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Conformal Coatings for Tin Whisker Risk Management

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Abstract
The objective of this study is to evaluate conformal coatings for mitigation of tin whisker growth. The conformal coatings chosen for the experiment are acrylic, polyurethane and parylene. The coatings were applied in thicknesses ranging from 0.5 to 3.0 mils on 198 bright tin plated coupons with a base metal of either Copper C110 or Alloy 42. Prior to coating, light scratches were applied to a portion of the coupons, and a second fraction of the coupons were bent at 45° angles to provide sources of stress thought to be a possible initiating factor in tin whisker growth. The coupons have been subjected to an environment of 50°C with 50% relative humidity for over five years. Throughout the trial period, the samples were inspected by both optical and scanning electron microscopy for tin whisker formation and penetration out of the coatings by tin whiskers. Tin whiskers were observed on each coupon included in the test, with stressed regions of the bent samples demonstrating significantly higher tin whisker densities. In addition, the Alloy 42 base metal samples showed greater tin whisker densities than the Copper C110 base metal samples. There were no observable instances of tin whisker penetration out of the coatings or tenting of the conformal coat materials for any of the non-stressed test coupons. The stressed coupons demonstrated tin whisker protrusion of the 1.0mil thick acrylic and polyurethane coatings for the Alloy 42 base metal samples. The greater thickness coatings (minimum of 2.0mils) did not demonstrate tenting or tin whisker protrusion. This paper will also include materials properties of the conformal coatings examined along with appropriate processing techniques in order to better understand the role of the coatings in tin whisker mitigation.

Introduction
A tin whisker is spontaneous growth of a tin crystal from tin-finished surfaces. The crystal often grows in a needle-like form, and due to the electrical conductivity of the anomaly, there is a resulting risk of current leakage and shorting due to bridging of adjacent conductors. There have been multiple studies into the mechanisms for whisker growth and both environmental and mechanical factors that may promote whisker growth[1-5].

Similarly there have been multiple studies on methods for mitigating tin whisker growth[6,7]. Mathew et. al. reviewed research into mitigation strategies such as conformal coating, electroplating techniques, surface treatments, alloying tin, use of various under-plates and annealing of the tin[6].

The conformal coating mitigation strategy has shown multiple results using various coating materials and environmental storage conditions. NASA studies[8-10] indicated that bright tin plated brass coupons, conformal coated with a uralane material, was able to prevent tin whisker protrusion following nine years of ambient storage when the coating thickness was at least 2.0mils. If the coating was thinner, there were observations of tin whisker protrusions.

Woodrow and Ledbury of the Boeing Corp. released two papers[11,12] examining tin whisker growth through multiple conformal coating materials. Both studies used bright tin plated brass test coupons. For the first study, when the test coupons were subjected to an environmental chamber set to 50°C with 50% relative humidity (RH), tin whisker penetration was noted after approximately one year for coatings of 1.5mils and less, but not for coatings of at least 3.9mils. For the second study, the test coupons were subjected to an environmental chamber set to 25°C with 97% RH. All of the test coupons exhibited tin whisker penetration of the conformal coatings, even on samples with up to 6.0mils of coating.

More recent work at the University of Maryland's Center for Advanced Life Cycle Engineering (CALCE) has further studied the interfacial strength of conformal coatings in comparison to the whisker buckling force[13] initially presented by Kadesch and Leidecker[8]. Preliminary testing indicated that conformal coatings of 25 microns (approximately 1.0mil) or less with a modulus of 100MPa or less are at risk of tin whisker penetration.

Reviewing the multiple studies on the use of conformal coatings as a mitigation technique for tin whiskers indicates that tin whiskers can grow through a coating. The apparent greatest contributing factor for the risk of a coating is the thickness. Coating thicknesses below 2.0mils appear to present a greater risk of tin whisker penetration, although extreme environmental conditions coupled with the type of tin plating could promote tin whisker growth through any type of coating at relatively large coating thicknesses. There have been no studies which have indicated specific conformal coating materials that have improved tin whisker mitigation properties.

Lockheed Martin Missiles and Fire Control (LMMFC), Orlando-Ocala, FL conformal coats 99% of all circuit boards using one of three (3) different conformal coating materials: acrylic, polyurethane and parylene. This study examined the affects of tin whisker growth on the three coatings, applied to test coupons at varying thicknesses.

Acrylic conformal coatings are perhaps the most popular of all conformal coating materials due to their ease of application, removal and forgiving nature[14]. Acrylics dry rapidly, reaching optimum physical properties in minutes, are fungus resistant and provide long pot life. Additionally, acrylics give off little or no heat during cure eliminating potential damage to heat-sensitive components. They do not shrink during cure and have good humidity resistance and exhibit low glass transition temperatures.

Polyurethane coatings are available as either single or two-component formulations[14]. Both formulations provide excellent humidity resistance and far greater chemical resistance than acrylic coatings. Single component polyurethanes, while easy to apply, enjoy long pot life but sometimes require very lengthy cure cycles to achieve full or optimum cure. Two component formulations can reach optimum cure properties in as little as one to three hours with the assistance of heat. However, when compared to single component formulations, two-component formulas can have a relatively short pot life sometimes making them difficult to work with. Since polyurethanes are polymerized and cross-linked in place, they have excellent resistance to chemicals, moisture and solvents. They are available in tough, abrasion-resistant varieties and also in low modulus varieties for extreme temperature ranges. Polyurethanes have good adhesion to most materials and provide for a robust coating process. The material is difficult to remove following cure except by thermal or mechanical means.

Parylene coating is chemically inert and moisture resistant[14]. Very thin, uniform layers can be applied to the surface with no pinholes or voids. Parylene coating has a high dielectric strength. Due to the nature of deposition process used to apply the coating, there are no volatiles generated. Parlylene coatings are extremely low weight and yet have the highest modulus of the three coatings being examined. The coating process must be performed in batch mode, using specialized coating equipment. Rework is difficult, and a microabrasion process is usually required to remove the coating.

The spray process used at LMMFC, Ocala for application of the acrylic and polyurethane coatings is automated with a rotating spray head. The motion of the head is designed to cover a given width from all angles. Masking is required to keep coating out of areas that should not be coated.

Parylene is applied at room temperature with deposition equipment that controls the coating rate and ultimate thickness. Polymer deposition takes place at the molecular level in three stages. The raw material dimer is vaporized under vacuum and heated to a dimeric gas. The gas is then pyrolized to cleave the dimer to its monomeric form. In the room temperature deposition chamber, the monomer gas deposits as a transparent polymer film.

Scope and Objective

This study was designed to examine the affects of tin whisker growth on the three coatings, applied to test coupons at varying thicknesses.

Test coupons consisting of two types of base material (Copper C110 alloy and Alloy 42) were electrodeposited with a layer of 'bright tin' plating. These are the typical base metals utilized for component leads. After plating and prior to conformal coating a quantity of the plated coupons were scratched to simulate those found during handling and shipping conditions, and another quantity of plated coupons were bent (w/o scratches) to induce tensile and compressive stresses on the plating. All of the test coupons were then conformal coated on approximately half of the surface with the other half remaining uncoated. The coupons were masked, coated, and then demasked to ensure the coating thickness was uniform and there was no thinning at the edges. The test coupons were placed in an environmentally controlled temperature / humidity chamber to promote the growth of the tin whiskers.

At specific time intervals, a sampling of test coupons were removed from the temperature / humidity chamber and evaluated for tin whisker growth on the plated and uncoated surfaces versus the plated and conformal coated surfaces. Data samples were collected and examined under high magnification, photomicrographs, or scanning electron micrographs. Energy dispersive spectroscopy (EDS) analysis also provided metallurgy to confirm anomalies as tin whiskers. All data collected was documented, logged and charted to show whisker growth and other variations.

The test had three primary objectives:

1. Grow tin whiskers on the bright tin plated test coupons.
2. Provide positive evidence that conformal coating, over a bright tin plated coupon protects against tin whiskers through growth reduction, abatement or containment.

3. Evaluate the different conformal coating materials and thicknesses to evaluate which materials and coating thicknesses provide the best protection against tin whisker growth.

Procedure and Materials
A diagrammed outline of the test coupon preparation procedure is shown in Figure 1.

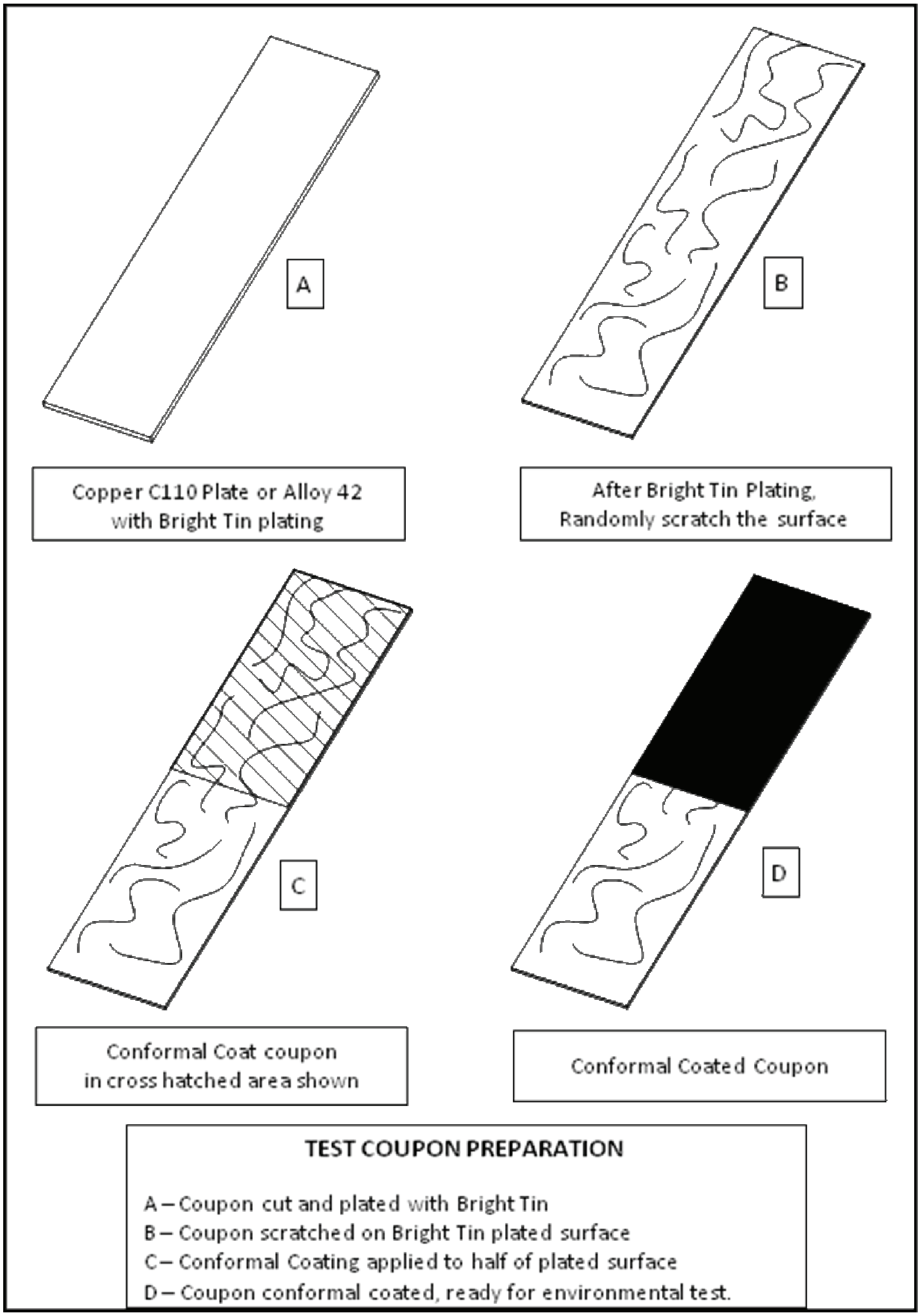

Figure 1 – Test coupon preparation procedure

Two different base metal materials were chosen for the testing – Copper C110 and Alloy 42. The test coupons measured 1in x 4in x 0.032in. The bright tin coatings were applied to the test coupons by electrodeposition according to ASTM B545. The thickness of the tin coating was 215-225µin. The test coupons were supplied and tin plated by Alexandria Metal Finishers. There were a total of 99 coupons with the Copper C110 base metal and 99 coupons with the Alloy 42 base metal.

Following the plating process, 69 Copper C110 base metal coupons and 69 Alloy 42 base metal coupons were 'scratched' along the surface. Brown paper wrapping material was cut in sheet sizes approximately 8.5in x 11in, wrinkled by 'balling and crushing' and then unraveled and flattened. Each coupon was separately wrapped (one sheet/coupon), then individually laid on a hard surface (i.e. table top) and shuffled around several times on each of the flat sides thereby randomly creating 'light' scratches on the tin surface. These scratches were intended to simulate those found on the surface of component leads as a result of shipping and handling. The typical 'light' scratch created by this method was photo documented.

Also following the plating process, 30 Copper C110 base metal coupons and 30 Alloy 42 base metal coupons had a 45° bend placed in 2 places as shown in Figure 2 using a machine vise with appropriate protection applied to the jaws of the vise (i.e. Teflon tape or equivalent). This bend was intended to put the tin plating under stress (i.e. compressive stress on the inside bend and tensile stress on the outer bend). Necessary precautions were taken to protect the transfer of metal to the tin plating during the bending process. These coupons do not have scratches in the tin plated surfaces.

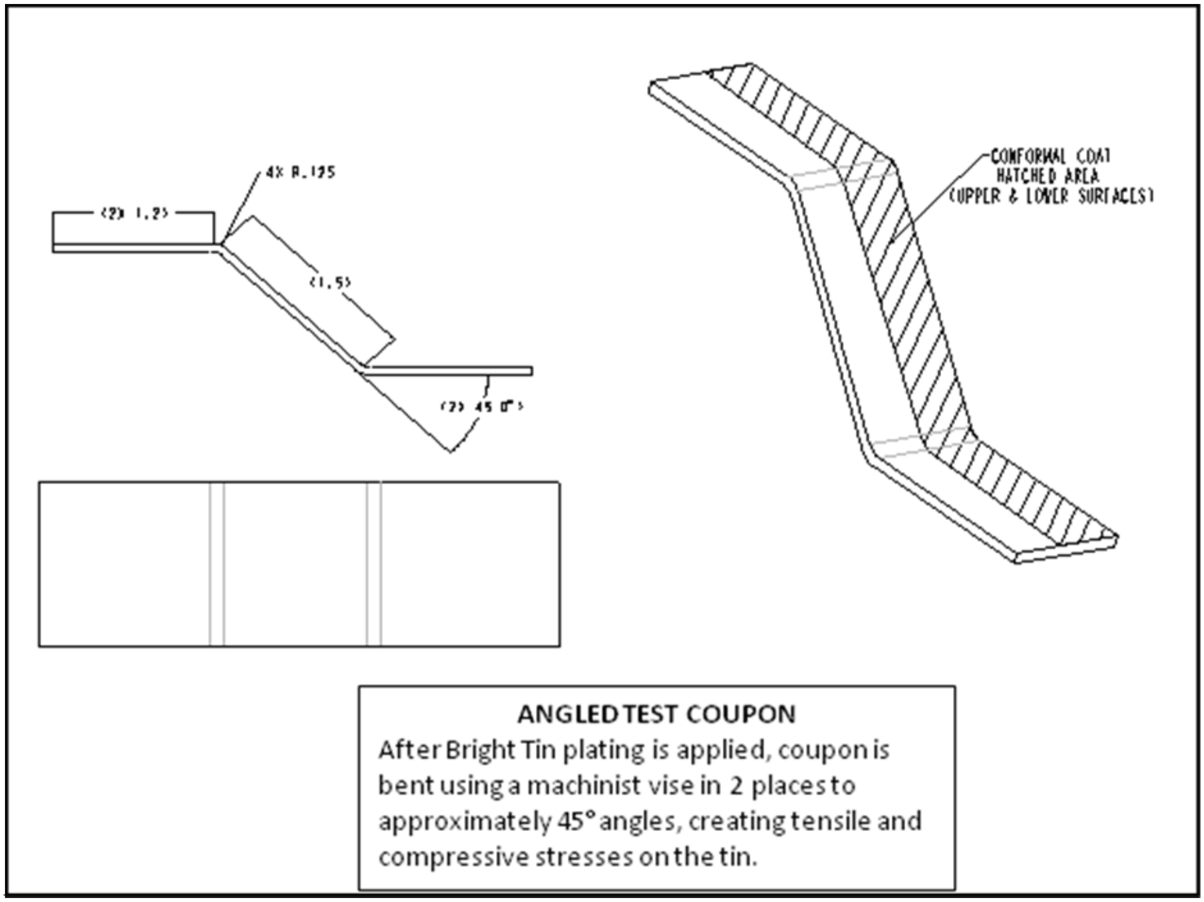

Figure 2 – Drawing of bent test coupons

The conformal coatings used in the testing were acrylic per MIL-C-46058, Type AR, polyurethane per MIL-C-4605, Type UR, and parylene per MIL-C-46058, type XY. Table 1 includes mechanical properties of the coatings used in the testing. The application thickness of the coatings was 1.0, 2.0 or 3.0mils for the acrylic and polyurethane coating and 0.5mils for the parylene coating. Prior to the coating process, the samples were cleaned using the existing in-line cleaner and then baked at 85°C for two hours. The appropriate areas of the coupons were masked using tape. The acrylic and polyurethane coatings were applied using a spray coat process and the parylene coating was applied using a vapor deposition process. All test coupons were coated by LMMFC, Ocala. The samples were labeled according to Table 2.

Table 1 – Properties of Confomal Coatings Used in Testing

Property	Test Method	Conformal Coating		
		Acrylic Type AR	Polyurethane Type UR	Parylene Type XY
Young's Modulus (psi)	ASTM D882	11,600	13,000	400,000
Elongation to Break (%)	ASTM D882		100-1000	200
Water Absorption (% after 24 hours)	ASTM D570	0.3	0.02-1.50	<0.1
Hardness	ASTM D785	M68-M105	10A-25D (Shore)	R80
Dielectric Strength (V/mil)	ASTM D149	3,500	3,500	5,600

NOTE: Properties from material technical data sheets

Table 2 – Test Coupon Matrix

Coupon Base Material	Conformal Coating	Coating Thickness	Coupon Identification Code	Number of Coupons
Copper C110	None – Bare	NA	CU-BASE	5
	Acrylic	1.0	CU-A-1	8
		2.0	CU-A-2	8
		3.0	CU-A-3	8
	Polyurethane	1.0	CU-U-1	10
		2.0	CU-U-2	10
		3.0	CU-U-3	10
	Parylene	0.5	CU-P-5	10
				Total Coupons: 69
Alloy 42	None – Bare	NA	AL-BASE	5
	Acrylic	1.0	AL-A-1	8
		2.0	AL-A-2	8
		3.0	AL-A-3	8
	Polyurethane	1.0	AL-U-1	10
		2.0	AL-U-2	10
		3.0	AL-U-3	10
	Parylene	0.5	AL-P-5	10
				Total Coupons: 69
Samples below angled 45° to stress the bright tin plating				
Copper C110	Acrylic	1.0	BCU-A-1	5
		2.0	BCU-A-2	5
		3.0	BCU-A-3	5
	Polyurethane	1.0	BCU-U-1	5
		2.0	BCU-U-2	5
		3.0	BCU-U-3	5
Alloy 42	Acrylic	1.0	BAL-A-1	5
		2.0	BAL-A-2	5
		3.0	BAL-A-3	5
	Polyurethane	1.0	BAL-U-1	5
		2.0	BAL-U-2	5
		3.0	BAL-U-3	5
				Total Coupons: 60
Test coupon size prior to plating: 1in x 4in x 0.032 in Plating: Electrodeposited bright tin (per ASTM B545); thickness 215-222µin 1.0mil = 0.001in = 25.4µm				

Following the conformal coating of the test coupons, and a visual inspection to insure continuity of the coating as well as a measurement of the coating thickness on approximately ten samples to insure that the proper coating thicknesses were applied, the samples were placed in an environmental chamber. The environmental chamber was capable of maintaining a temperature of 50° ± 10°C and a relative humidity of 50% ± 15%. The oven was equipped with a fail-safe device to ensure against overheating. The internal working envelope of the environmental chamber was 16in x 16in X 12in. The temperature and humidity was continually monitored by an electronic recording device. The date of the initial insertion of the coupons to the environmental chamber was June 15, 2004.

On one occasion during the last quarter of each year, a sample of test coupons was removed from the environmental chamber and inspected. The inspection consisted first of optical microscopy, using the indirect light procedures described on the 'NASA Tin Whisker Homepage' website[15]. Anomalies in the integrity of the conformal coating were noted, and any areas with suspect tin whisker growth were noted and inspected further using scanning electron microscopy. SEM was also used on the areas of the test coupons without conformal coating to determine the length and density of tin whiskers.

Results and Discussion

Original inspection of the test coupons following application of the tin plating indicated no observable anomalies in plating integrity (Figure 3). Cross-sections of ten samples confirmed the plating thickness to be between 215 and 225µin. The thickness of the applied conformal coating was confirmed from several previous processing tests run to evaluate processing parameters for required coating thickness. Inspection of the conformal coating integrity indicated no significant anomalies. The coating thickness at the line of demarcation for the flat samples tended to be slightly less than that for the remainder of the sample but not significantly.

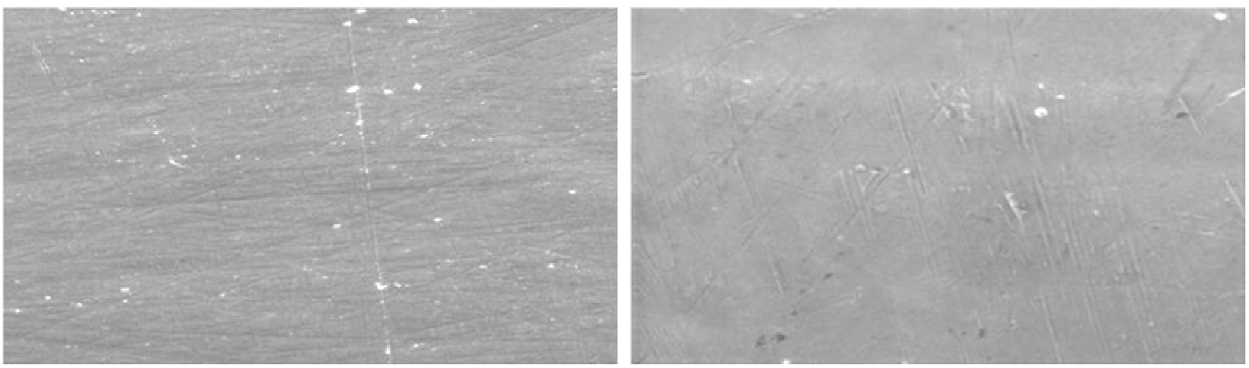

Figure 3 – Scanning electron micrographs (800X magnification) demonstrating the condition of the surface of the tin plating prior to conformal coating for both the Copper C110 base metal (left) and Alloy42 base metal (right)

Figure 4 includes scanning electron micrographs of the tin plating on a Copper C110 base metal coupon at the location of the bend prior to conformal coating. There are observable stress cracks in the tin plating caused by the bending process. The tin plating on the Alloy 42 base metal appeared similar.

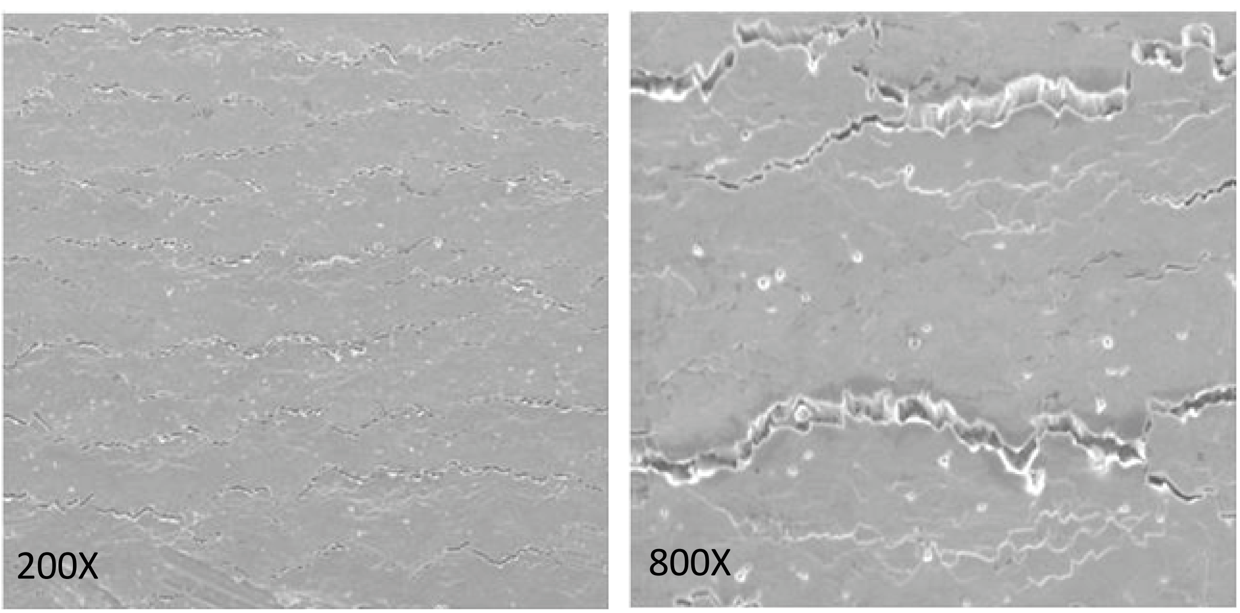

Figure 4 – Scanning electron micrographs of the tin plating following the bending process on the Copper C110 base metal.

Table 3 includes whisker density values for the ***uncoated*** samples for both the Copper C110 base metal and the Alloy42 base metal on the control samples and on the bent samples for both regions in tension and compression. As of the fourth quarter of 2009 sampling, the whisker density on the Alloy 42 base metal control sample (47 whiskers/mm^2) was greater than that of the whisker density on the Copper C110 base metal control sample (26 whiskers/mm^2). The largest tin whiskers and odd-shaped eruptions observable on the control samples approached 4.0mils, indicating that whiskers were present with minimum lengths dimensionally capable of extending through the conformal coating thicknesses applied to the test coupons (Figure 5). The effect of the light scratches applied to the surface of the control samples was negligible with no observable pattern of whiskers accumulating along the scratches.

As of the fourth quarter 2009 sampling, the whisker densities in the stressed regions were considerably higher than that for the control samples (Figure 5). The regions in tension exhibited greater whisker densities than the regions in compression for both the Copper C110 and Alloy 42 base metal coupons. The whiskers tended to grow along tensile stress cracks in the tin plating caused by the bending process. The Alloy 42 coupons had significantly greater tin whisker density in both regions of tension (291 whiskers/mm^2) and compression (130 whiskers/mm^2) than that of the bent Copper C110 base metal coupons (42 whiskers/mm^2 in regions of tension and 31 whiskers/mm^2 in regions of compression). The length of tin whiskers growing along the surface of the samples from both base metals approached 8mils.

Table 3 – Average Tin Whisker Densities on *Uncoated* Regions throughout Environmental Exposure

Sample	Whisker Density (# / mm^2)					
	2004	**2005**	**2006**	**2007**	**2008**	**2009**
Copper C110	0	2	5	13	19	26
Alloy 42	0	4	11	21	33	47
Copper C110 Bent (Tension)	0	3	9	20	29	42
Alloy 42 Bent (Tension)	4	38	71	131	212	291
Copper C110 Bent (Compression)	0	2	7	16	22	31
Alloy 42 Bent (Compression)	3	18	41	74	94	130

There were no observed tin whisker protrusions through any of the conformal coating materials used on the coupons that were not bent for both base metals. In addition, there was no indication of tenting of the conformal coat where a tin whisker may push the coating away from the tin plating. There were tin whiskers or odd-shaped eruptions observed beneath the conformal coating for samples of both base metals and all coating types. The tin growths observable through the conformal coatings were first noted during the sampling in the fourth quarter of 2006 (approximately 30 months of environmental exposure). The presence of conformal coating over the tin whiskers was confirmed by EDS. Figure 6 includes a scanning electron micrograph of a tin whisker observed beneath 2.0mil thick acrylic coating, along with a second micrograph of the whisker following removal of the coating. The growth on the surface was confirmed as tin by EDS. The sample used for the micrograph was an Alloy 42 base metal bent sample in a region of tension.

There was observable tenting but no tin whisker protrusion of the 1.0mil thick acrylic conformal coating on the regions in tension for the Copper C110 base metal samples during the sampling in the fourth quarter of 2009 (Figure 7). In addition, there was no indication of tenting or tin whisker protrusion for the 2.0 and 3.0mils thick acrylic conformal coating or any of the thicknesses of polyurethane conformal coating. The regions in compression similarly showed no evidence of tenting or tin whisker penetration for any of the coated areas of the Copper C110 base metal samples.

For the bent Alloy 42 base metal samples, there was tin whisker protrusion of both the 1.0mil thick acrylic and polyurethane conformal coatings in both the regions of tension and compression (Figure 8). The Alloy 42 base metal samples with conformal coatings of 2.0 and 3.0mils showed no indication of tenting or tin whisker protrusion for either the acrylic or polyurethane materials. The observations of the test coupons as of the fourth quarter of 2009 are summarized in Table 4.

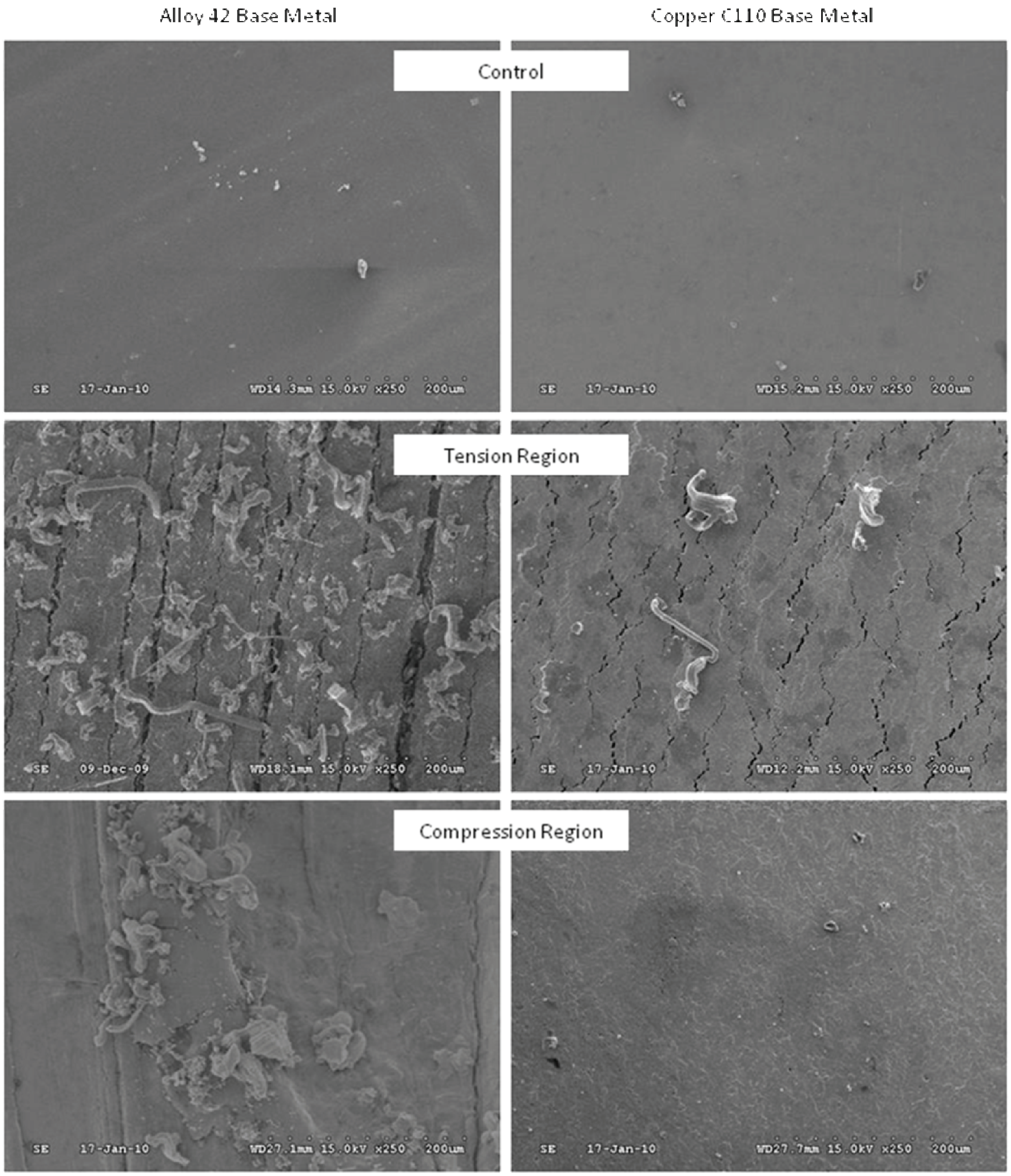

Figure 5 – Scanning electron micrographs (250X magnification) demonstrating the density of tin whiskers on the uncoated areas of the control samples (top two micrographs), the regions of tension for the bent coupons (middle two micrographs) and the regions of compression for the bent coupons (bottom two micrographs.

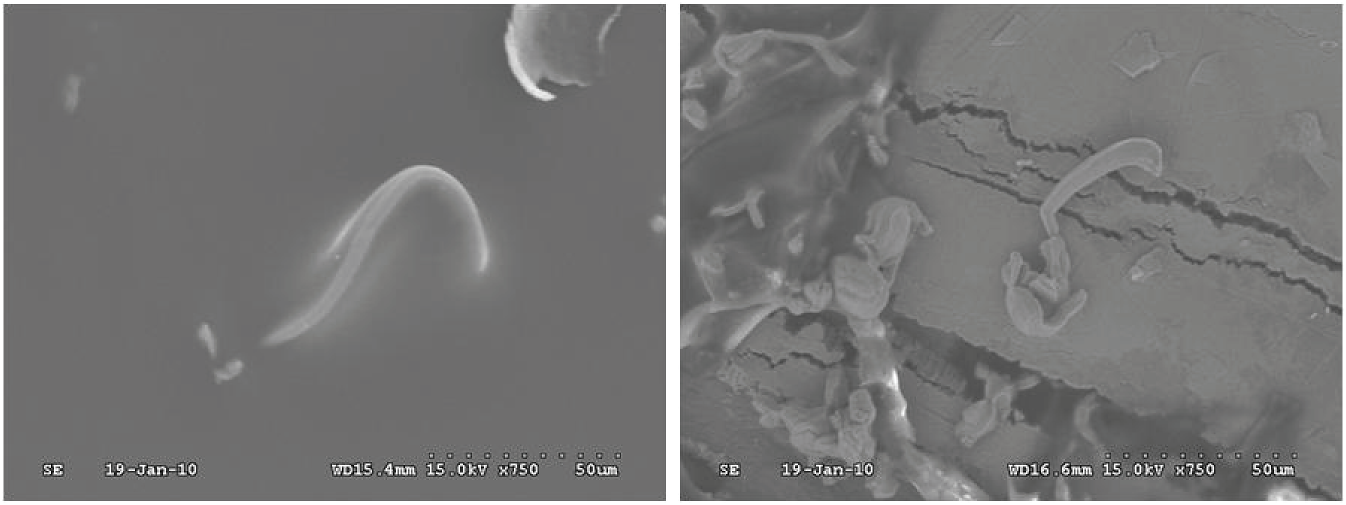

Figure 6 – Scanning electron micrographs of a tin whisker observed beneath 2.0mil thick acrylic conformal coating (left) and the same tin whisker following removal of the conformal coating.

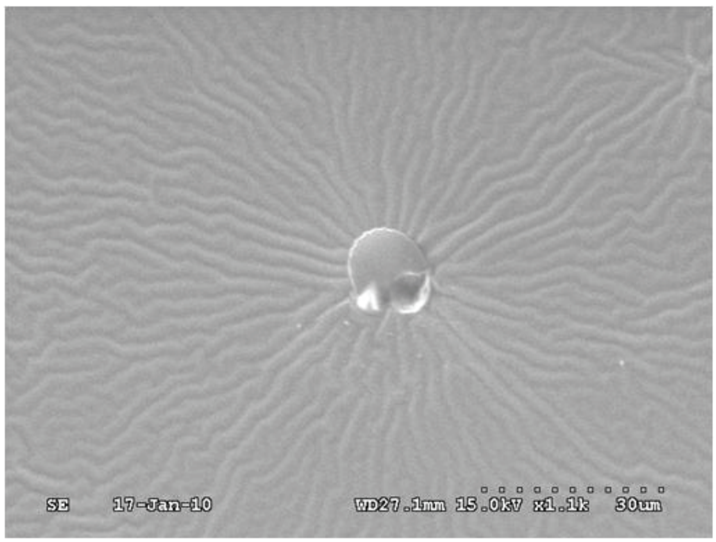

Figure 7 – Scanning electron micrograph characteristic of tenting of the 1.0mil thick acrylic coating in a region of tension on a bent Copper C110 base metal coupon.

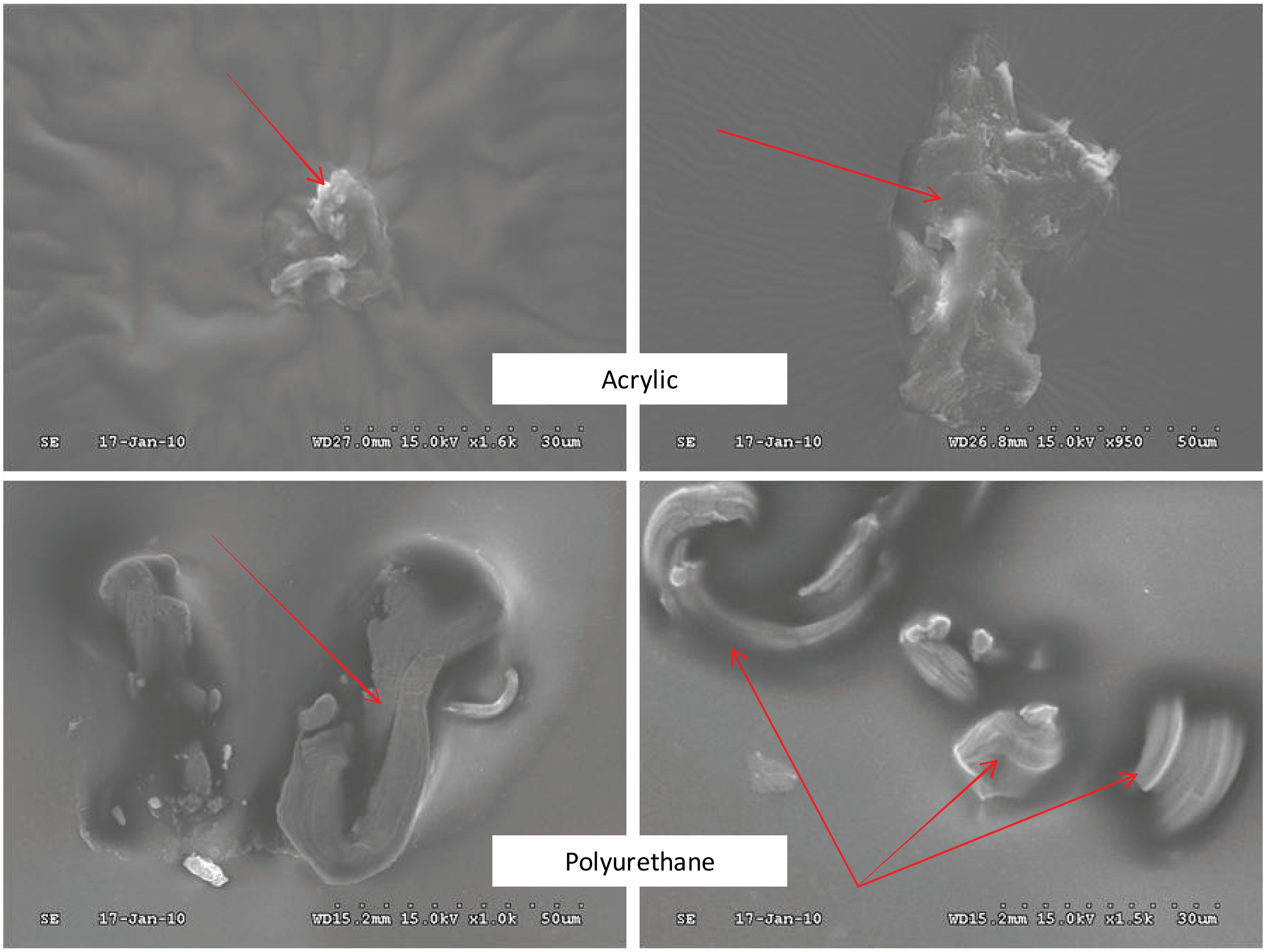

Figure 8 – Scanning electron micrographs characteristic of tin whisker protrusions in both regions of tension and compression for the bent Alloy 42 base metal coupons with 1.0mil thick acrylic and polyurethane conformal coatings. The red arrows denote the tin whiskers protruding from the conformal coating.

Table 4 – Tin Whisker Observations at end of Experiment

Coupon Base Material	Conformal Coating	Coating Thickness (mils)	Coupon ID Code	Observations
Copper C110	Acrylic	1.0	CU-A-1	No tenting or tin whisker protrusions
		2.0	CU-A-2	No tenting or tin whisker protrusions
		3.0	CU-A-3	No tenting or tin whisker protrusions
	Polyurethane	1.0	CU-U-1	No tenting or tin whisker protrusions
		2.0	CU-U-2	No tenting or tin whisker protrusions
		3.0	CU-U-3	No tenting or tin whisker protrusions
	Parylene	0.5	CU-P-5	No tenting or tin whisker protrusions
Alloy 42	Acrylic	1.0	AL-A-1	No tenting or tin whisker protrusions
		2.0	AL-A-2	No tenting or tin whisker protrusions
		3.0	AL-A-3	No tenting or tin whisker protrusions
	Polyurethane	1.0	AL-U-1	No tenting or tin whisker protrusions
		2.0	AL-U-2	No tenting or tin whisker protrusions
		3.0	AL-U-3	No tenting or tin whisker protrusions
	Parylene	0.5	AL-P-5	No tenting or tin whisker protrusions
Samples below angled 45° to stress the bright tin plating				
Copper C110	Acrylic	1.0	BCU-A-1	Tenting in tension regions; no protrusions
		2.0	BCU-A-2	No tenting or tin whisker protrusions
		3.0	BCU-A-3	No tenting or tin whisker protrusions
	Polyurethane	1.0	BCU-U-1	No tenting or tin whisker protrusions
		2.0	BCU-U-2	No tenting or tin whisker protrusions
		3.0	BCU-U-3	No tenting or tin whisker protrusions
Alloy 42	Acrylic	1.0	BAL-A-1	Tin whisker protrusions in compression and tension regions onlty
		2.0	BAL-A-2	No tenting or tin whisker protrusions
		3.0	BAL-A-3	No tenting or tin whisker protrusions
	Polyurethane	1.0	BAL-U-1	Tin whisker protrusions in compression and tension regions only
		2.0	BAL-U-2	No tenting or tin whisker protrusions
		3.0	BAL-U-3	No tenting or tin whisker protrusions

Conclusions

The Alloy 42 base metal test coupons exhibited higher tin whisker densities in uncoated regions than that of the Copper C110 base metal test coupons. The stressing of the test coupons by applying a 45° bend in two locations caused a significant increase in tin whisker density for both regions of tension and compression. The effect of the bending was noticeably more significant for the Alloy 42 base metal test coupons and the regions of tension had higher whisker density than the regions of compression. The negative effect of Alloy 42 base metal on the propensity of electrodeposited bright tin coatings to whisker has been shown in previous research. In addition, the effect of stressing tin plating resulting in increased tin whisker density has also been previously reported. The observation in this experiment that tensile stresses caused a greater effect on tin whisker density than compressive stresses is in contrast with most previous research.

The conformal coatings used in this experiment mitigated tin whisker protrusions for the test coupons that were ***not stressed***. Parylene coating at a thickness of 0.5mils and both acrylic and polyurethane coatings with a minimum thickness of 1.0mils did not exhibit any tenting following the 5.5 years of environmental exposure to 50°C and 50% RH.

Tenting was observable on the 1.0mil thick acrylic coating in regions of tension for the bent Copper C110 base metal samples; however there were no indications of tin whisker protrusions. There was observable tin whisker protrusions for both the 1.0mil thick acrylic coating and the 1.0mil thick polyurethane coating in regions of tension and compression for the bent Alloy 42 base metal samples. The thicker coatings (minimum thickness of 2.0mils) did not exhibit any tenting or tin whisker protrusions. This is in agreement with the recent CALCE study stating that coatings of 1.0mils and thickness and low modulus are at risk for tin whisker penetration.

The conformal coating materials used in this testing mitigated the growth of tin whiskers through the coating for this specific electrodeposited tin plating and this specific environmental exposure when there were no additional stresses applied to the coupons. It should be noted that the tin plating selected and applied during this experiment were intentionally designed to promote the growth of tin whiskers and would not normally be considered as an acceptable plating for component leads of real hardware. Parylene, which has a significantly higher modulus demonstrated in this experiment the ability to mitigate tin whiskers at a thickness of 0.5mils; however there were no stressed (bent) samples for parylene. The bent samples indicate that stressed regions of tin plating will have a greater tendency to whisker. Additional testing on real world component leads mounted to circuit cards is warranted to determine minimum requirements for each coating type. Current test data shows tin whisker mitigation at minimum coating thicknesses of 2.0mils for both acrylic and polyurethane coatings and 0.5 mils for parylene coatings.

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