diffusion is pinned due to available vacancy flux within the material (limited grain growth) but at the material surface vacancies may enter when the oxide coating is breached. [1]
- Whisker grain boundary generally at oblique angle to the surface. [1] [2]
- Growth is from material adding to the root of the whisker not the tip.
- All specifics over whisker nucleation still not fully understood: why does a specific grain grow while others do not? Is a catalyst required or only the above factors?
- Internal (compressive) stresses may be installed in a number of ways: corrosion, intermetallic formation, CTE mismatch, mechanical deformation (plastic or elastic loading), etc.
- We cannot predict which tin grains will grow, nor density of whisker growth given a sample preparation and environment. So, fundamentally, we still do not understand the physics of the growth mechanism.



[1] “Current Tin Whiskers Theory and Mitigation Practices Guideline,” JP002, JEDEC/IPC Joint Publication, Mar. 2006.
[2] George T. Galyon and I. Palmer, “An Integrated Theory of Whisker Formation: The Physical Metallurgy of Whisker Formation and the Role of Internal Stresses”, IEEE Transactions on Electronic Packaging Manufacturing, 28(1): pp. 17-30, Jan. 2005.

Economic Driver- RoHS Compliance

- Over 30 countries have adopted RoHS or RoHS like legislation starting in 2006. Exemptions to pure tin use are in general ending.
- “ESA and European space industry have been granted a waiver to continue using tin–lead alloy for solder, but not an indefinite one.” [1]
- Maximum concentration tolerated (by weight) for materials: **lead, 0.1%.**
- Space/military parts makeup less than 1% of total EEE component market demand.
- COTS usage expected to increase in future missions.
- Many COTS components are only available in pure tin finishes.
- Tin-lead finishes will become increasingly difficult to procure.
- Pure tin plating is the most common replacement for tin-lead plating.

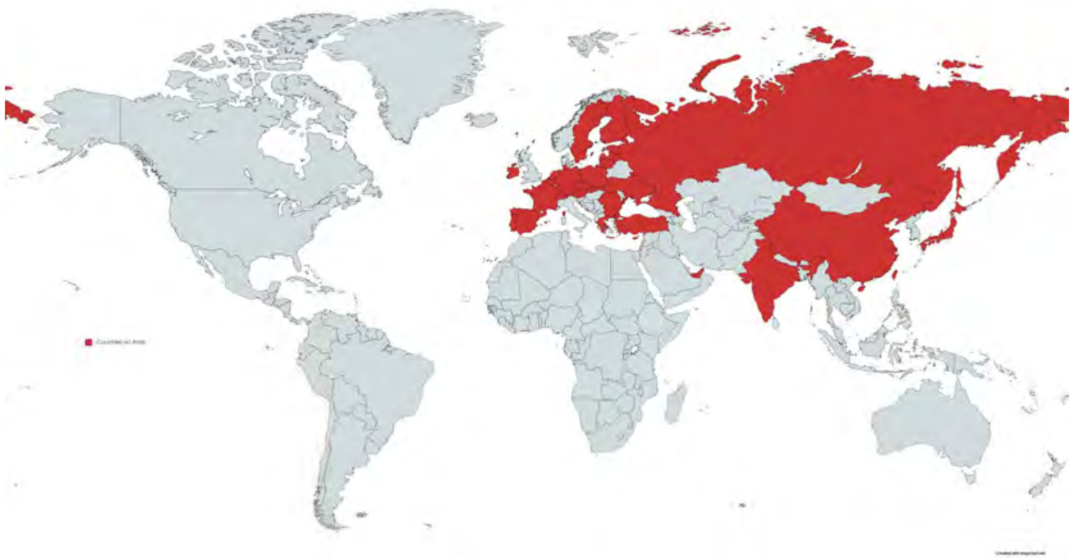
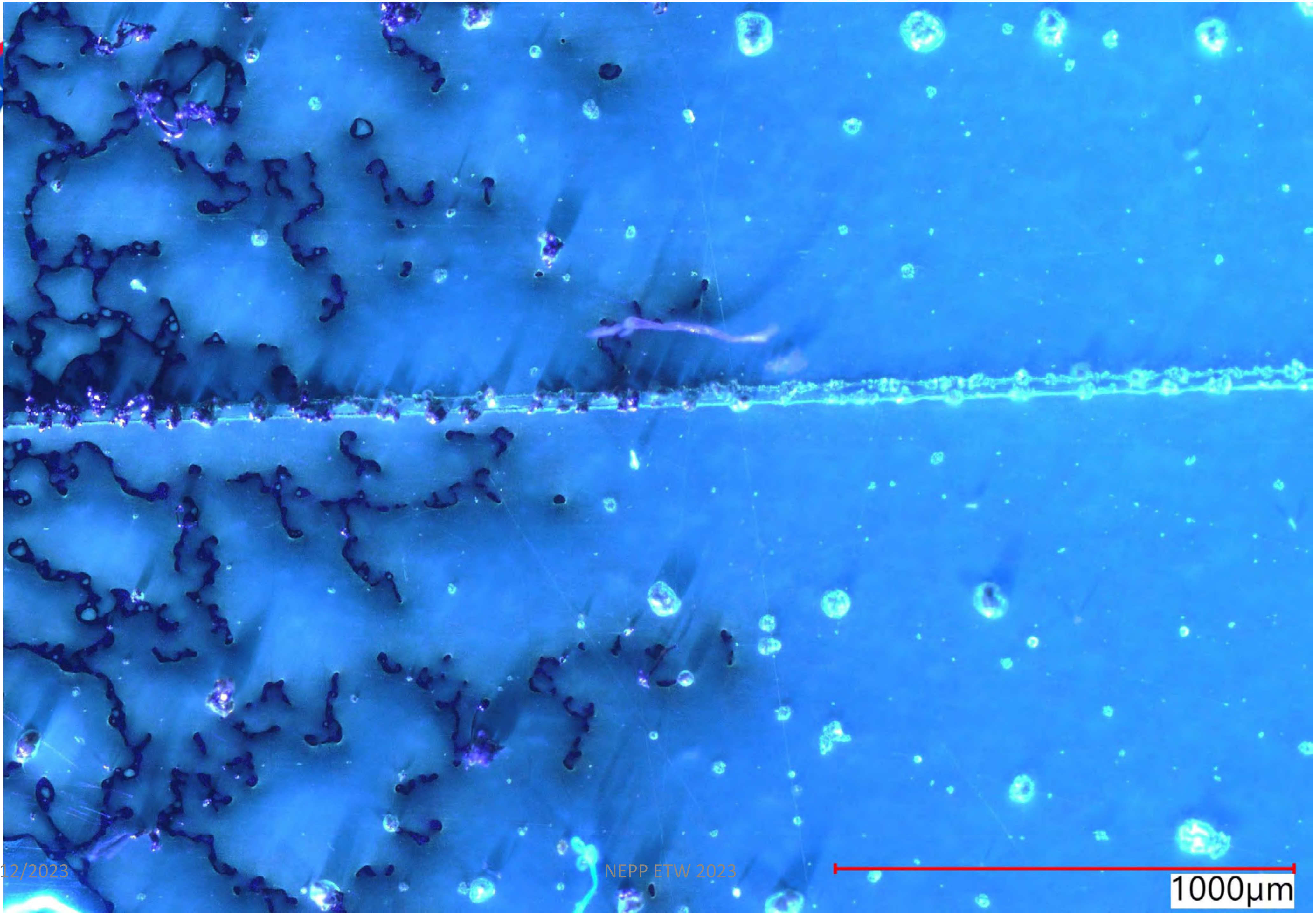


Figure: Countries with RoHS or RoHS like legislation in place. Created with mapchart.net (Creative Commons).

[1] The European Space Agency, “Tin whisker.” ESA – Tin whisker. https://www.esa.int/ESA_Multimedia/Images/2017/11/Tin_whisker (accessed June 6, 2023).


1000µm