Strategic Environmental Research and Development Program (SERDP) Nanoparticle enhanced conformal coating project: Coating modeling for tin whisker mitigation

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DoD/EPA/DOE SERDP WP-2213: Novel Whisker Mitigating Composite Conformal Coat Assessment

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Technology Focus

- *Develop and evaluate nanoparticle filled conformal coatings designed to provide long term whisker penetration resistance and coverage on tin rich metal surfaces prone to whisker growth in commercial lead-free electronics used in modern DoD systems.*

Research Objectives

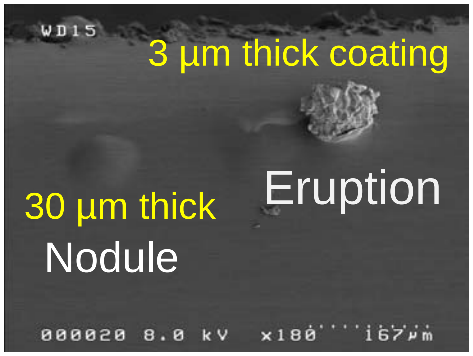
- *Identify the fundamental mechanisms by which conformal coatings provide long-term tin whisker penetration resistance and inhibit nucleation/growth. Correlate mechanical properties and coverage thickness to whisker penetration resistance.*

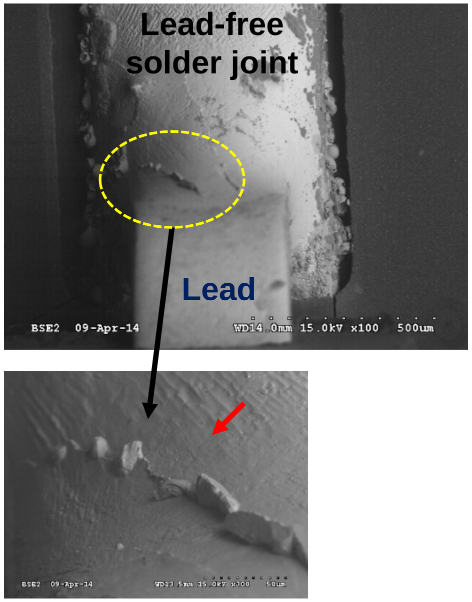
Project Progress and Results

- *Functionalized nanosilica and non-functional nanoalumina enhanced polyurethane conformal coatings have shown improved spray coating coverage characteristics and crack resistance during thermal cycling fatigue testing. Lead-free assembly whisker mitigation validation testing is in process.*

Technology Transition

- *Current project partners provide coating materials to industry. SERDP test data will be considered during updates to the DoD adopted IPC standards for coating materials and coverage.*





Coating fracture risk area:
Tin growth between primary tin dendrites after thermal cycling

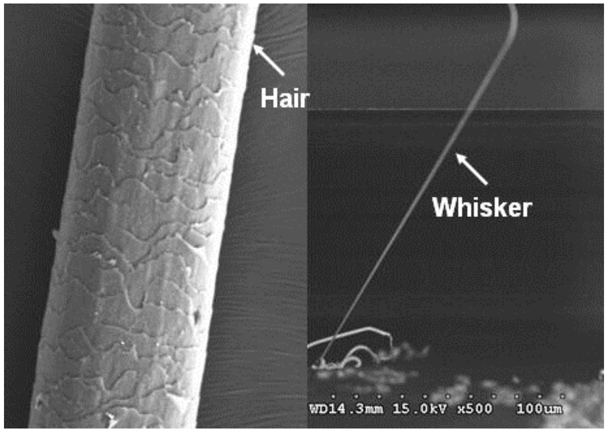
Outline/Agenda

- Introduction
  - Whiskers
  - Coating mitigation
- Analysis
- A simple experiment
- Conclusions
- Q & A

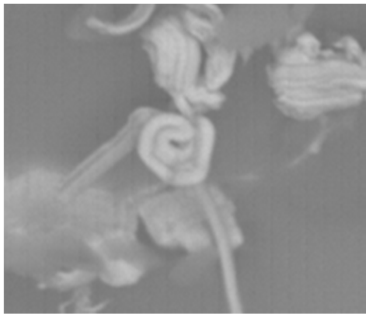
Tin Whiskers: Effect

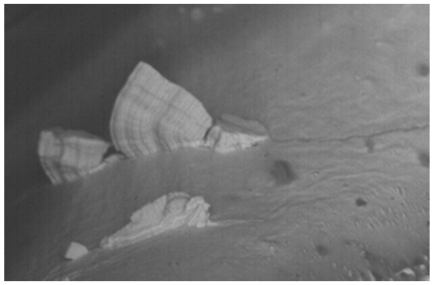
- Electrical short circuits
  - Intermittent if current is more than 10s of mA
  - Permanent if current is less than 10s of mA
  - Can cause erratic electrical system operation
    - Found in accelerometer pedal assemblies (H. Leidecker, L. Panashchenko, J. Brusse, “Electrical Failure of an Accelerator Pedal Position Sensor Caused by a Tin Whisker and Investigative Techniques Used for Whisker Detection”)
- Debris/Contamination
  - Interferes with optical paths and MEMS
- Metal Vapor Arc
  - Whisker shorts can vaporize into a conductive plasma able to conduct hundreds of amps.

Whiskers: Description



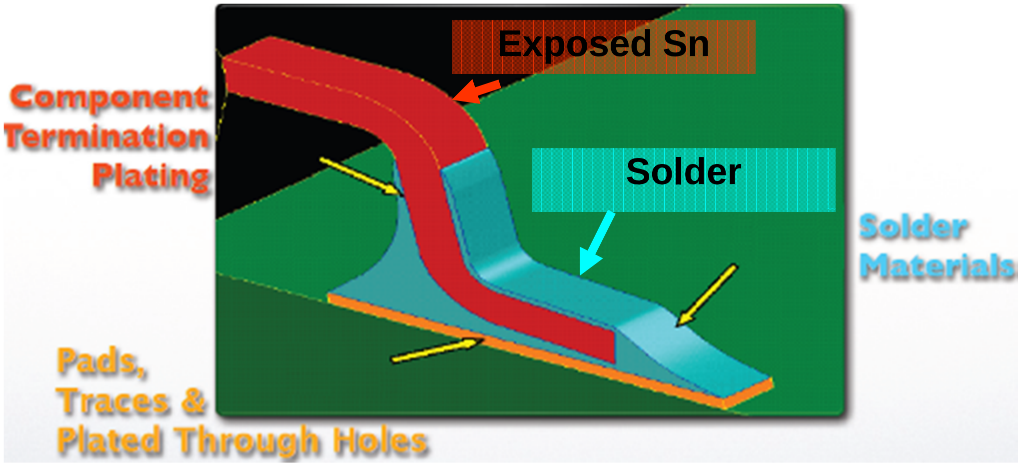
- Metals that grow whiskers include
  - Tin, Zinc, Cadmium
- Metallic whiskers are crystalline filamentary structures
- Grow outward from metal surfaces
- More commonly found in electrodeposited Sn coating and Sn based alloys
- Shape
  - Filaments
    - Straight
    - Kinked
    - Spiral
  - Nodules
  - Odd-shaped eruptions
- Typical length strongly dependent upon circumstances
  - No whiskers, 10 µm, 500 µm, 1 mm, 10 mm, 25 mm
- Typical thickness – 0.5 to 50 microns
- Whisker density varies greatly – no whiskers to over 1000 mm^2

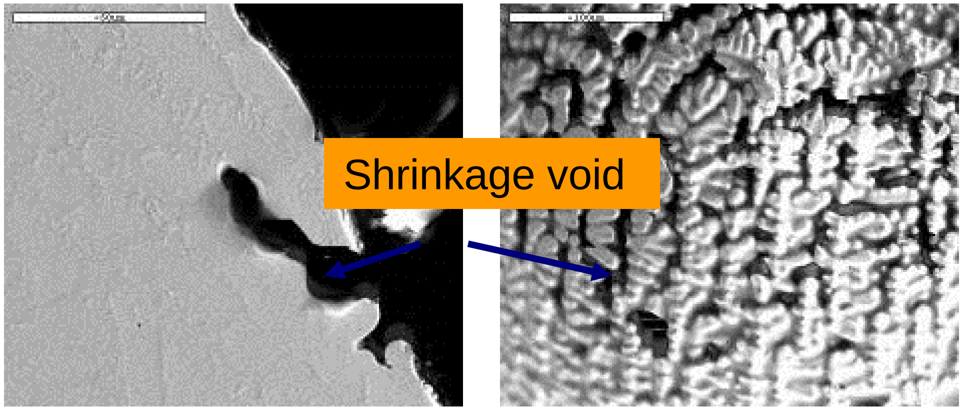




Whiskers in Pb-free solder joints

- No lead(Pb) in electroplated Sn finish – *propensity for whisker formation*
- Poorer wetting – *more exposed Sn plating for same type of components*
- More aggressive fluxes to improve wetting – ionic contamination, oxidation and corrosion *promoting whisker growth*
- Sn-Ag-Cu solder – *what about whisker growth?*
    - Rough surface – trapped contamination, difficult to clean – *higher propensity to whisker*



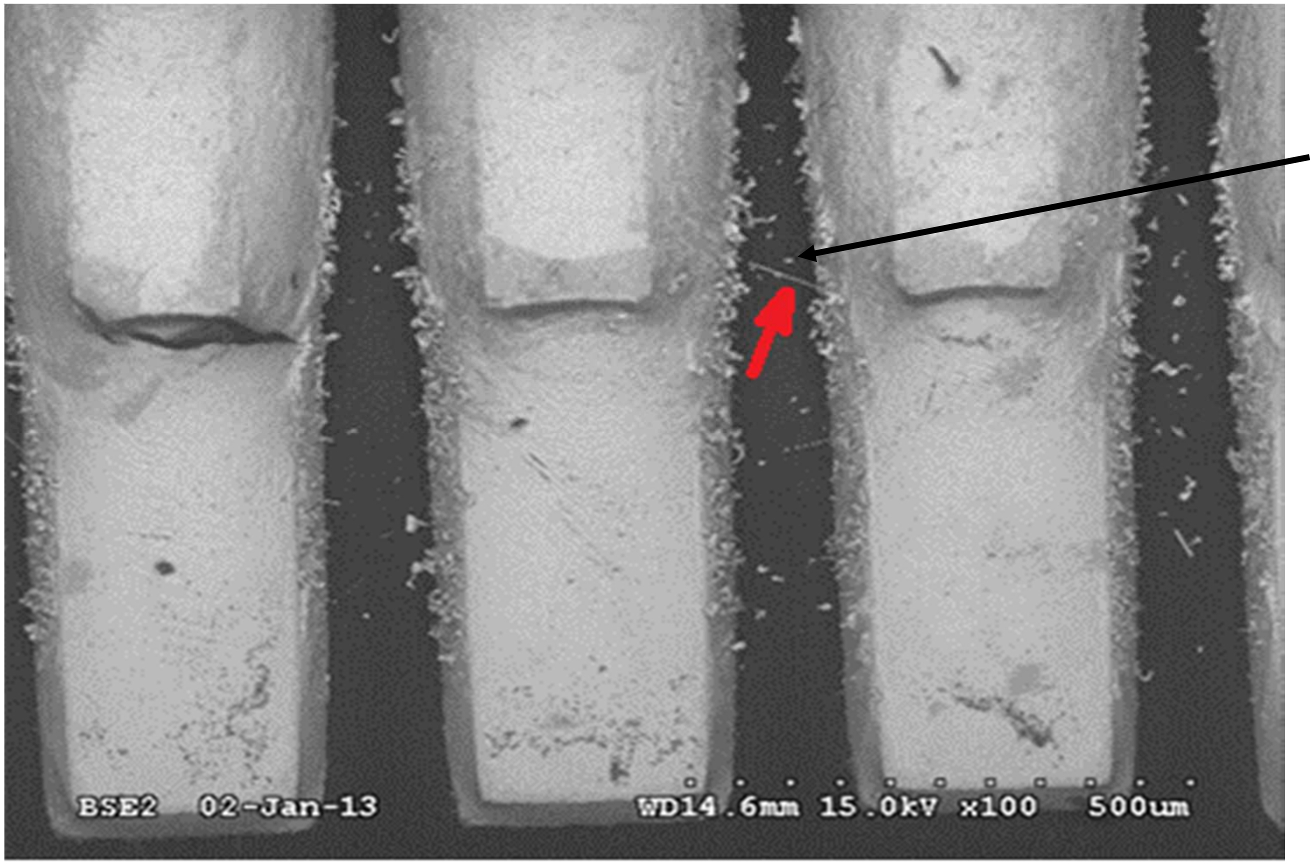


cross-section

top view

Lead-free solder joint roughness, SEM

Whiskers in Pb-free solder joints

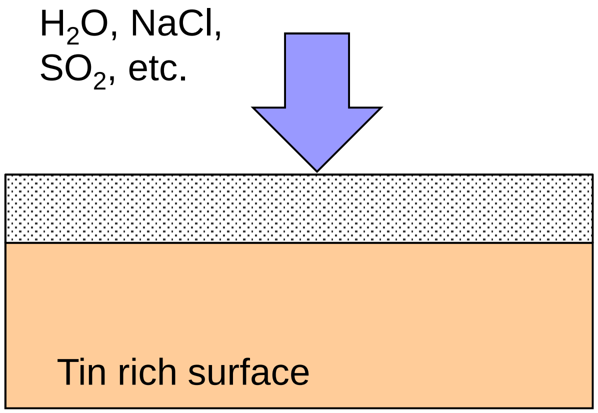


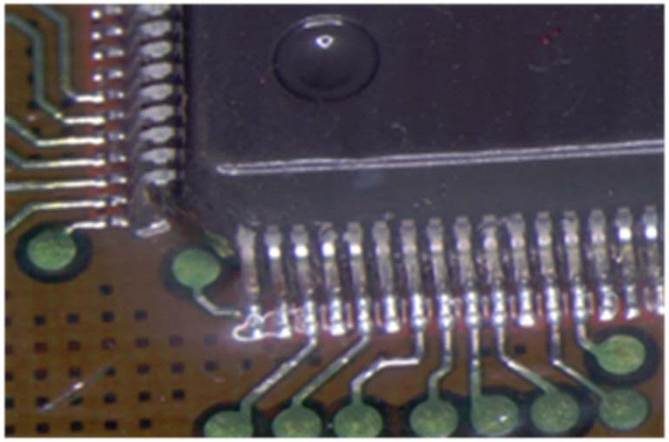
If assembly
was coated,
this region
would be
well covered

64 pin thin quad flat pack, 0.4 mm pitch
Cleaned part before assembly and cleaned after soldering
4,000 hours at 85ºC/85%RH

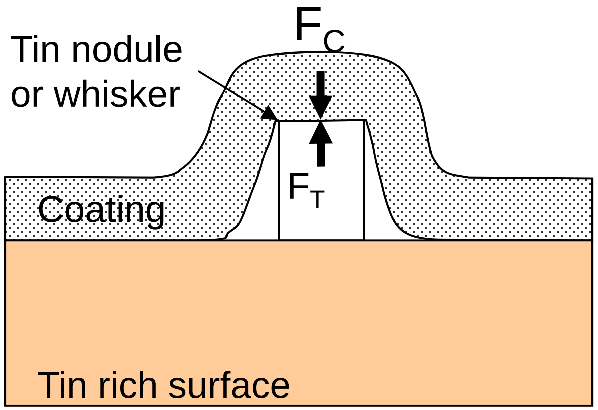
Coating whisker mitigation

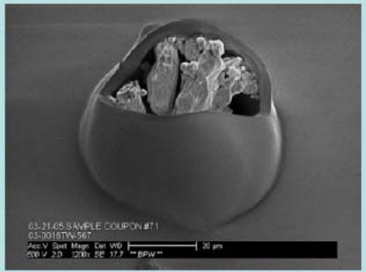
Reducing corrosion





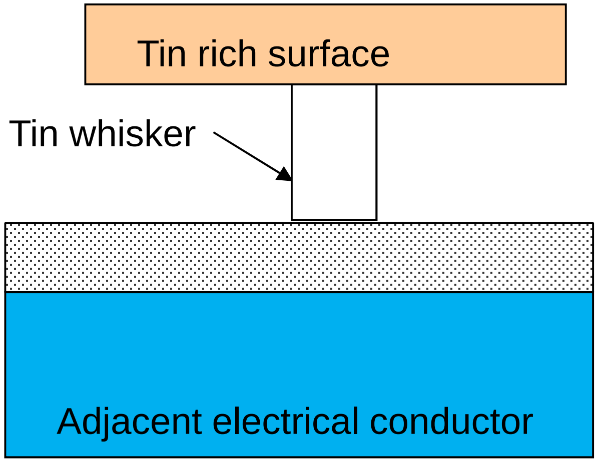
Containing whiskers

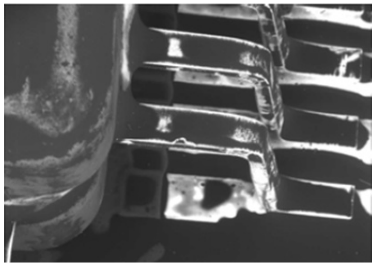




Whiskers puncturing silicone coating
(Woodrow 2006)

Preventing contact





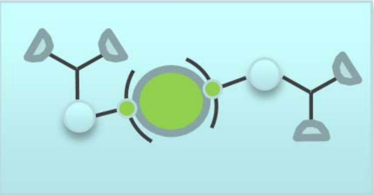
Coverage thin on corners
and vertical surfaces (CALCE 2010)
(light areas =thin coating)

Decades of coating use in Aerospace and Defense for moisture protection

WP2213 Project nanoparticle enhanced coating improvement effort

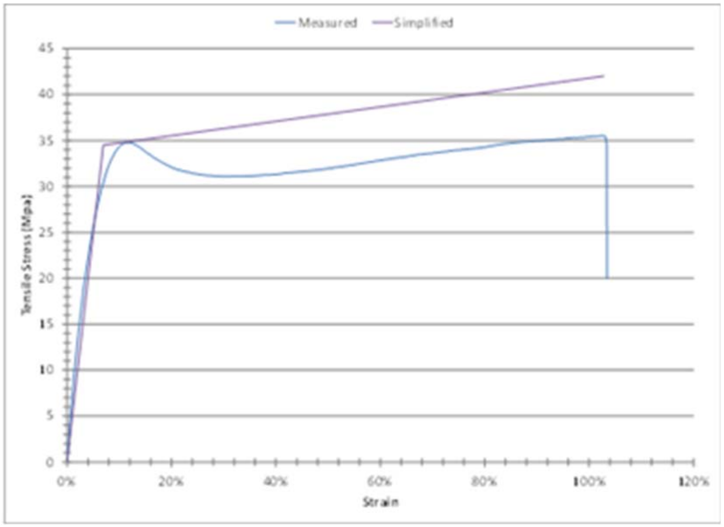
Functionalized nanosilica particles:

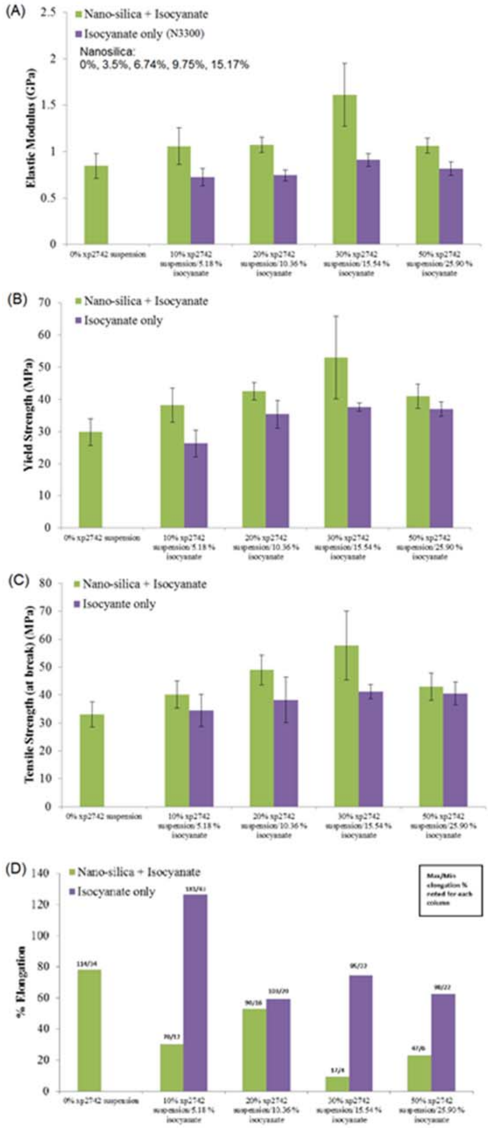
Chemically bound to urethane resin



Sub-micron particles have smaller impact on viscosity than micron sized particles

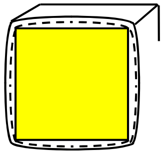
Coating strength improvement





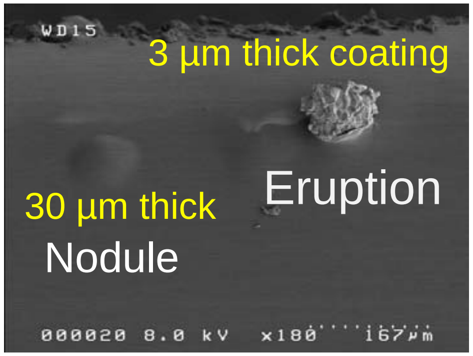
Coverage improvement

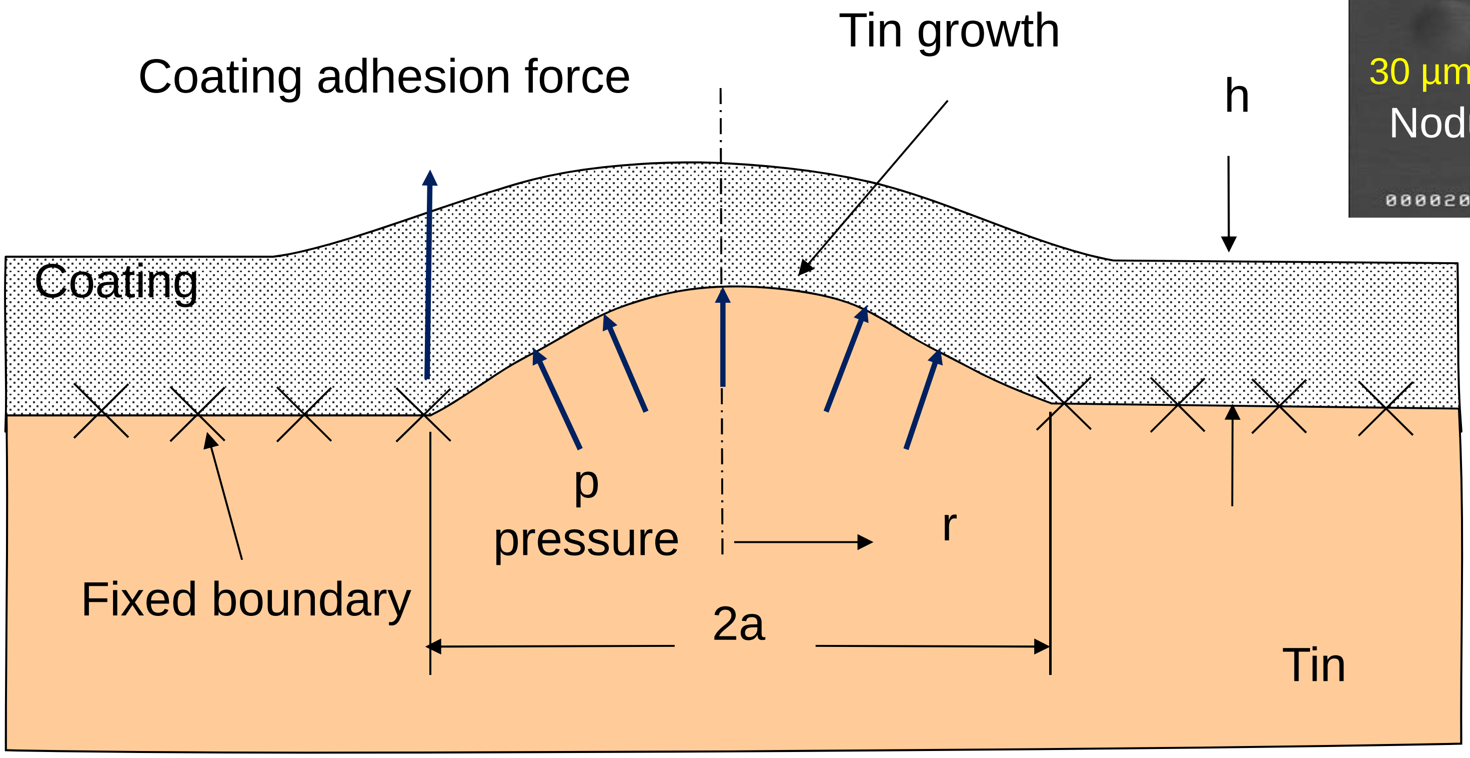
Improved corner coverage with multiple dips



Improved mechanical/physical properties → reduce whisker penetration

WP2213 Whisker mitigation modeling



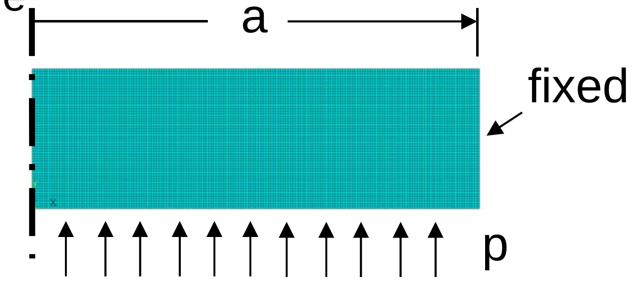


Tin nodule forms a dome under coating
pressure = tin yield strength

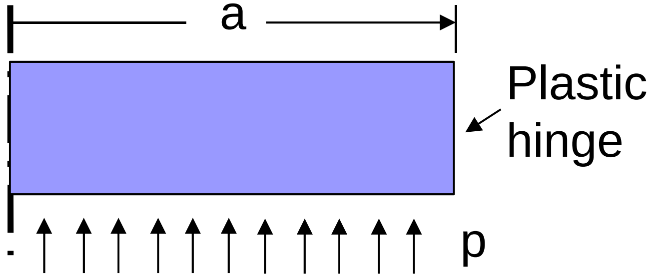
Coating rupture and coating delamination determined for a combination of nodule size, coating strength, modulus and thickness

WP2213 Whisker mitigation modeling: Three approaches

A. Rupture: Non-linear finite element analysis (FEA) to calculate the deflection in the coating to determine if the coating will rupture



B. Rupture: Classical non-linear (plastic hinge) analysis to determine the deflection in the coating at rupture for comparison to FEA



C. Delamination: Classical analysis to determine the energy release rate to delaminate the coating to determine in the coating will blister

Deflection → Coating energy → Energy release rate

Critical pressure found where solutions become unstable
Rupture or delamination point

WP2213 Whisker mitigation modeling: Three approaches

B. Classical non-linear (plastic hinge) analysis to determine the deflection in the coating for comparison to FEA

$$p_{crit} = \frac{8 \cdot \sqrt{3} \cdot h^{2} \cdot \sigma_{crit}}{3 \cdot a \cdot \sqrt{\left[9 \cdot (\nu - 1)^{2}\right] \cdot a^{2} + 16 \cdot K_{s}^{2} \cdot h^{2}}}$$

K_s used for displacement correlation to FEA

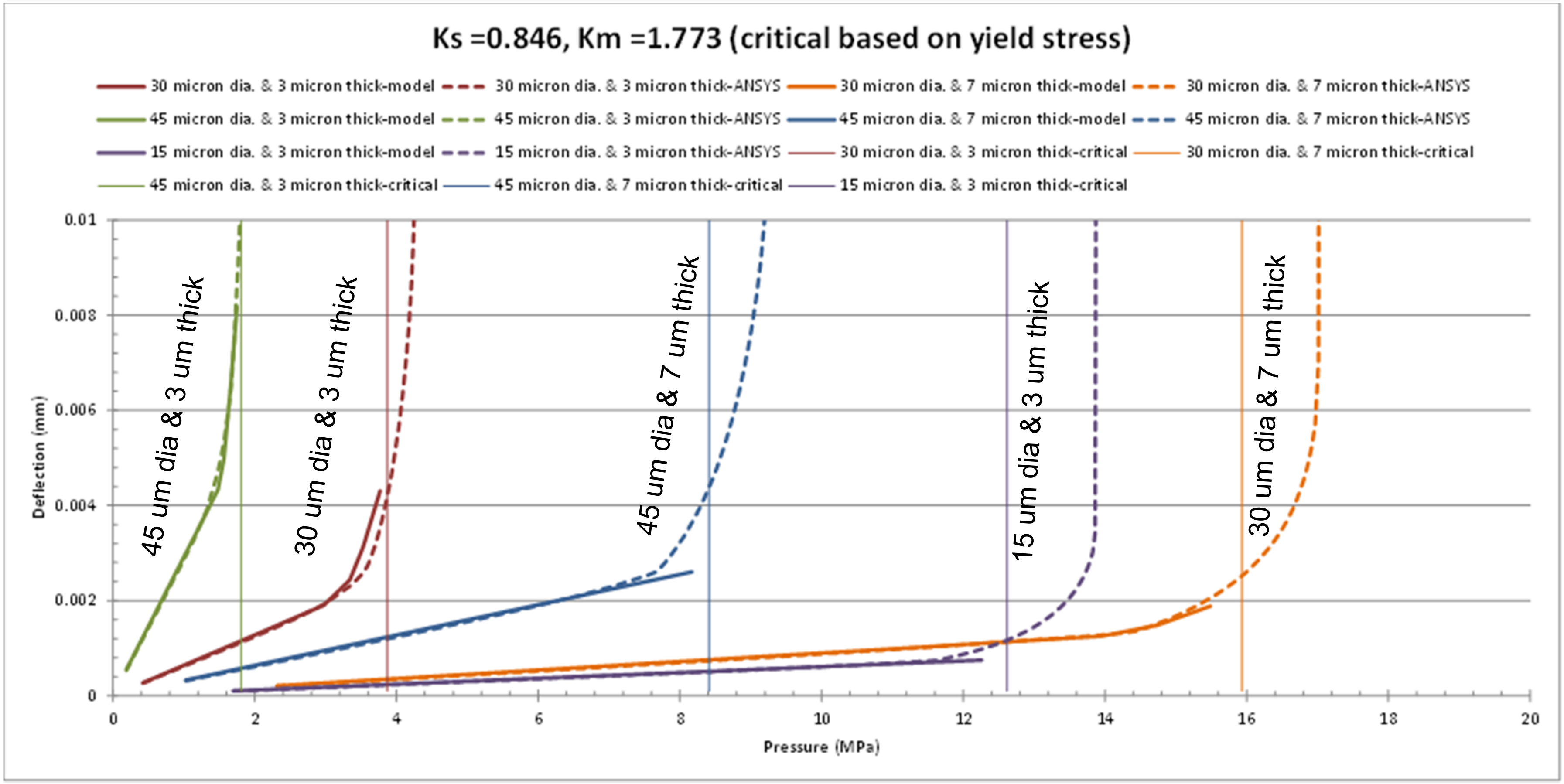
WP2213 Whisker mitigation modeling: Three approaches

C. Classical analysis to determine the energy release rate to delaminate the coating to determine in the coating will blister

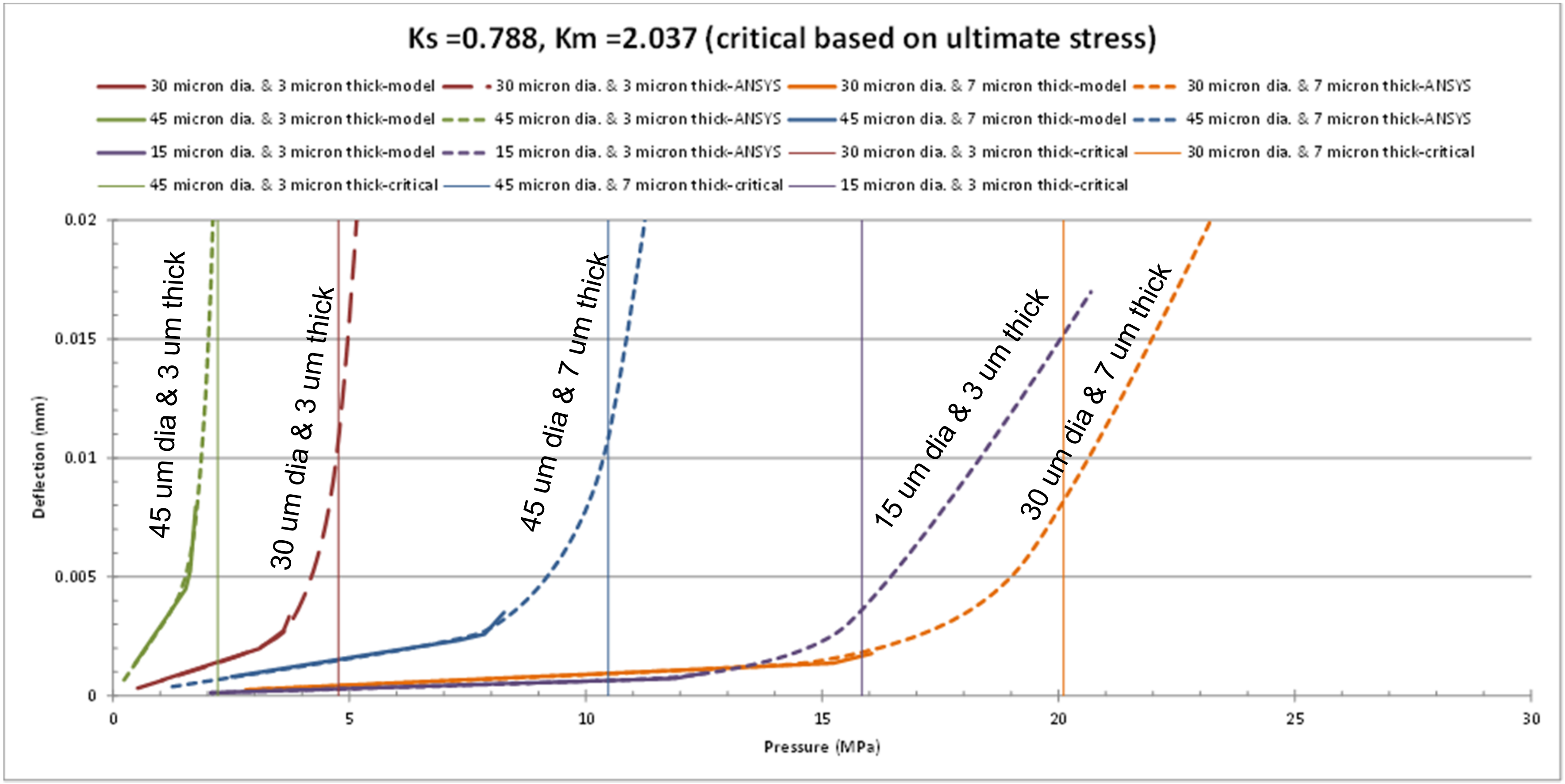
$$G = \frac{a^2 \cdot p^2 \cdot (\nu + 1) \cdot \left(a^2 - a^2 \cdot \nu + 6 \cdot h^2\right)}{16 \cdot E \cdot h^3}$$

Energy release rate during delamination
→ Experimentally measured

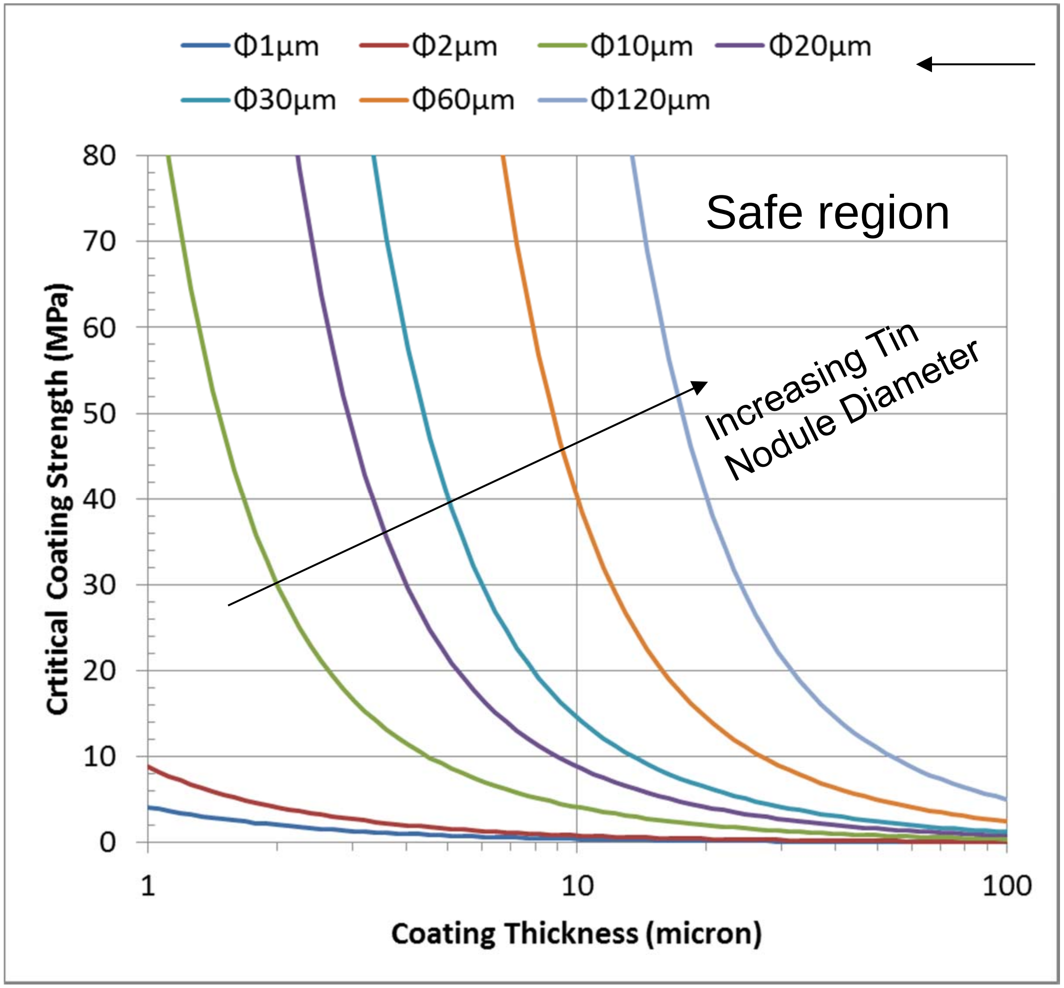
Comparison of elastic/perfectly plastic FEA and classical models



Comparison of maximum tensile at maximum elongation FEA and classical models



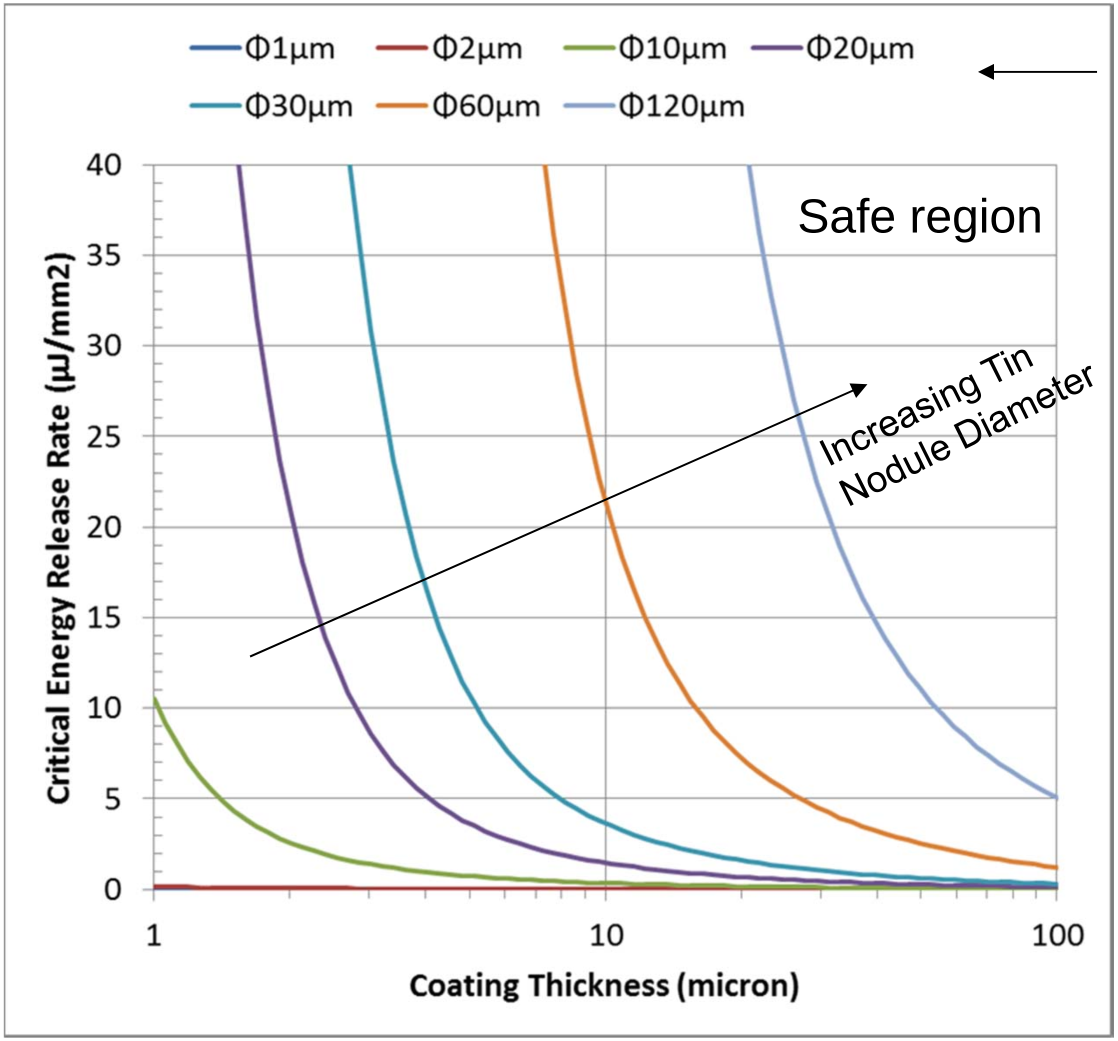
Critical coating strength required versus coating thickness



Nodule/Whisker Diameter

Larger nodule requires greater coating strength or thicker coating

Energy release rate required versus coating thickness

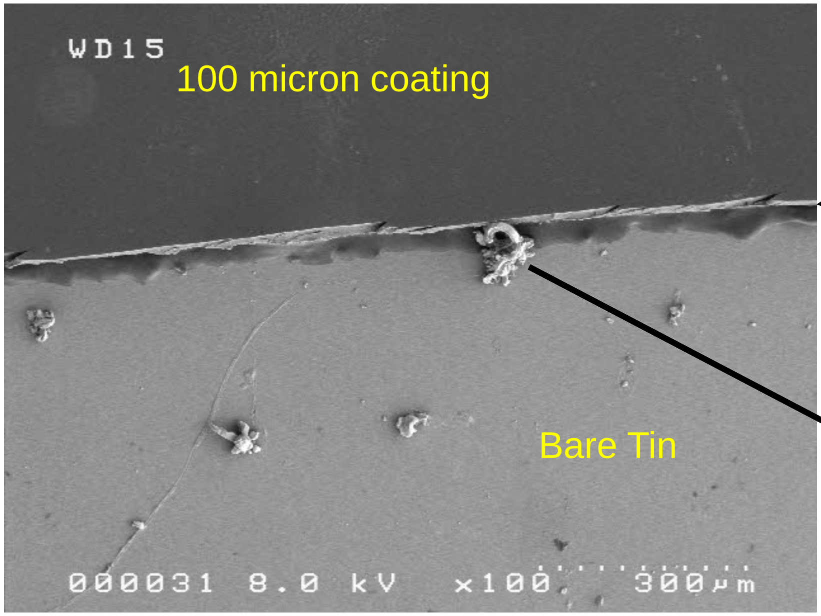


Nodule/Whisker Diameter

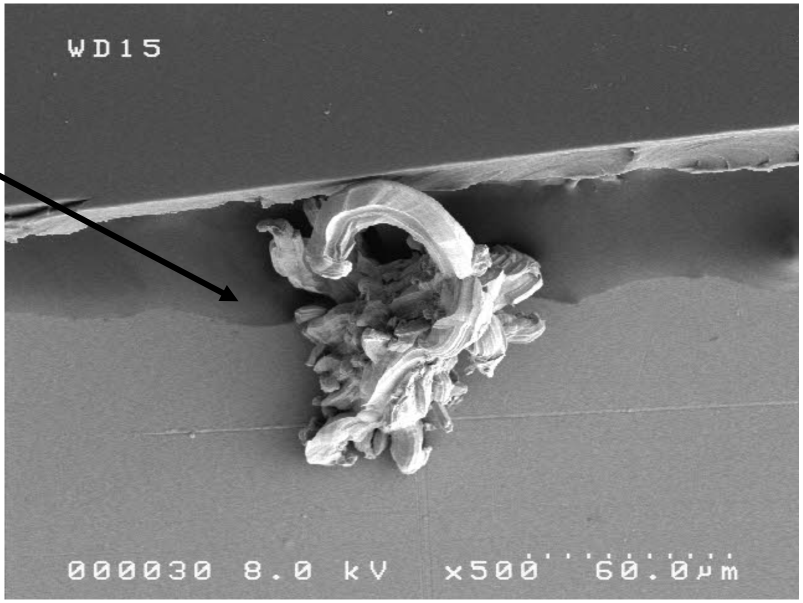
Larger nodule requires greater coating adhesion or thicker coating to prevent delamination

A simple experiment

Bright tin: 20 micron thick
Substrate: C110 copper
Coating: PC18M+30%XP2742 Draw coated
Coating thickness: 100 microns thinned to ~3 microns at inner corner
Exposure: 2,500 (500+2,000) hours 60°C/60%RH

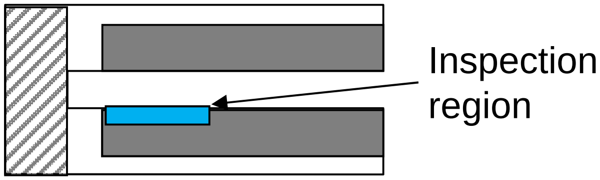


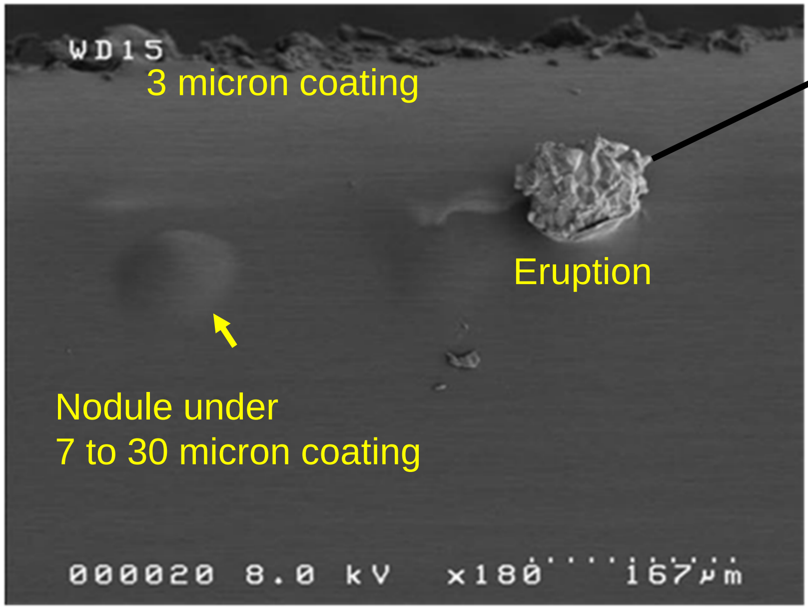
Tape line (Tape used as draw coating spacer)

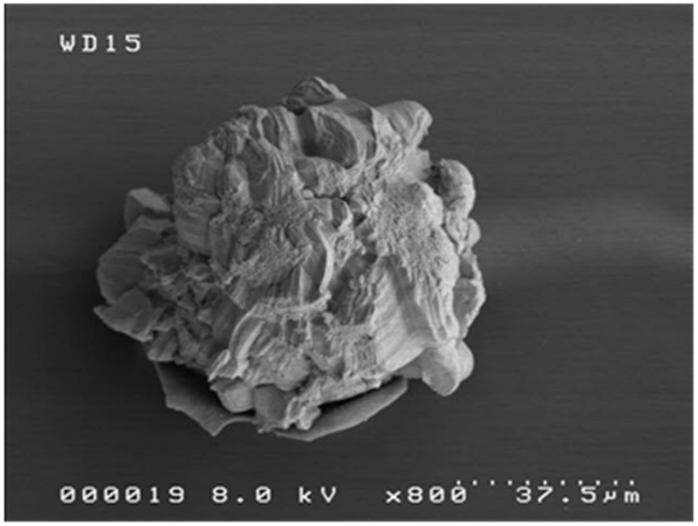


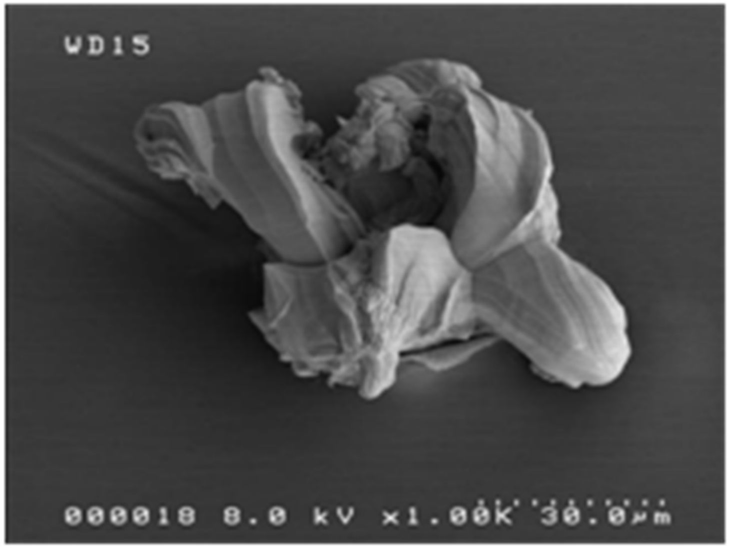
Whisker and nodule growth observed in bare tin area

Nodules and eruptions in thinner coating areas



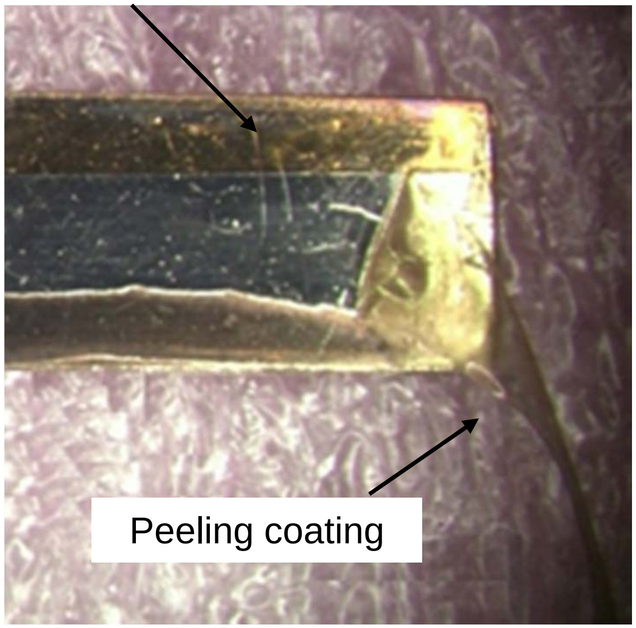






Inspection after coating removal

Original bare Sn (discolored)



Sn under dissolved coating

Peeling coating

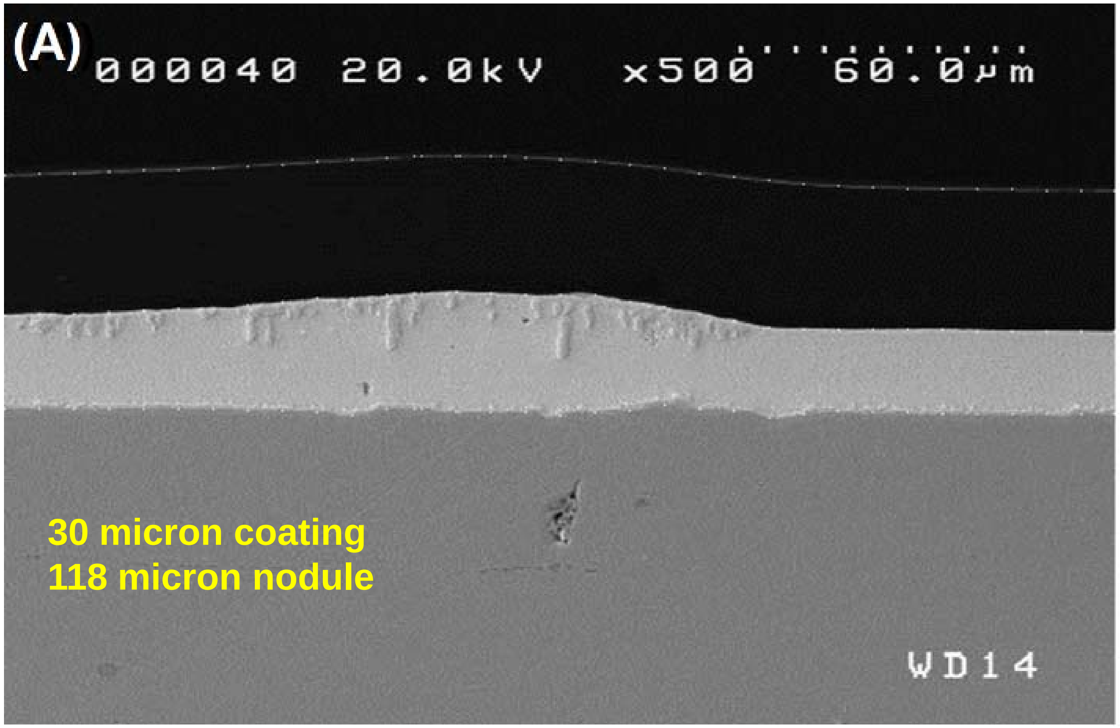
Dissolved coating with Uresolve™ solvent

Original bare Sn

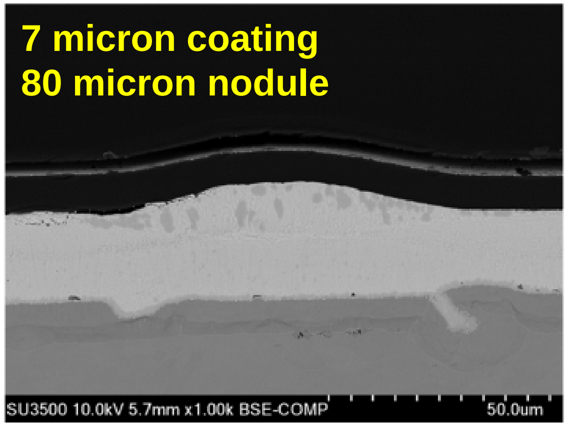
Sn under dissolved coating

Few or no nodules or whiskers under 100 micron coating area

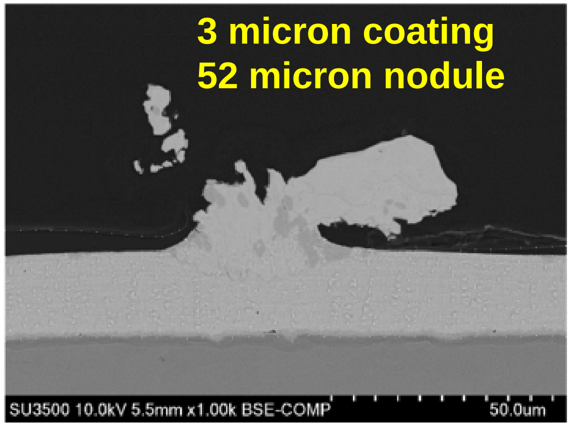
Cross-sections



30 micron coating
118 micron nodule

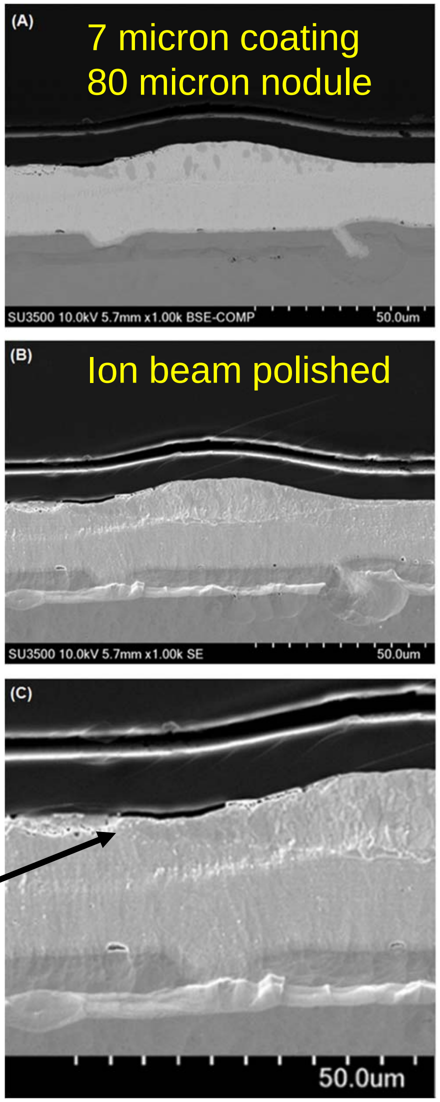


7 micron coating
80 micron nodule



3 micron coating
52 micron nodule

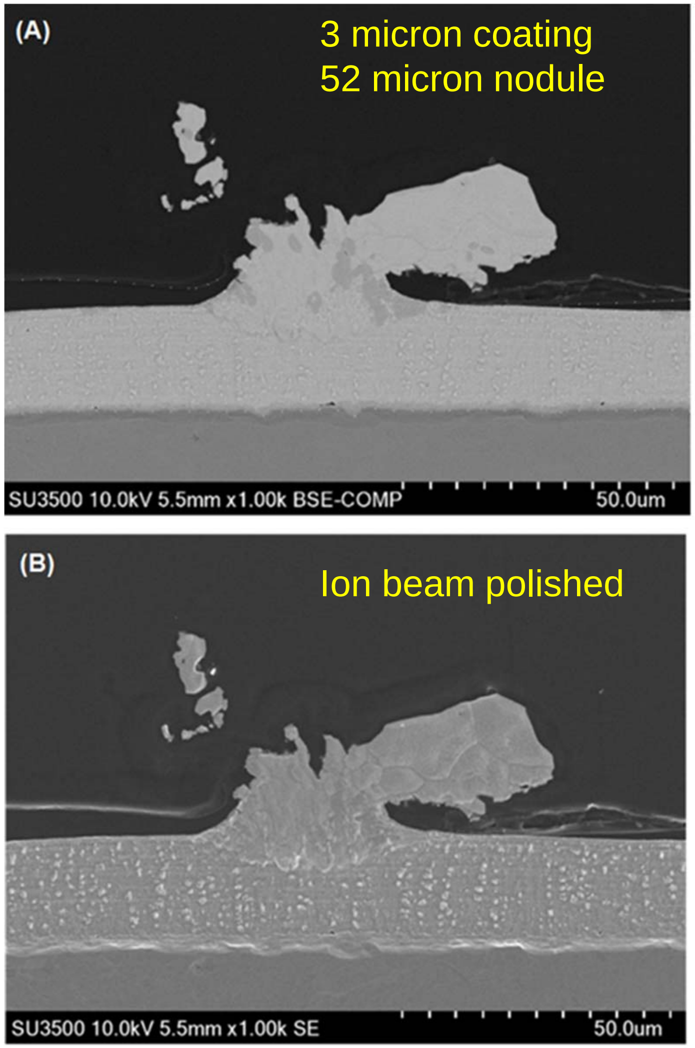
A Simple Experiment



7 micron coating
80 micron nodule

Ion beam polished

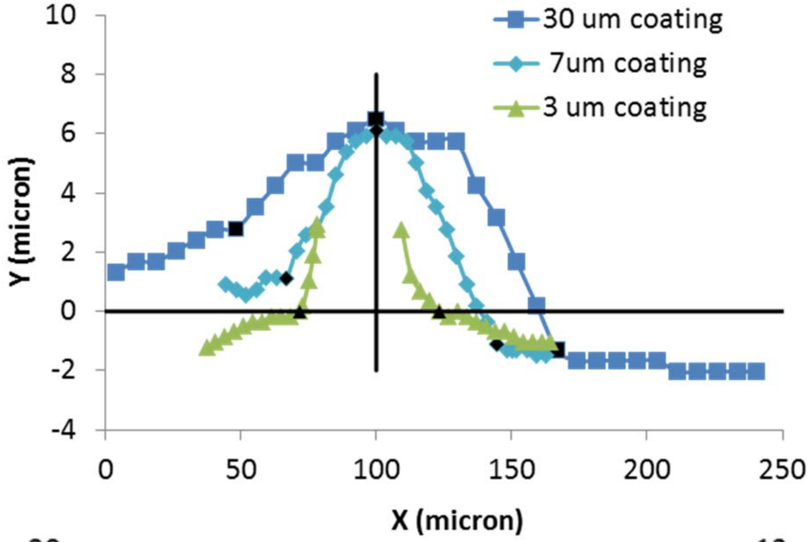
Delamination

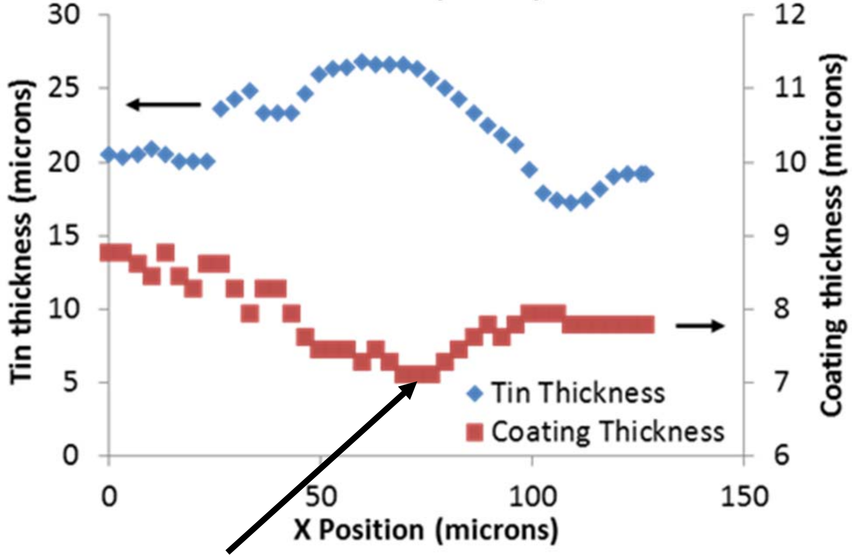


3 micron coating
52 micron nodule

Ion beam polished

A Simple Experiment

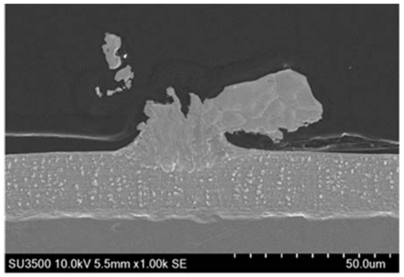




Thinned coating

Nominal coating thickness	Average coating thickness in flat region (microns)	Minimum coating thickness at top of dome (microns)	Dome diameter (microns)	Dome height (microns)
3 um	3.4	Ruptured	51.6	Ruptured
7 um	8.2	7.1	79.5	6.8
30 um	30.2	28.5	118.5	5.7

Critical coating strength required versus coating thickness



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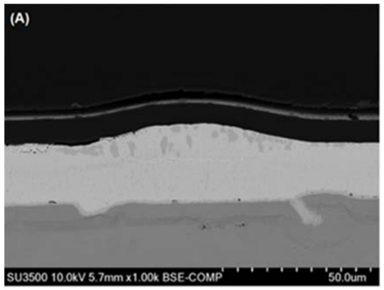

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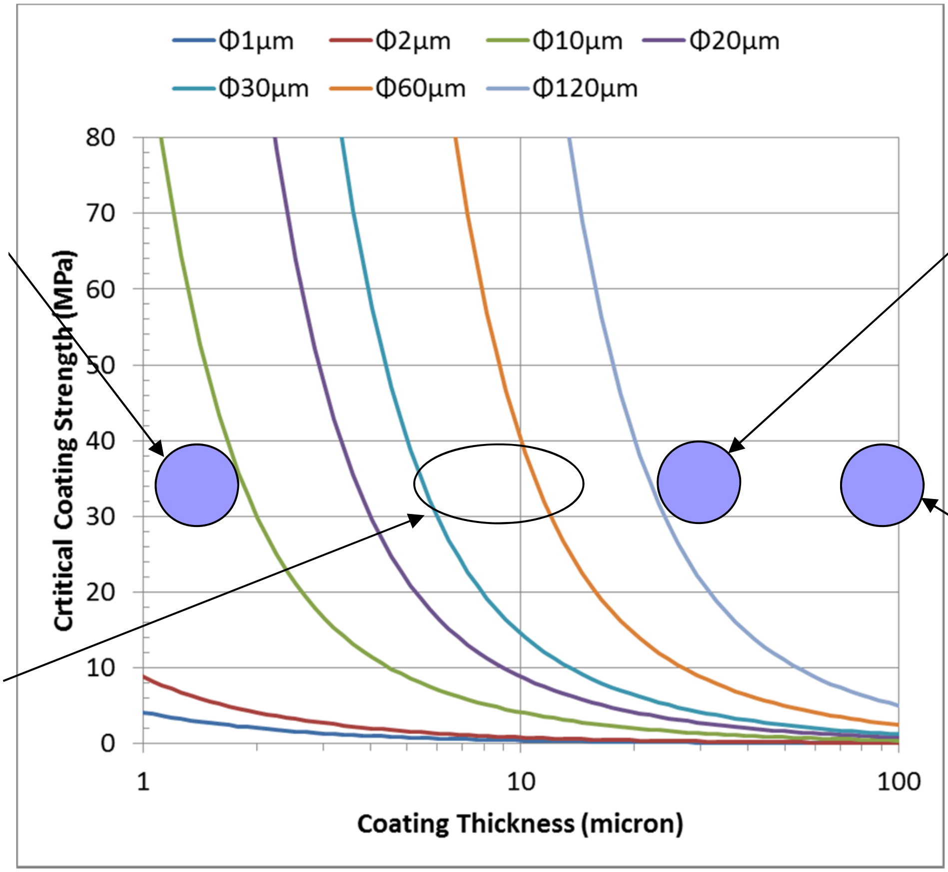
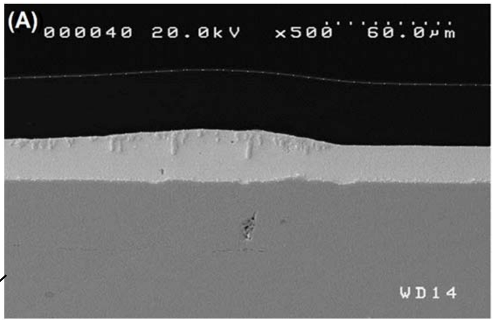


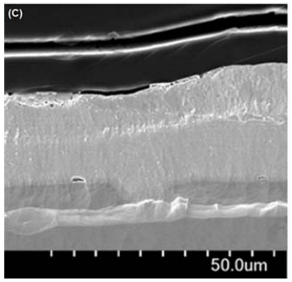


30 micron coating
118 micron nodule

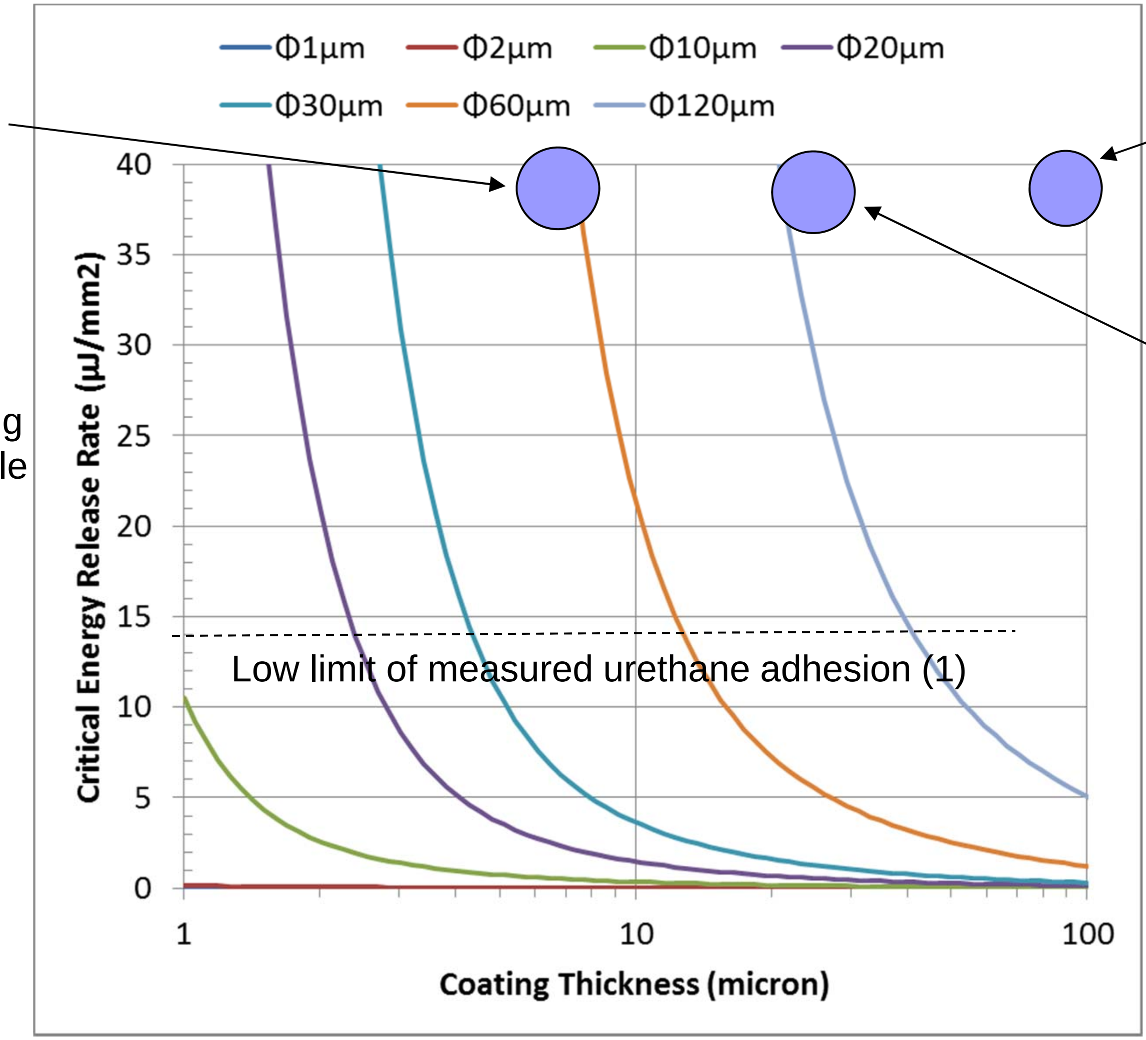
No nodules under 100 micron coating

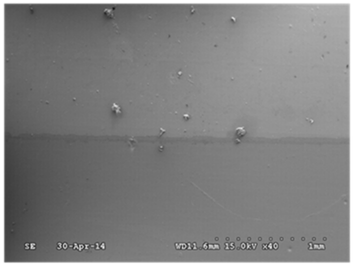
Larger nodule requires greater coating strength or thicker coating

Energy release rate required versus coating thickness

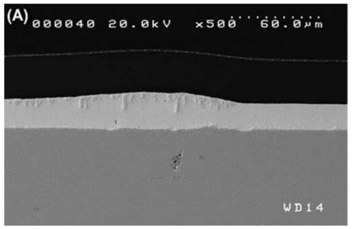


Delamination
7 micron thick coating
With 58 micron nodule





100 micron thick coating
No nodules



30 micron coating
118 micron nodule

(1) urethane-epoxy interface failed before urethane-tin interface

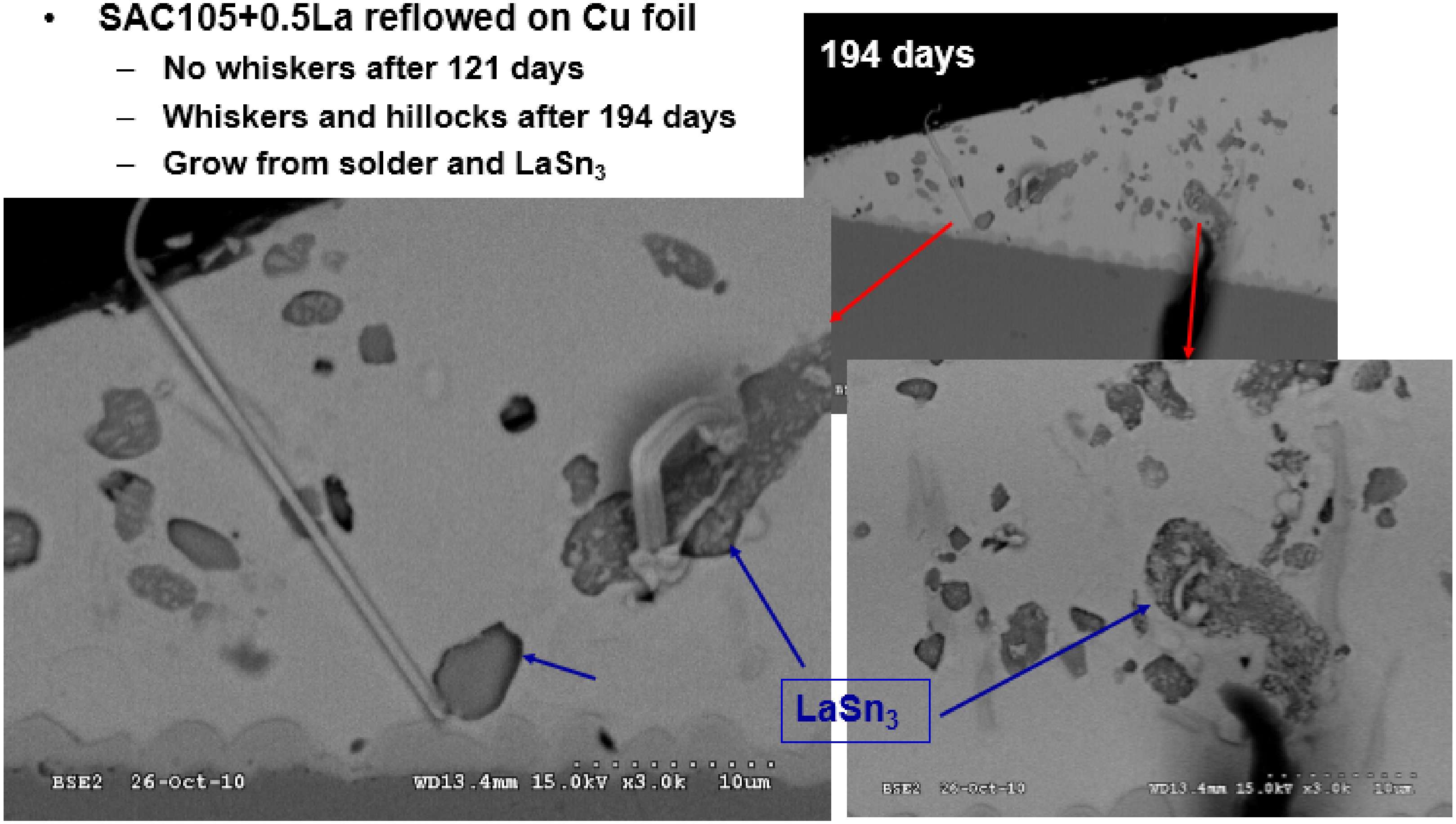
Conclusions

- The FEA modeling predicted rupture of a three micron thick coating which was consistent with the rigid coating experimental observations.
- Energy release rate results also indicate that delamination of a 100 micron coating thickness is unlikely for typical whisker diameters.
- There is a combination of coating thickness, strength and adhesion that can provide whisker mitigation
- In contrast to smaller diameter whiskers, larger diameter tin nodule formations have greater potential to rupture the coating
- The whisker growth surface stress relaxation phenomena causing formation of the tin filament structure is altered in the presence of a coating having high adhesion, high strength, and sufficient thickness
- Note: Although rigid coatings can inhibit tin nodule/whisker formation they need to be evaluated for potential impacts to solder joint thermal cycling fatigue reliability

QUESTIONS

Whiskers From Solder Joint Cross-sections in N_2 Chamber

- SAC105+0.5La reflowed on Cu foil
  - No whiskers after 121 days
  - Whiskers and hillocks after 194 days
  - Grow from solder and $LaSn_3$



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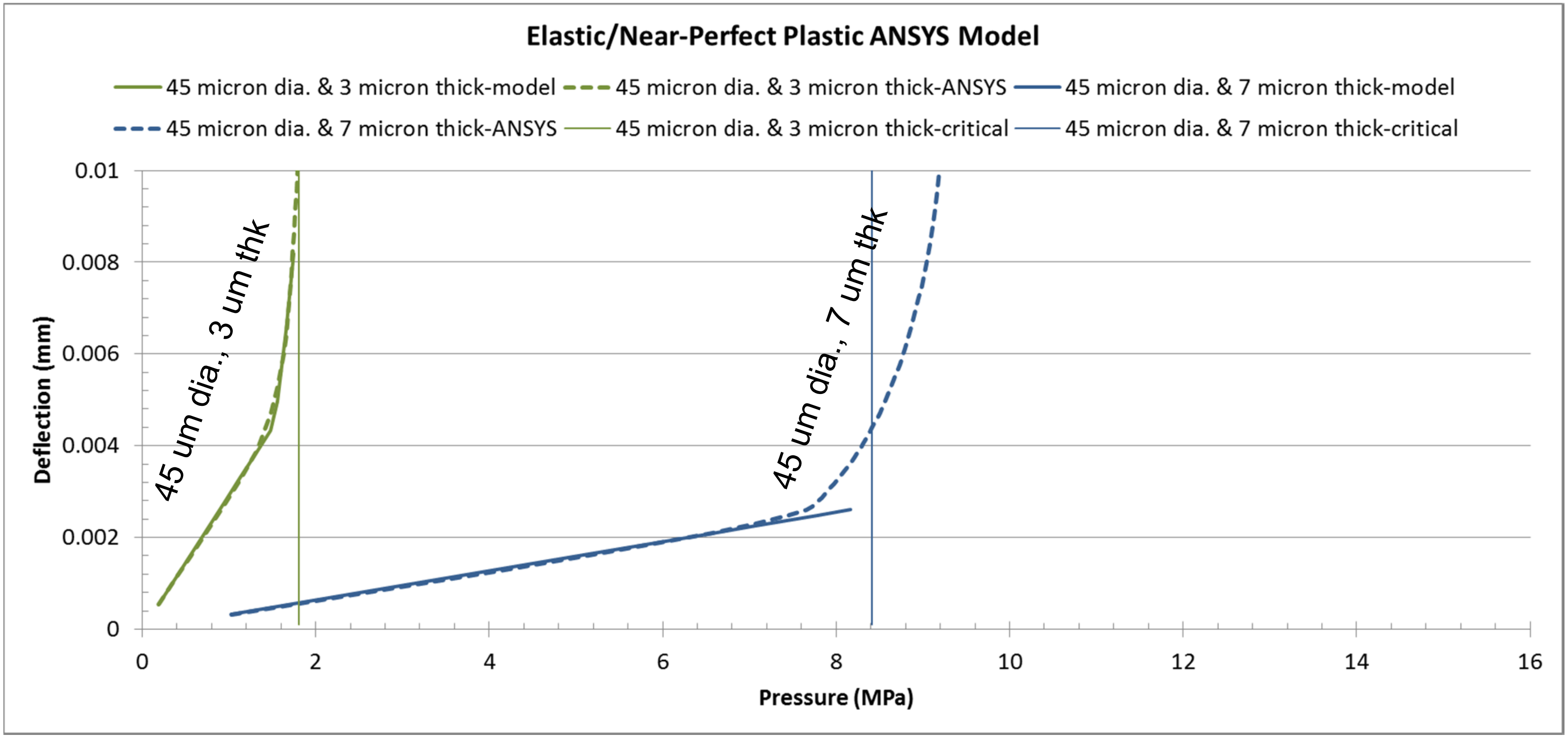
Comparison of elastic/perfectly plastic FEA and classical models



Comparison of elastic/perfectly plastic FEA and classical models