Whisker Penetration into Conformal Coating

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Abstract
Tin whiskers are needle-like crystals of tin growing from pure tin or high-tin alloy surfaces, which may grow long enough to cause electrical shorts. Conformal coatings provide some protection against these shorts, partly by suppressing or slowing whisker growth, but primarily by deflecting or buckling a whisker growing from an opposing surface. The longer an unsupported cantilevered whisker, the more likely it is to bend or deflect. This paper addresses the capability of a whisker to penetrate an adjacent coating, and does not consider the effect of a coating on the propensity for whisker growth. In the present work, an analysis was conducted to determine the critical spacing between coated conductors below which a whisker is likely to penetrate the conformal coating on the adjacent conductor and cause a short. The analysis is based on the critical buckling force of an angled whisker using two different boundary conditions: fixed at one end where the whisker slides along the coating surface, or fixed at one end and hinged at the other, where friction prevents the whisker from sliding. By using the critical compressive strength of the coating (derived from Durometer measurement) and the area of the whisker tip, the critical force needed to penetrate the coating is determined and compared to the tin whisker buckling force. The computed compressive force that is required for the whisker to penetrate the coating can be considerably less than if the coating is assumed to behave elastically. By solving the buckling relationship for whisker length at various whisker angles, the minimum coated-conductor spacing is determined as a function of whisker angle. Then, by comparing the computed spacing-angle relationship with published data on the distribution of whisker angles, the minimum expected (mean) coating gap can be determined, in addition to the absolute minimum gap. Based on this analysis, whisker re-penetration is unlikely for components with lead pitch of 1.27-mm and above, though risk is higher for fine-pitch components with some "soft" coatings.

Introduction
Tin whiskers are elongated crystals of pure tin that can grow from tin plated surfaces (see Figure 1). These whiskers can be up to 10 mm long and 10 microns in diameter, but are typically less than 1 mm long and 3 microns in diameter [1]. In addition, in some cases conformal coating can be used to mitigate the deleterious effects of tin whiskers [2]. Many electronic assemblies use conformal coating to protect conductors from liquid moisture and foreign objects. In most cases, a problem would occur when a tin whisker contacts an uncoated surface or penetrates the coating of a coated surface. This paper addresses the propensity for a tin whisker to penetrate a conformal coating from outside the coating surface.

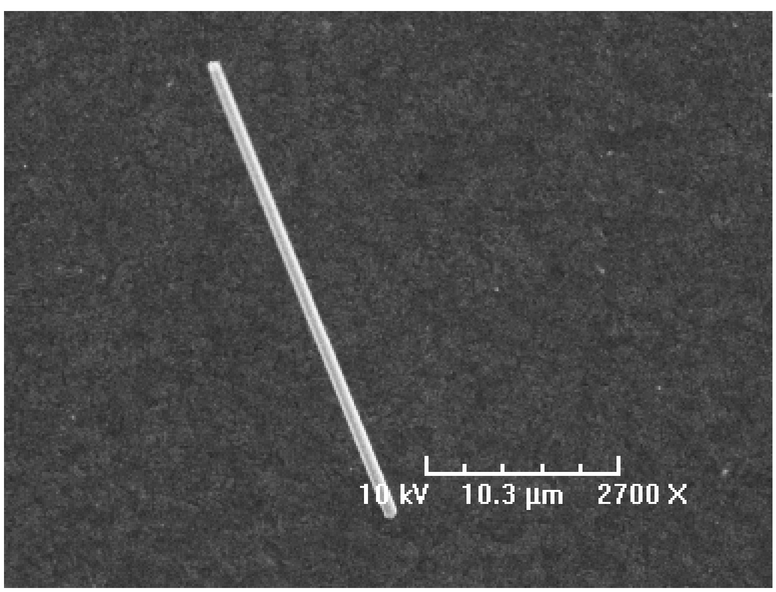

Figure 1 - Tin Whisker (from BAE Systems)

This analysis is based on buckling of an angled whisker that is fixed at the source surface, and either (1) slides along the destination coating surface, or (2) is hinged at the destination where there is sufficient friction that the whisker doesn't slide.

Using readily available Durometer (hardness) data for the coating as a representation of the critical stress, the product of this stress and the area of the whisker tip determine the force. The critical coating force is compared to the critical buckling force of the whisker at the two boundary conditions. By solving the buckling relationship for length, the minimum spacing to avoid penetration of the coating is determined. Although 1.27-mm pitch components are at minimal risk for whisker re-penetration, this is not the case for fine pitch (0.635-mm) components with some of the softer coatings.

Analytical Development

In this work, a straight tin whisker is considered to bridge the gap between two coating surfaces spaced by a distance (s). The whisker originates from a source surface (lower surface in Figure 2) and grows to a destination surface (upper surface in Figure 2). Once the whisker reaches the destination surface, it will either penetrate the surface or buckle.

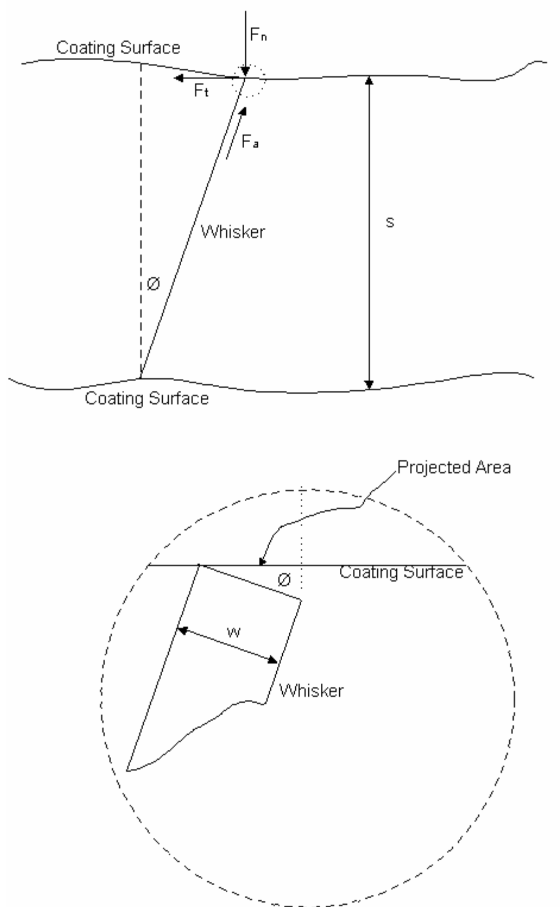

Figure 2 - Whisker Geometry

Friction Relationships

The whisker would be expected to slide along destination surface if the tangential force (F_t) due to the whisker is greater than the friction force. Using standard friction relationships, sliding will occur when the tangent of the angle of the whisker from the normal (ϕ) is greater than the coefficient of friction (μ). When sliding occurs, the normal force on the coating surface (F_n) is related to the axial force on the whisker (F_a) as follows:

$$F_a = F_n \cdot \cos(\phi) + \mu \cdot F_n \cdot \sin(\phi)$$

$$F_n = \frac{F_a}{(\cos(\phi) + \mu \cdot \sin(\phi))}$$

where ϕ is the angle of the whisker from the normal, and μ is the coefficient of friction. When sliding does not occur, the relationship between whisker axial and normal force is given by the geometry of the forces acting on the whisker tip:

$$F_n = F_a \cdot \cos(\phi)$$

Whisker Penetration

The normal stress (σ) in the destination coating at the whisker tip is determined by the normal force (F_n) and the projected whisker contact area (see
Figure 2) as given by the following equation: Where A is the area of the whisker tip.

$$\sigma = \frac{F_n}{A \cdot \cos(\phi)}$$

Substituting the normal force relationships from above, the relationship between stress and axial force (F_a) is obtained for the sliding and non-sliding cases respectively:

$$\sigma = \frac{F_a}{[(\cos(\phi) + \mu \cdot \sin(\phi)) \cdot A \cdot \cos(\phi)]}$$

$$\sigma = \frac{F_a}{A}$$

It is expected that penetration of the destination coating will occur when some form of inelastic deformation or yielding occurs. Defining a critical coating stress (σ_{cr}) that, if exceeded, will result in penetration of the coating, the critical whisker force that results in penetration (F_p) can be determined for the sliding and non-sliding cases:

$$F_p = \left[(\cos(\phi))^2 + \cos(\phi) \cdot \mu \cdot \sin(\phi)\right] \cdot \sigma_{cr} \cdot A$$

$$F_p = \sigma_{cr} \cdot A$$

Whisker Buckling

Whisker buckling can be calculated by classical buckling relationships of a cantilevered beam [3]. For the purposes of this study, it is assumed that the whisker has a fixed boundary condition at the source of the whisker. The boundary condition at the other end depends on the friction between the whisker and the destination coating as described above. If sliding occurs, the boundary condition is considered to be free. If sliding does not occur, the boundary condition is considered to be hinged. The critical buckling force (P_{cr}) for the fixed-free condition is given by the following relationship:

$$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{4 \cdot l^2}$$

Where E is the whisker elastic modulus, l is the whisker length, and I is the whisker moment of inertia. Similarly for the fixed-hinged condition:

$$P_{cr} = \frac{20.19 \cdot E \cdot I}{l^2}$$

Critical Spacing

By equating the critical buckling force (P_{cr}) and the critical penetration force (F_p), and expressing the whisker length (l) in terms of coating spacing, the critical spacing (s_{cr}) for sliding and non-sliding cases can be determined:

$$s_{cr} = \frac{\pi}{2} \cdot \sqrt{\frac{1}{[\sigma_{cr} \cdot A \cdot (1 + \mu \cdot \tan(\phi))]} \cdot E \cdot I}$$

$$s_{cr} = \cos(\phi) \sqrt{\frac{20.19}{(\sigma_{cr} \cdot A)} \cdot E \cdot I}$$

where ϕ is the angle from the normal, E is the modulus of elasticity, I is the moment of inertia and A is the cross-sectional area for the whisker, and σ_{cr} is the critical coating stress. For a square whisker cross-section, the above equations are expressed as follows:

$$s_{cr} = 0.45346 \cdot w \cdot \sqrt{\frac{E}{\sigma_{cr}} \cdot \frac{1}{(1 + \mu \cdot \tan(\phi))}}$$

$$s_{cr} = 1.297 \cdot w \cdot \cos(\phi) \cdot \sqrt{\frac{E}{\sigma_{cr}}}$$

Where w is the whisker width.

Material Properties

From the above equations, it can be seen that the only material properties determining the propensity for a tin whisker to penetrate a coating are the modulus of elasticity of the whisker and the critical coating stress. The whisker elastic modulus of 44.3 GPa is obtained readily from literature [4].

The critical coating stress is more difficult to determine, but a Durometer (Shore) hardness test [5] provides a reasonable estimate for a coating being penetrated by a whisker. In this test, a spring-loaded indenter is pressed into the test sample, and deflection is indicated on a 0 to 100 scale, with a reading of 100 representing zero deflection. The spring rate and indenter shape can be varied depending on the specific type of the test, as does the deflection at 0 reading. Typical readings are expected between 20 and 90, so the test type is selected to give readings in this range. The effective area of the indenter and the indenter force can be calculated for each Durometer reading/type based on the test specification, which can be used to determine the average indenter pressure (see
Figure 3).

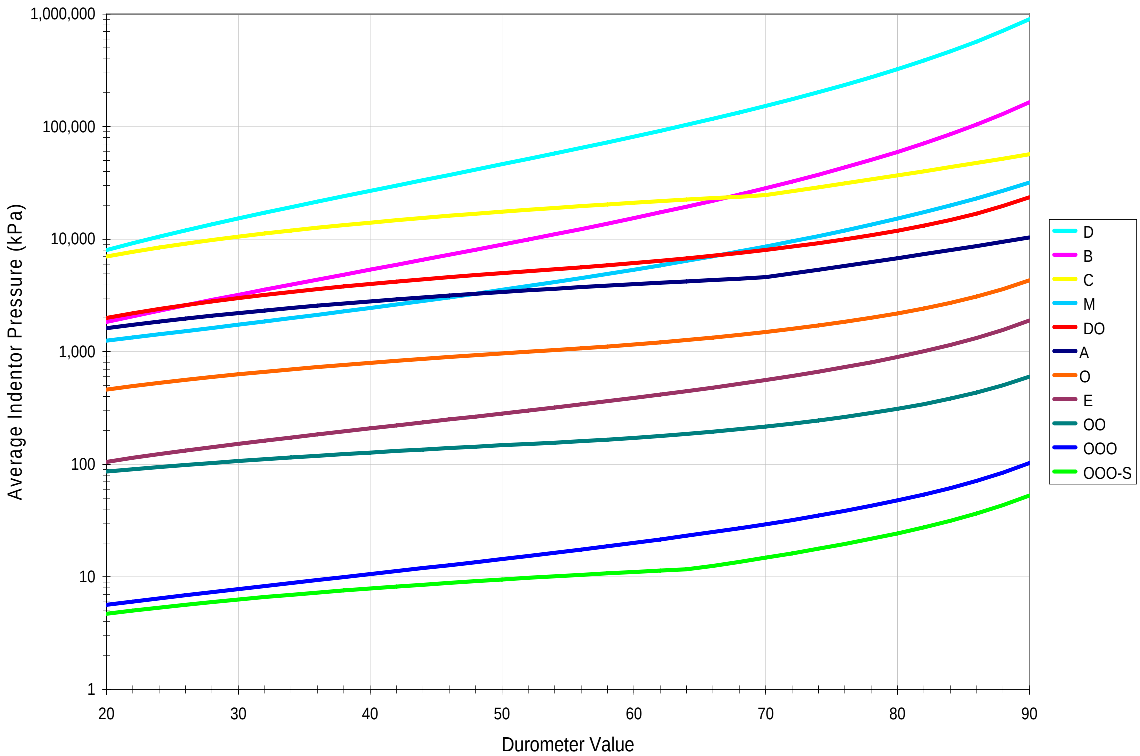

Figure 3 – Critical Stress/Pressure Values for Various Durometer Values/Types

Durometer values are readily available for a variety of conformal coatings. It is interesting to compare the deflection given by a linear model to that obtained form a Durometer test. Kadesh and Leidecker [6] provided the following equation for linear elastic penetration of a tin whisker:

$$D = \frac{\left(1 - \upsilon^2\right) \cdot F}{E_c \cdot d}$$

Where D is the deflection, F is the force, d is the whisker/indenter diameter, and E_c and υ are the elastic modulus and Poisson's ratio of the coating. By expressing the force in terms of stress and diameter, and solving for the ratio between deflection and diameter the following equation is obtained:

$$\frac{D}{d} = \frac{\pi}{4} \cdot \frac{\left(1 - \upsilon^2\right)}{E_c} \cdot \sigma$$

Where D/d is the deflection to diameter ratio, and σ is the coating stress.
By referring to the Durometer specification [5] the deflection to diameter ratio (deflection ratio) can be calculated for the corresponding pressure values described above (see

Figure 3). Using the above equation in conjunction with the critical coating stress and the coating stiffness, the deflection ratio can be calculated for the linear elastic case. Comparing the linear deflection ratio with that implied by the Durometer test gives an indication of the amount of yielding present for a variety of conformal coatings (see Table I). Although the yielding in Dymax 9-986 and Uralane 5750 is minimal confirming the linear approach of Kadesh and Leidecker [6], a Durometer/hardness-based approach is better for other coatings.

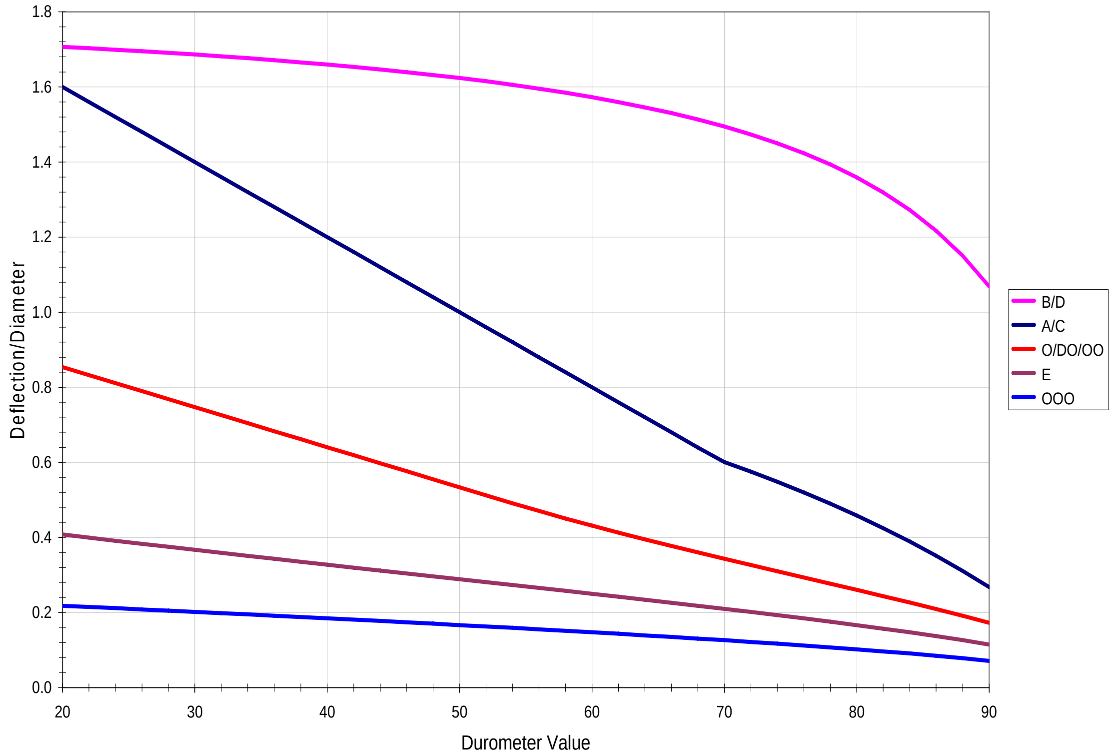

Figure 4 - Deflection/Diameter values for Various Durometer Values/Types

Table I - Coating Performance and Yielding

Coating	**Durometer**	**Critical Stress (MPa)**	**Stiffness Constant (MPa)**	**Deflection/Diameter Linear**	**Deflection/Diameter Durometer**
Uralane 5750 [6,10]	A50	3.39	3.05	0.87	1.00
Dymax 984 [7]	D80	324	455	0.56	1.36
Dymax 9-20557 [7]	D60	81.4	265	0.24	1.57
Dymax 9-986 [7]	A65	4.28	5.88	0.57	0.70
Aptek 7503 [8]	A55	3.69	6.44	0.45	0.90
Humiseal 1B31 [9,14]		11.60	65.77	0.14	0.18
			$\frac{E_c}{1-\upsilon^2}$		

Results

Using a coefficient of friction of 0.3, a whisker width of 3µm, and the critical stress values from Table I and Reference 11, the critical spacing is determined a variety of conformal coatings as a function of whisker angle. These results are plotted in Figure 5, it should be noted that the step in the curve is due to the transition between digging into the coating and sliding.

As expected, the worst-case condition occurs for a 0° (perpendicular) whisker. It is important to note that the critical spacing values refer to coating spacing and not conductor spacing. Combining the relationship between critical spacing and angle with published probability of whiskers at various angles [13] gives a mean critical conductor spacing. Mean and worst-case critical spacing values for the coatings of interest are summarized in Table II.

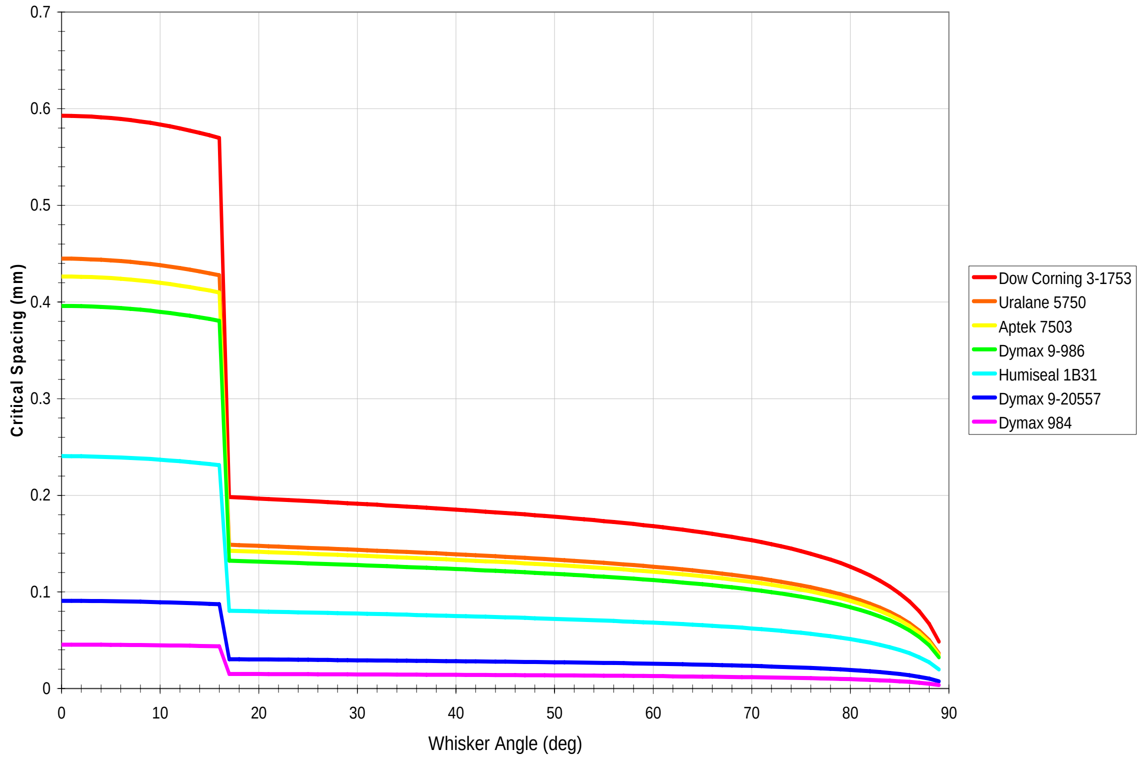

Figure 5 - Effect of Whisker Angle on Critical Spacing

Table II - Critical Spacing Values for Various Coatings

	Critical Spacing (mm)	
	Worst-Case	**Mean**
Uralane 5750	0.44	0.24
Dymax 984	0.05	0.02
Dymax 9-20557	0.09	0.05
Dymax 9-986	0.40	0.22
Aptek 7503	0.43	0.23
Humiseal 1B31	0.24	0.13
Dow Corning 3-1753	0.59	0.32

Conclusion

Although tin whiskers can have diameters up to 10 microns, the largest typical diameter is 3 microns [13], which is the value used in this study. Since smaller whiskers would buckle at lower forces, the values in Table II represent a worst-case typical condition. Coating spacing greater than the worst-case values in Table II would be extremely unlikely to result in a whisker-related short because any whisker would buckle before penetrating the coating. Conversely, spacing less than the mean values could experience coating penetration by whiskers and related electrical issues.

Although there is published information on the distribution of whisker lengths, there is little or no information on whisker diameters. A possible future study could develop a distribution of whisker diameters and combine with this approach to determine the probability of whisker buckling as a function of coating spacing.

As an example, a typical SOIC (small-outline integrated circuit) component has a lead pitch of 1.27 mm and a minimum lead spacing of 0.78 mm. A typical coating thickness of 0.075 mm on each surface would result in 0.63 spacing between the coating. This is larger than the worst-case value in Table II, so it would not be likely for a whisker to penetrate any of the listed coatings. A PQFP (plastic quad flat pack) component with a lead pitch of 0.635 mm and a minimum lead spacing of

0.229 mm could have a minimum coating spacing of 0.078 mm, which would be at risk for penetration for most of the listed coatings (except Dymax 984 and 9-20557). For such a component, additional measures should be taken to mitigate whisker growth.

References

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BAE SYSTEMS

Whisker Penetration into Conformal Coating – APEX 2007

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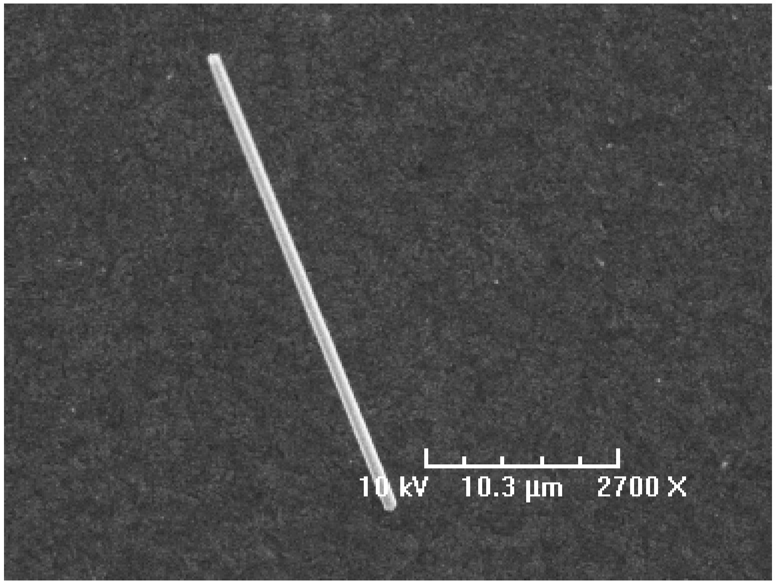
Outline

- Introduction/Background
- Analytical Development
- Material Properties
- Results
- Conclusion

Introduction/Background – What Are Tin Whiskers?

- Long crystals of pure tin
  - Grow from tin plated surfaces
  - Largest dimensions
    - 10 mm long
    - 10 µm dia.
  - Typically dimensions
    - <1 mm long
    - <3 µm dia.
- Problem would occur…
  - Tin whisker contacts an uncoated surface
  - Penetrates the coating of an adjacent coated surface



Whiskers Can Breach A Coated Surface

- Conformal Coat does not stop whisker growth, it only seems to slow them down.

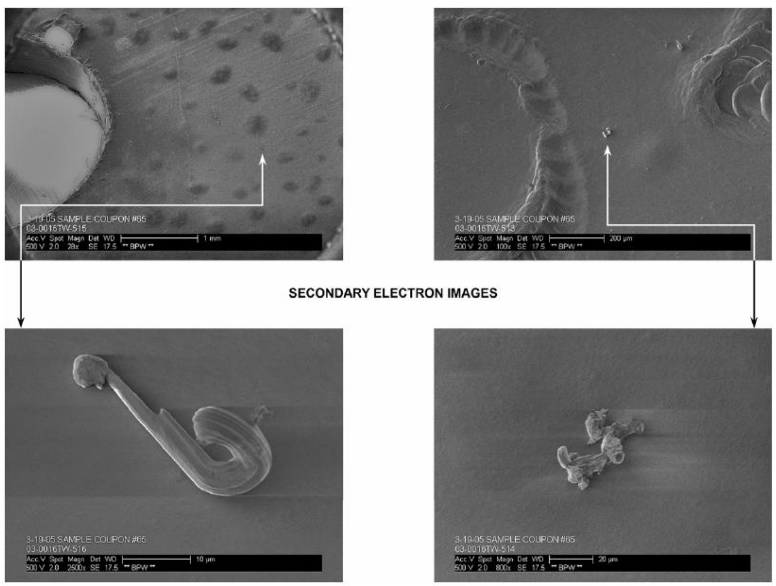


Figure 35. Whiskers Penetrating Parylene C – 0.4 Mils (401 Days at Ambient + 347 Days in 25°C/97%RH). Note Tenting of Parylene C due to OSE's (Upper Left Photo).

Whiskers breaching Parylene Coating

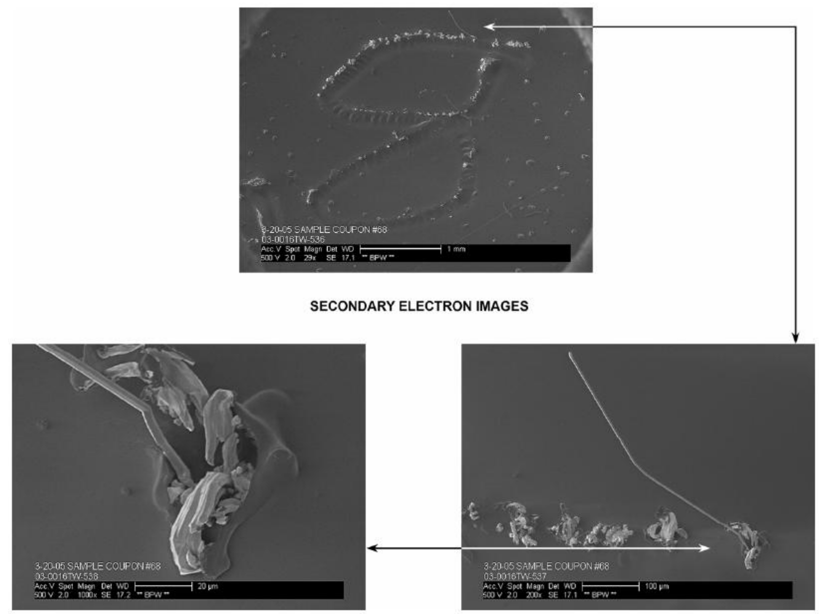


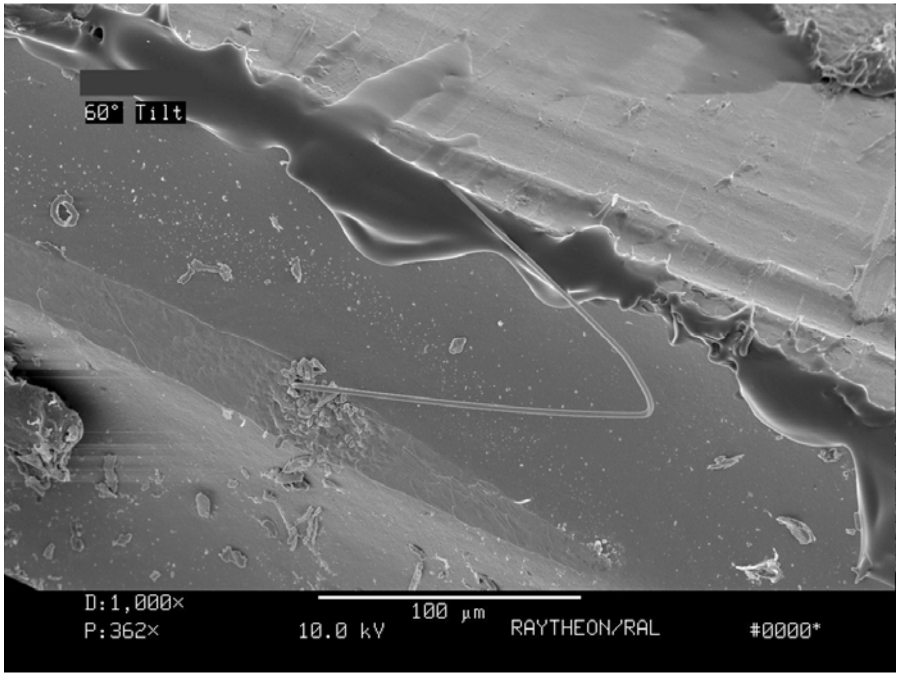
Figure 23. Whiskers and OSE's Penetrating Coating C on Scribe Mark – 1.1 Mils (401 Days at Ambient + 347 Days in 25°C/97%RH)

Whiskers and OSEs breaching Acrylic Coating

(Woodrow SMTAI September 2006
http://nepp.nasa.gov/whisker/reference/tech_papers/2006-Woodrow-Conformal-Coating-PartII.pdf)

Conformal Coating Effects

- Conformal coating
  - Typically protects conductors from liquid moisture and foreign objects
  - Can mitigate the effects of tin whiskers
- Tin whiskers that are long crystals…
  - May buckle before penetrating coating from the outside
- This paper addresses propensity for tin whisker to penetrate conformal coating from the outside by comparing…
  - Whisker critical buckling force
  - Force to penetrate coating



(D. Pinsky, Raytheon)

IF BUCKLING FORCE < PENETRATION FORCE THE COATING WILL NOT BE PENETRATED

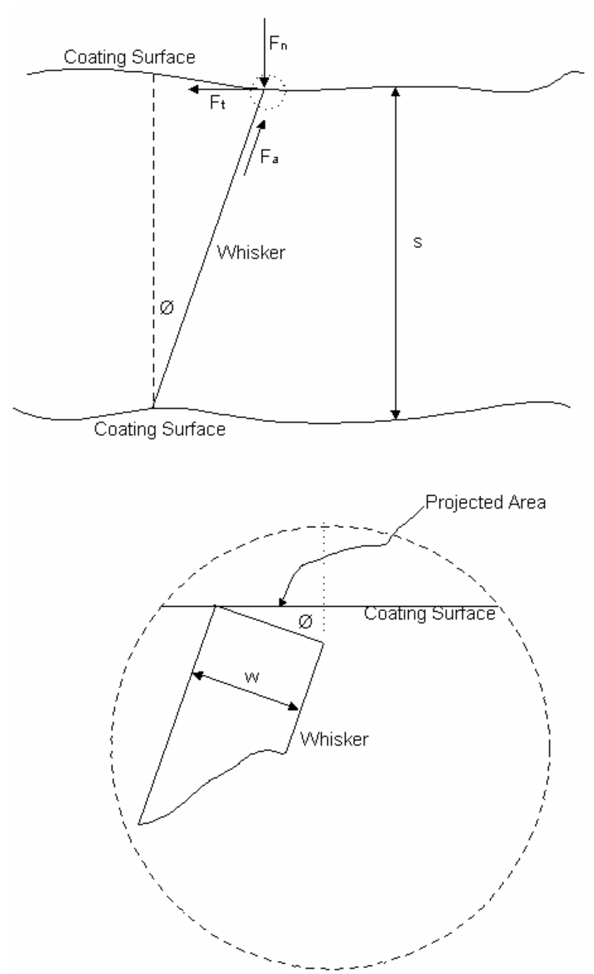
Tin Whisker Mitigation Strategy

- Use conformal coatings for most airborne and high-rel designs.
- Use hot solder dip on selected components to further mitigate the risk of tin whisker failures.
- In making these determinations, there is little available basis for performing concrete and meaningful calculations about risk.
- As an industry, we are learning much about whiskers, but we still have a long way to go.

WITH LIMITED INFORMATION AVAILABLE, WE MUST STILL TRY TO STAY AHEAD OF THE CURVE

Analytical Development – Background/System Geometry

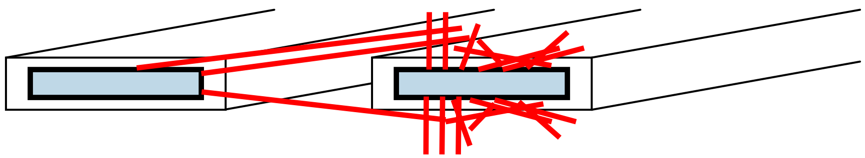
- Straight tin whisker
  - Bridge gap between two coating surfaces
  - Spaced by a distance (s)
- The whisker originates from source surface (lower surface in figure)
- Grows to destination surface (upper surface in figure)
- Whisker reaches destination surface…
  - Penetrate the surface?
  - Buckle?
  - Slide/deflect?



CC Penetration Model Assumptions

We make the following assumptions in this model:

1. Most probable scenario for failure is represented by a single whisker growing from the side of a component lead, and making contact with an adjacent conductor that is not electrically common.
2. We do not consider the case of a whisker shorting to another whisker in this analysis.



3. Conformal coat covers the sides of the leads, with a known and uniform thickness. Coating does not bridge between leads.
4. Shorting of a particular pair of adjacent component leads will result in a detectable fault.
5. The coating strength can be derived from “hardness” measurements (Durometer).
6. Whisker tip is blunt.
7. Use room temperature material properties.

Analytical Development – Friction Effects

- Condition 1 - Whisker slides along destination surface
  - If tangential force > friction force
  - Using friction relationships
    - Tangent of angle from normal is greater than coefficient of friction
    - Whisker axial force driven by normal and friction force
- Condition 2 – Whisker does not slide
  - If tangential force < friction force
  - Whisker axial force driven by geometry

Sliding:

$$F_n = \frac{F_a}{\left(\cos(\phi) + \mu \cdot \sin(\phi)\right)}$$

Non-Sliding:

$$F_n = F_a \cdot \cos(\phi)$$

F_n = Coating Normal Force

F_a = Whisker Axial Force

ϕ = Angle to Normal

Analytical Development – Whisker Penetration

- Normal stress in destination coating at whisker tip determined by
  - Normal force
  - Projected whisker contact area
- Penetration expected
  - When inelastic deformation/yielding of the coating occurs
- Define critical coating stress
  - Coating is penetrated when this is exceeded
  - Use to determine critical whisker force for sliding and non-sliding cases

Sliding:

$$F_p = \left(\cos(\phi)^2 + \cos(\phi) \cdot \mu \cdot \sin(\phi)\right) \cdot \sigma_{cr} \cdot A$$

Non-Sliding:

$$F_p = \sigma_{cr} \cdot A$$

F_p = Axial Whisker Force to Penetrate Coating

A = Area of Whisker Tip

ϕ = Angle to Normal

σ_{cr} = Critical Coating Stress

Analytical Development – Whisker Buckling

- Based on classical buckling of cantilevered beam
- Assumed fixed boundary condition at source of whisker
  - Constrained by surrounding coating (conservative)
- Boundary condition at destination depends on friction as described above
  - Sliding – destination boundary free
  - No sliding – destination boundary hinged

Sliding:

$$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{4 \cdot l^2}$$

Non-Sliding:

$$P_{cr} = \frac{20.19 \cdot E \cdot I}{l^2}$$

P_{cr} = Whisker Critical Buckling Force

E = Whisker Elastic Modulus

l = Whisker Length

I = Whisker Moment of Inertia

Analytical Development – Critical Coating Spacing

- Critical spacing determined for sliding and non-sliding cases
  - Equating critical buckling force and the critical penetration force
  - Expressing whisker length in terms of coating spacing
  - Assuming square cross-section

Sliding:

$$s_{cr} = 0.45346 \cdot w \cdot \sqrt{\frac{E}{\sigma_{cr}} \cdot \frac{1}{(1 + \mu \cdot \tan(\phi))}}$$

Non-sliding:

$$s_{cr} = 1.297 \cdot w \cdot \cos(\phi) \cdot \sqrt{\frac{E}{\sigma_{cr}}}$$

s_{cr} = Critical Coating Spacing

w = Whisker Width

E = Whisker Elastic Modulus

σ_{cr} = Critical Coating Stress

ϕ = Angle to Normal

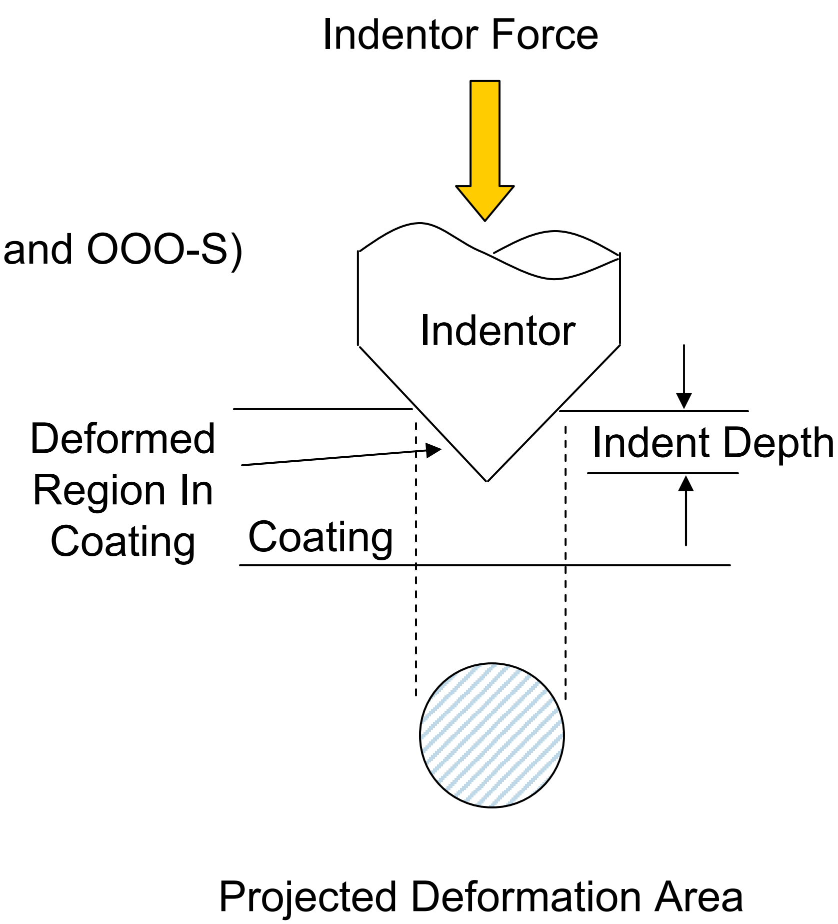
Material Properties - Background

Only two material properties required:

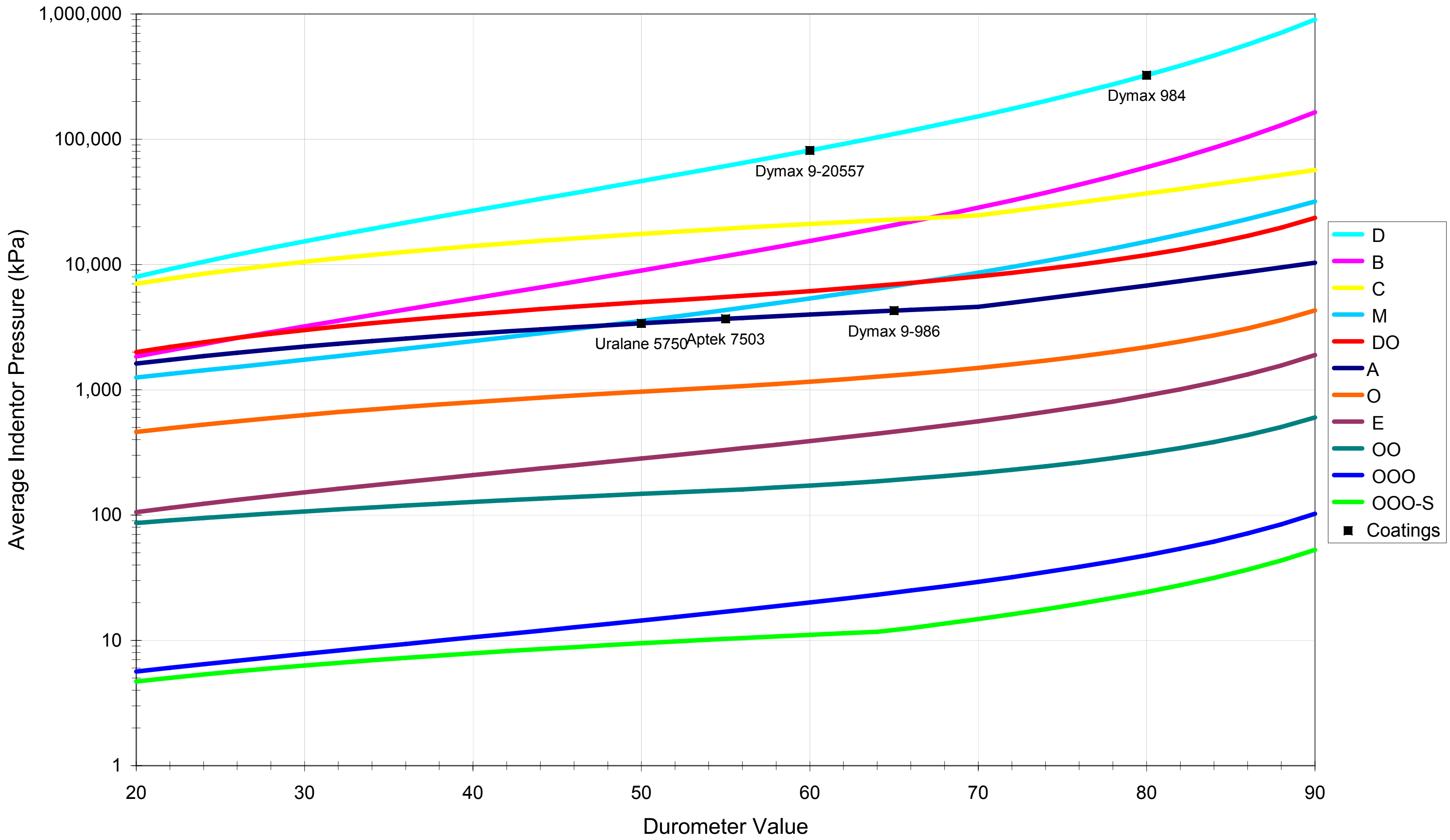
- Modulus of elasticity of the whisker (44.3 GPa from literature)
- Critical coating stress
  - This is a better representation of critical stress than reported properties like yield strength.
    - Compressive property, not tensile
    - Actual measurement of the thin film properties, not bulk polymer
    - This is an actual penetration (yield) measure, not simply elastic deflection
  - Durometer (Shore) hardness test (ASTM D2240)
  - Spring-loaded indenter is pressed into the test sample
    - Deflection indicated on a 0 to 100 scale
    - 100 represents zero deflection
    - Spring rate and indenter shape depend on type of test,
    - Deflection at 0 reading depends on type of test
  - Typical readings are expected between 20 and 90
    - Test type is selected for readings in this range
  - Average indenter pressure determined from
    - Effective area of the indenter
    - Indenter force

Material Properties – ASTM D2240 Notes

- Indenter Shapes
  - Truncated cone (types A and C)
  - Cone (types B, D, and M)
  - Spherical radius (types O, DO, OO, OOO, and OOO-S)
  - Ball (type E)
- Maximum Deflection
  - 2.5 mm except for types M and OOO-S
  - 1.25 mm for type M
  - 5 mm for type OOO-S
- Indenter Forces
  - 0.55 N to 8.05 N (types A, B, E, and O)
  - 0 N to 44.5 N (types C, D, DO)
  - 0.32 N to 0.77 N (type M)
  - 0.20 N to 1.11 N (types OO and OOO)
  - 0.17 N to 1.93 N (type OOO-S)



Material Properties – Critical Stress vs. Durometer



Material Properties – Critical Stress for Various Coatings

Coating	Durometer	Critical Stress (MPa)
Uralane 5750	A50	3.39
Dymax 984	D80	324
Dymax 9-20557	D60	81.4
Dymax 9-986	A65	4.28
Aptek 7503	A55	3.69
Humiseal 1B31		11.60

Results – Critical Coating Spacing

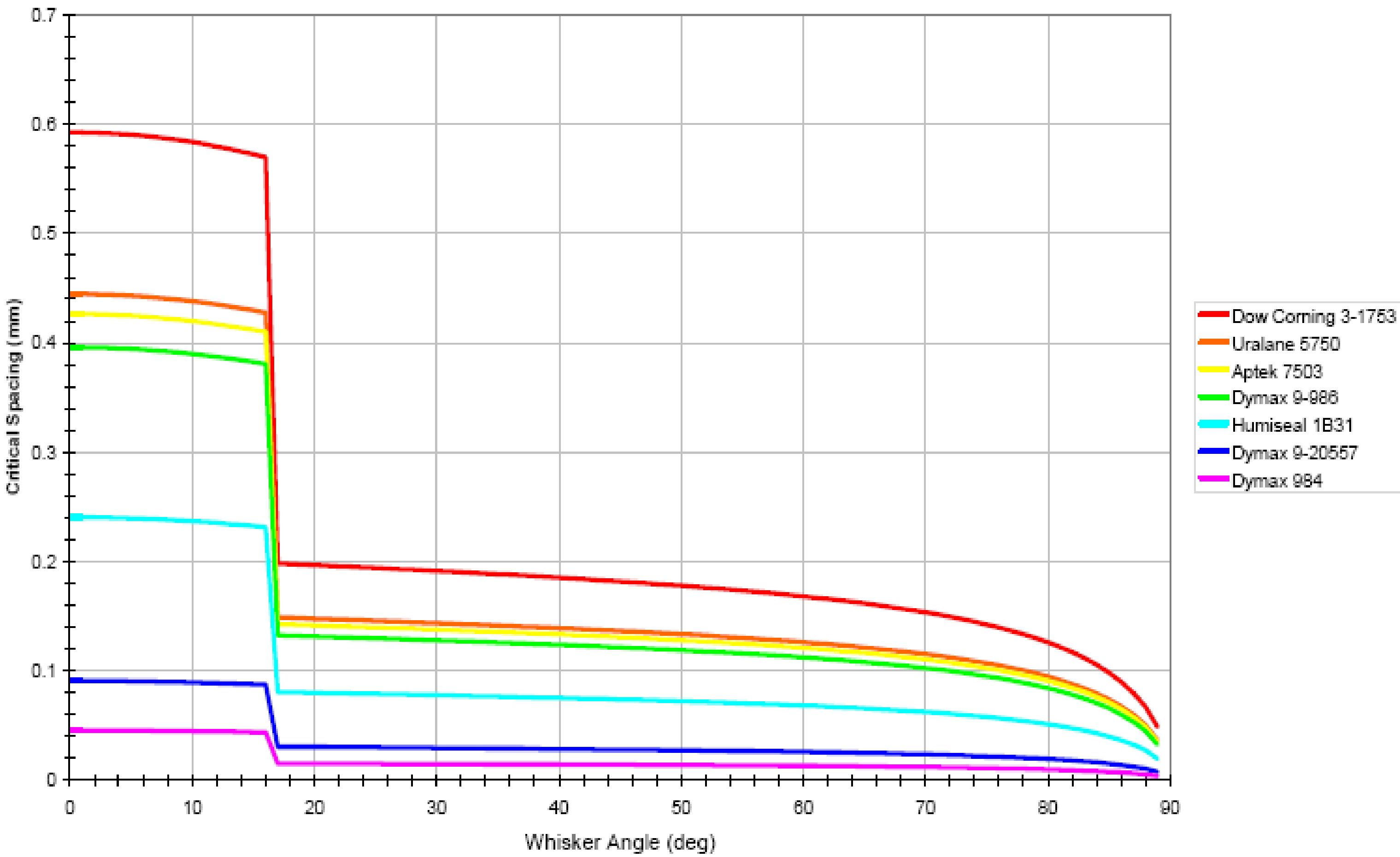
- Critical coating spacing determined for various coatings
  - Coefficient of friction = 0.3
  - Whisker width = 3µm
  - Critical stress values from previous slide
- Function of whisker angle
  - Worst-case condition occurs for a 0° (perpendicular) whisker
- Coating spacing not conductor spacing
- Mean critical coating spacing
  - Critical spacing and angle
  - Published probability of whiskers at various angles

	Critical Spacing (mm)	
	Worst-Case	**Mean**
Uralane 5750	0.44	0.24
Dymax 984	0.05	0.02
Dymax 9-20557	0.09	0.05
Dymax 9-986	0.40	0.22
Aptek 7503	0.43	0.23
Humiseal 1B31	0.24	0.13
Dow Corning 3-1753	0.59	0.32

Use data with caution: Initial indentation tests indicate that 1B31 acrylic at 40ºC is softer than 3-1753 silicone rubber at room temp.

NOTE: Worst case spacing is for a whisker growing directly normal to the coating.

Effect Of Whisker Angle On Critical Spacing



Examples

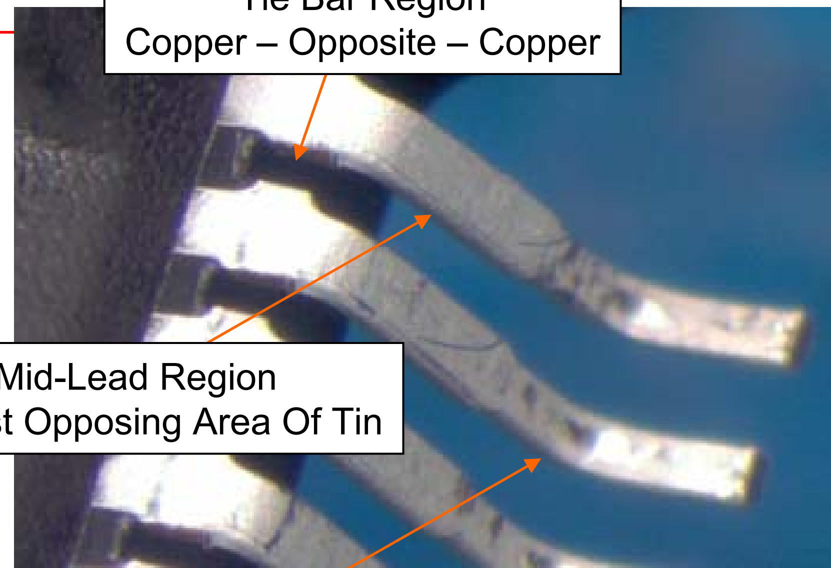
- Tin whiskers
  - Diameters
    - Up to 10 μm
    - Typical 3 μm (assumed here)
  - Smaller whiskers buckle at lower forces
  - Spacing table represents worst-case condition for a typical whisker
- Coating spacing
  - If larger than worst-case value:
    - A whisker-related short is extremely unlikely
    - Whisker would buckle before penetration
  - If less than the mean value:
    - A whisker could penetrate the coating and cause an electrical short

- Examples
  - Typical SOIC (small-outline integrated circuit)
    - Lead pitch = 1.27 mm
    - Minimum lead spacing = 0.78 mm
    - Coating thickness = 0.075 mm (each surface)
    - 0.63 mm spacing between coatings
    - Larger than worst-case value in Table
    - Whisker penetration unlikely
  - Typical PQFP (plastic quad flat pack
    - Lead pitch of 0.635 mm
    - Minimum lead spacing of 0.229 mm
    - 0.078 mm spacing between coatings
    - Risk for penetration for most coatings (except Dymax 984 and 9-20557)
    - Additional measures should be taken to mitigate whisker growth.

Where is the minimum spacing?

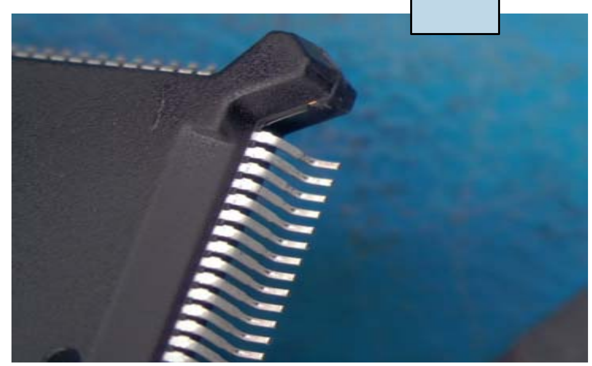
- There are many different lead configurations.
- Spacing is often less than the portion of the lead soldered to the PWB.
- Tie bar region
  - ~150 um (6 mils) minimum
- Mid-Lead region
  - ~280 um (11 mils) nominal
  - ~230 um (9 mils) minimum
- Solder foot region
  - ~ 390 um (15.5 mils) nominal
  - ~ 350 um (14 mils) minimum

Tie Bar Region
Copper – Opposite – Copper



Mid-Lead Region
Largest Opposing Area Of Tin

Solder Foot Region
Mostly Covered By Assembly Solder



Questions/Follow-On Work

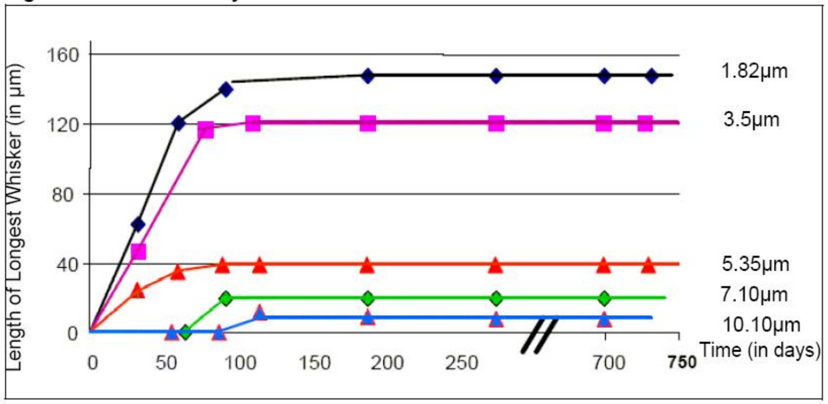
- What is the distribution of whiskers diameters?
  - Buckling force is proportional to the whisker diameter.
- Is there better data on whisker angle distribution on actual component leads?
- Is there data on the distribution of kinked whiskers?
- How long are typical maximum unkinked whiskers growing from a conformal coated lead surface?
- What makes a free whisker kink as it grows?
- Need more info on conformal coat properties
  - Strength over temperature
  - Under very slow deformation (as with a slowly growing tin whisker)
- Need more info on parameters controlling thickness of conformal coating deposited on sides of leads
  - Viscosity, surface tension, wetting angle, etc.
- Need to supplement analysis with experimental verification of whisker penetration on actual component leads, under typical service conditions.

Whisker Length

Whisker Length vs. Room Temperature Storage Time
(STMicro Application Note AN2035, 2006)

"Whisker Length is Leveling Off"

Figure 4. Protection by thickness



<u>15 ½ years of whisker growth</u>

Tin plated brass with copper barrier layer:

- •Continuous Growth Observed during 15 ½ years to lengths between 1 and 3.5 m.
- •Nucleation periods up to 5 months.

Tin plated steel with copper barrier layer:

- •Somewhat similar to brass with a copper barrier, but many extremely long whiskers were seen having lengths greater than 4.5 mm after 15.5 years.

Fused Tin Platings:

- •Absolutely no whiskering nucleated in 15 ½ years
- •Fused tin-plating on brass, copper-plated brass and steel

(Dunn, B., "15 years of tin whisker growth – results of SEM inspections made on tin electroplated C-Rings", European Space Research and Technology Center, ESTEC Materials Report 4562, 22 March 2006.)

Difficult to make definitive statements regarding whisker growth factors .

Questions?