

REPORT

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Evaluation of the Ability of Conformal Coatings to Inhibit Tin Whiskering

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Evaluation of the Ability of Conformal Coatings to Inhibit Tin Whiskering

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ABSTRACT

A technique using specially electroplated, interdigitated discs, developed at the National Physical Laboratory, has been used to determine the relative ability of conformal coatings to mitigate against Sn whisker growth. A range of acrylic, polyurethane, silicone and urethane acrylate coatings have been evaluated and all were shown to inhibit the growth of whiskers compared to uncoated control samples over a 150 day period. All the control samples without conformal coatings, developed whiskers of $>250\text{ }\mu\text{m}$ in length, sufficient to cause electrical shorts between the discs within 14 days.

Where coating coverage was defect-free and of sufficient thickness, only a limited number of coatings (two acrylic coatings and a urethane acrylate coating) were found to have whiskers penetrating through the coating. Whiskers penetrating out from under coatings were found extensively in areas where the coatings were thinner, or where there were other coverage issues. All the coatings evaluated, except two of the polyurethane coatings, exhibited whisker growth from under coated plates in the region of sharp corners. Where both plates of the samples were coated, five of the coatings evaluated did not exhibit electrical shorts at any time during the 150 days of testing. These were one acrylic, two polyurethane and two silicone coatings.

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1 INTRODUCTION

The introduction of European legislation that bans the use of lead in electronics (reference 1), has led industry to embrace new finishes on components that are lead-free. The electronics industry prefers to use fusible tin alloy coatings, since they have superior solderability, and consequently are more tolerant of deficiencies in the assembly process. However, none of the possible replacement alloys for SnPb plated finishes are a clear favourite compared to pure tin. They all have significant disadvantages from a plating perspective, while offering no advantages in the soldering process. Hence, pure tin is now dominating lead-free component supply. The Achilles' heel of pure tin is the phenomena of spontaneous single crystal Sn growths, known as whiskers, which can occur under certain conditions. Whiskers can grow up to several millimetres in length and short out to adjacent contacts.

Although a widely known phenomena, tin whisker growth is not common, and new plating chemistries have been developed that greatly reduce whisker propensity. However, a "whisker-free" finish has yet to found and many consider this an unachievable goal. For many high reliability users, this is a real problem. They cannot obtain SnPb component coatings for many components but require a whisker-free assembly. Well documented failures due to tin whiskers range from communication satellites losses, missile and military radar failures, nuclear power station reactor shutdowns, through heart pacemakers and medical monitors, to poor reliability in consumer applications. NASA has an excellent web-site with many details on the occurrence of Sn whiskers (reference 2).

The mechanisms for initiation and growth of Sn whiskers are still a matter of much research, but the most generally accepted mechanism is the generation of stress in the plating by intermetallic growth. The diffusion of Cu from the leadframe into the Sn plating and vice versa results in the formation of intermetallic compounds, such as Cu_6Sn_5 . The growth of the intermetallics, creates compressive stresses on the adjacent Sn grains. The stresses may be relieved through the formation of whiskers (shown in Figure 1).

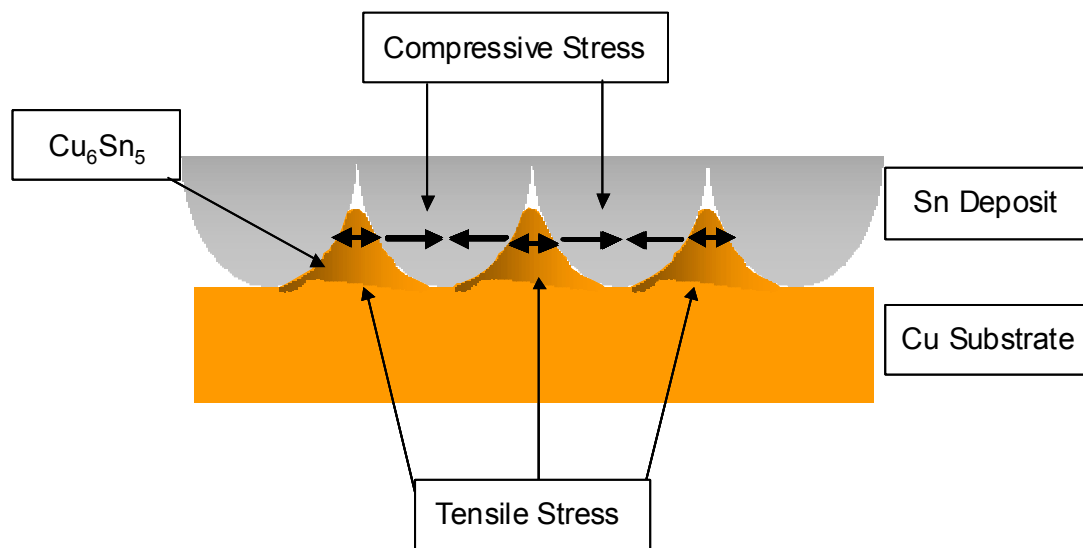


Figure 1: Mechanism for generation of internal stress in Sn platings (Adapted from reference 3).

The use of conformal coatings has been suggested as a means of controlling whisker growth, either by inhibiting the initiation of growth or by preventing whisker growths shorting between adjacent conductors (references 4 to 8). Work carried out by Boeing on commercially available coatings has shown suppression of tin whiskers when compared to the uncoated controls (references 6 and 7). However, all of the commercial coatings were eventually penetrated by whiskers, indicating that these coatings cannot be depended on as a foolproof mitigation strategy.

Discussion between NPL and conformal coating suppliers has indicated that innovative conformal coatings could be formulated to improve whisker penetration characteristics and possible whisker suppression as well. But such coatings would require a suitable test methodology to determine the effects of chemistry variations on Sn whisker mitigation. Thus NPL formed a group of coatings suppliers and end-users with the assistance of UK government funding, to develop a suitable methodology. Earlier trials on a restricted number of coatings to develop the test methodology have been reported previously (reference 10). The work reported here covers the evaluation of a wider range of coatings.

2 METHODOLOGY

2.1 TEST VEHICLE DESIGN

A test vehicle structure utilising parallel copper sheets electroplated with Sn and resembling a capacitor has been developed. Specially designed plates were etched in Olin194 copper sheet as a series of approximately 25 mm diameter interconnected discs with mounting holes and electrical connection tags, as shown in Figure 2. The interconnecting arms were necked to enable easy folding at regular points. To overcome shorts caused by whiskers growing out from insufficiently coated areas such as edges of plates or shorting back through similar areas, one set of plates was etched several

millimetres smaller. This extended the distance between the edges of adjacent discs. The smaller discs were generally used for the uncoated detection discs.

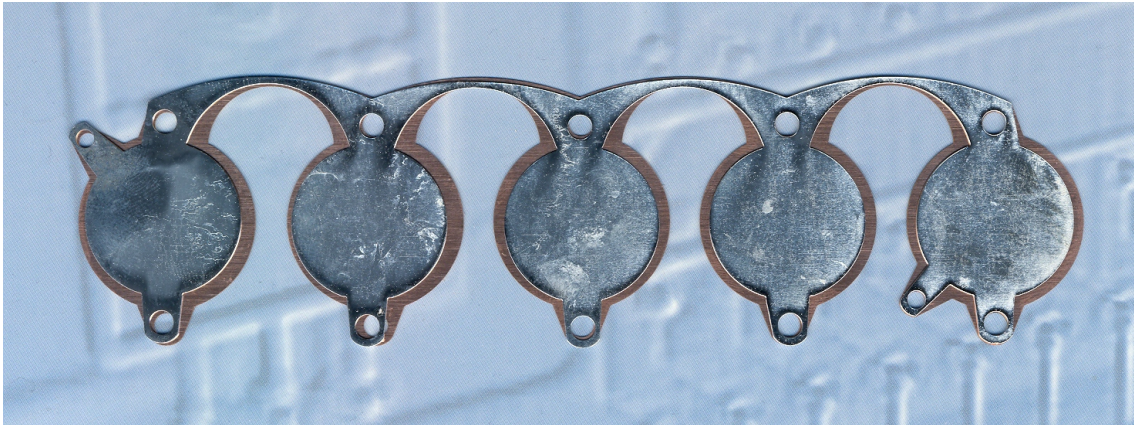


Figure 2: Plates showing smaller discs in comparison to larger (uncoated) discs

After appropriate plating and conformal coating, the etched sheets are concertinaed so that the discs became parallel as shown in Figure 3. Two such sheets were then assembled together so that an arrangement of alternate interconnected parallel plates was achieved. The interconnecting arms for each set of plates were assembled on opposite sides to ensure that only the circular plates are overlapping.



Figure 3: Folded sheet

The adjacent plates were separated by 0.25 mm thick plastic spacers (elongated for ease of assembly), and the entire structure was then mounted on two nylon machine screws and secured with nylon wing nuts. The resultant structure is shown in Figure 4 and Figure 5.

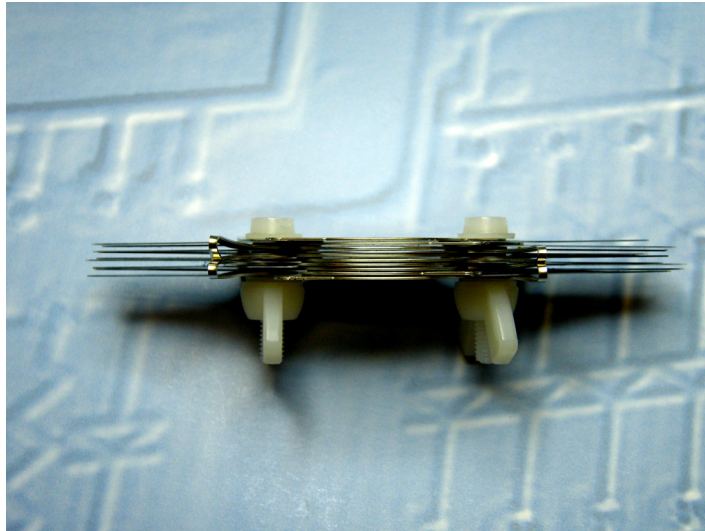


Figure 4: Two interlinked etched sheets with plastic spacers and mounting bolts

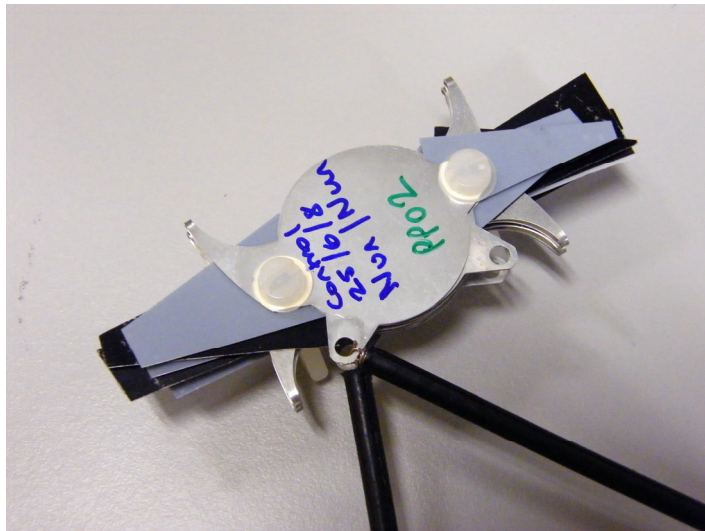


Figure 5: Parallel plate test vehicle showing elongated spacers and electrical test probes

This structure consisted of ten plates in two interconnected sets, each set insulated from the other with 0.25 mm thick spacers, resulting in 4950 mm² of overlapping plate area. The gap between the plates is shown in detail in Figure 6. By monitoring for an electrical short between the two sets of isolated plates, any Sn whiskers that grow from a plate with sufficient length to reach an adjacent plate, can thus be detected.

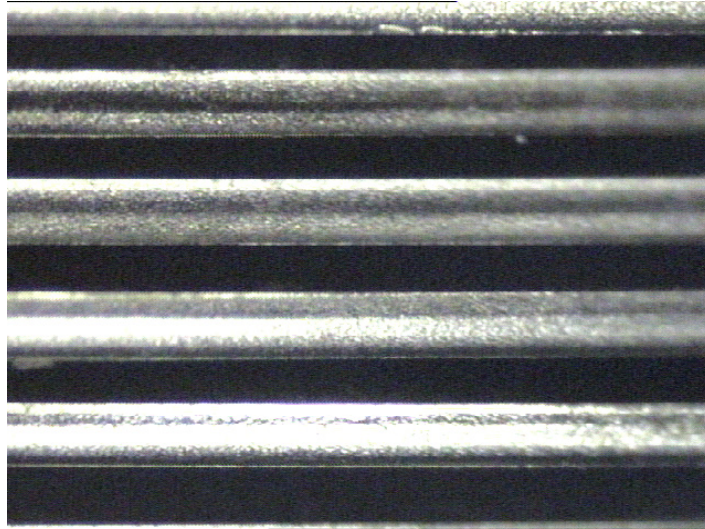


Figure 6: Detail of test vehicle showing 0.25 mm gaps, and 400 μ m plates

2.2 PLATING

All samples were electroplated as flat sheets in our in-house facility. A custom bright tin electroplating process was used, based on a stannous sulphate bath. This chemistry was developed in a previous NPL project (reference 9) and has been shown to be prone to developing Sn whiskers. To further increase the propensity to whisker, the Sn was electroplated to a thickness considerably less than normal for electronic components ($<2\text{ }\mu\text{m}$) to enable the intermetallic growth at the Sn/Cu interface to rapidly increase the internal stress in the plating. For plates intended only for detection of whiskers, the Sn was electroplated to at least $10\text{ }\mu\text{m}$, to inhibit the growth of whiskers.

2.3 SAMPLE COATING

After electroplating with the correct thickness of Sn, samples (as flat sheets) were coated by project partners with the conformal coatings as detailed below. All coating thicknesses and application methods were as per manufacturers guidelines.

2.4 ELECTRICAL TEST

Trials were conducted to determine the current carrying capacity of a single whisker. This was necessary to ensure that the electrical test parameters used were insufficient to destroy a single whisker by fusing. These trials indicated that currents in excess of $50\text{ }\mu\text{A}$ destroyed a whisker and that 3 V was sufficient to enable conduction.

For whisker detection in the coated and plated parallel plate samples, a test voltage of 4 V was used from a constant current power supply. The current flowing through any short circuit was limited to $2\text{ }\mu\text{A}$ by using $1.8\text{ M}\Omega$ resistor in series. An ammeter of suitable sensitivity was used to detect if an electrical short were present. Initially, samples were tested immediately after assembly and then at weekly intervals for the first month and then at monthly intervals. If a sample failed electrical test, the external surfaces of the outer two plates and outer extremes of other plates, were visually inspected using a binocular microscope for presence of whiskers. If whiskers were located at the edges of the plates, these were removed by tweezers and the sample retested. If the sample remained short circuit, then a short soft brush would be used

along the edges to remove any unseen whiskers. If the sample were then measured open circuit, the sample would be logged as intermittent. Samples exhibiting whiskers penetrating out of the coating on the two outer plates were also inspected and imaged using a scanning electron microscope.

2.5 TEST VEHICLE ARRANGEMENTS

The test vehicle was fabricated with four different plating and coating configurations, as detailed below and shown in Figure 7, to investigate whisker growth in different areas.

Type 1 (whisker out) vehicles were designed to monitor for whisker growth from beneath a conformal coating. The plates to be coated were electroplated with thin Sn ($<2\ \mu\text{m}$) to generate whiskers. The uncoated plates were electroplated with thick Sn ($>10\ \mu\text{m}$) to act as a detector plate.

Type 2 (whisker in) vehicles were designed to monitor for whisker growth through a conformal coating from an external uncoated source. The plates to be coated were electroplated with thick Sn ($>10\ \mu\text{m}$) to act as a detector plate. The uncoated plates were electroplated with thin Sn ($<2\ \mu\text{m}$) to generate whiskers.

Type 3 (whisker in/out) were designed to monitor for whisker growth out from under a conformal coating and then back through an adjacent coating. Both plates to be coated were electroplated with thin Sn ($<2\ \mu\text{m}$) to generate whiskers.

Type 4, designed as control samples. The plates are left uncoated and electroplated with thin Sn ($<2\ \mu\text{m}$) to generate whiskers.

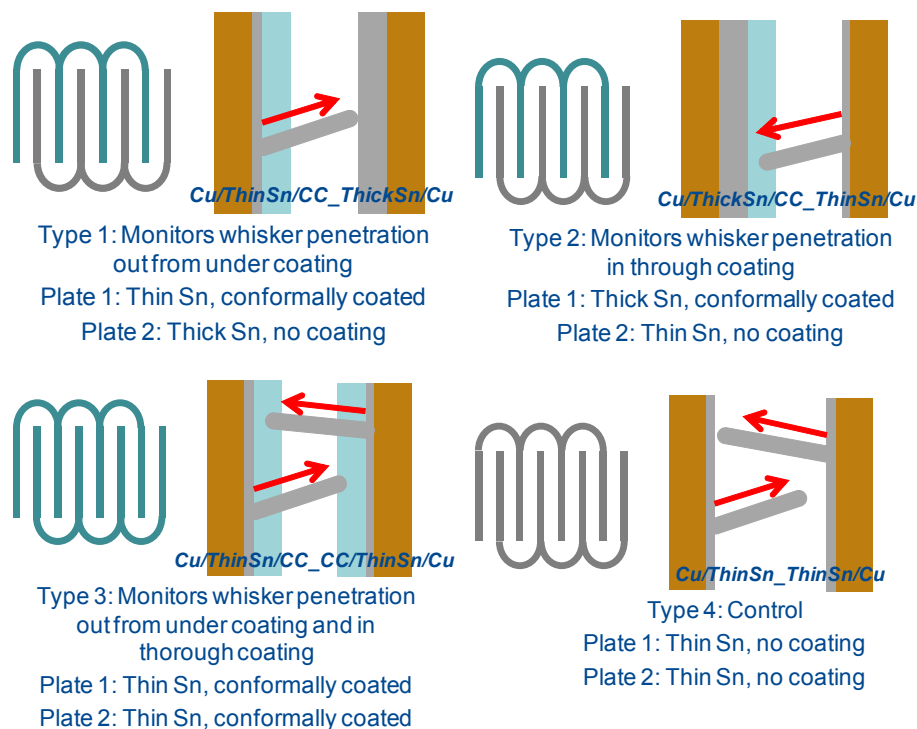


Figure 7: Schematics of the four types of test vehicle arrangement

2.6 CONFORMAL COATINGS

Two samples of each type of test vehicle were fabricated for 7 polyurethanes (designated P1 to P7), 4 acrylics (A1 to A4), 2 urethane acrylates (U1 & U2) and 7 silicones (S1 to S7). A summary of coatings is given in Table 1. Coatings P4, P5 and P6 were specially formulated using the same polyurethane material but with different levels of plasticiser to modify coating hardness, graded P4 hardest to P6 softest.

Table 1: Summary of Coating Types

Designation	Coating Type
P1to P7	Polyurethane
A1to A4	Acrylic
U1 & U2	Urethane acrylates
S1 to S7	Silicones

2.7 SAMPLE AGEING

All samples were aged at ambient temperature (22°C +/- 1°C) and humidity (40% +5%, -10%) for up to 150 days.

2.8 COATING THICKNESS MEASUREMENT

A travelling microscope was used to measure the vertical distance between ink spot on surface of coating to plated surface.

3 RESULTS

3.1 CONTROL SAMPLE

All control samples exhibited electrical shorts within 14 days of electroplating. Visual examination of control samples showed a high density of whiskers across all plated surfaces with whiskers in excess of 1 mm in length after 4 weeks. Examples of typical control samples are shown in Figure 8 and Figure 9.

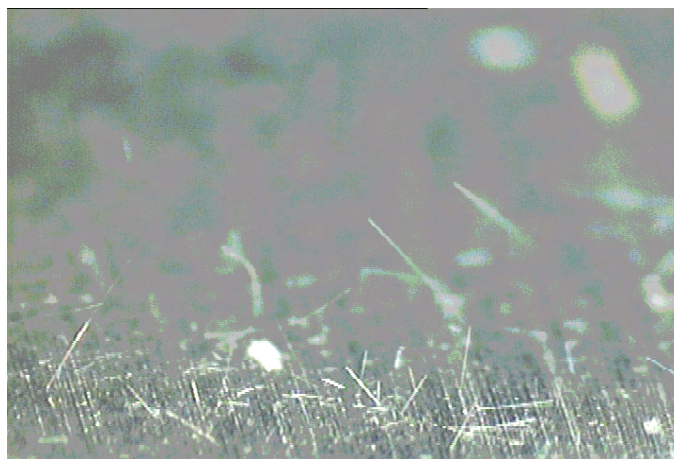


Figure 8: Outer surface of typical control sample after 43 days showing whiskers over 1 mm in length

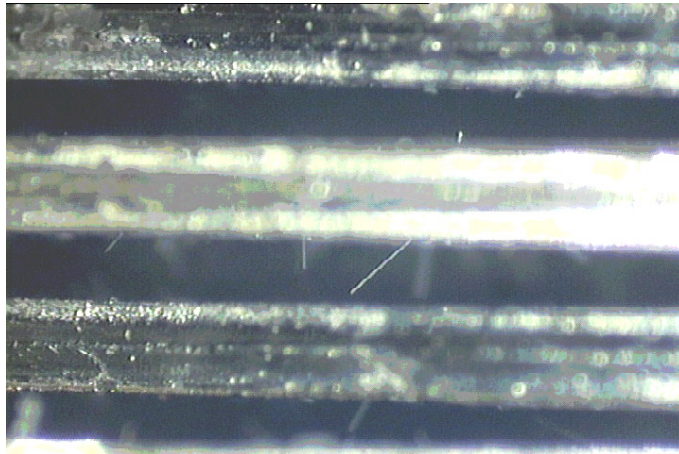


Figure 9: Detail of typical control sample gap (0.25 mm) showing bridging whisker after 3 days.

3.2 COATED SAMPLES

The electrical measurements of the coated samples are given in Table 2. Where a sample were initially logged at intermittent, if it went permanently short circuit, the number of day is noted in brackets.

Table 2: Summary of Electrical Test Measurements of Coated Samples

Coating	Sample Style	Time to first intermittent (days)	Time to first short (days)	Still open circuit (days)
A1	WI		100	152
	WO	100		152
	WIO			150 ⁽¹⁾ , 150 ⁽¹⁾
A2	WI	146		146
	WO			146, 146
	WIO			146, 146
A3	WI		18, 18	
	WO		18, 18	
	WIO	144	92	
A4	WI	19	40, (93)	
	WO		19, 19	
	WIO		93	145
P1	WI		152	152
	WO	100	100	
	WIO			150 ⁽¹⁾ , 150 ⁽¹⁾
P2	WI	39	92, (92)	
	WO	18	39, (39)	
	WIO	92, 144		
P3	WI	93	93, (145)	
	WO	40	19, (93)	
	WIO	40, 40		
P4	WI	95	(149)	149
	WO		39, 95	
	WIO	149, 149		
P5	WI		26	152
	WO			152, 152
P6	WI		152	152
	WO			152, 152
P7	WI		146, 146	
	WO			146, 146
	WIO			146, 146
S1	WI		41	146
	WO	20	(94)	146
	WIO		41	146
S2	WI	20, 94		
	WO			146, 146
	WIO			146, 146
S3	WI		19, 40	
	WO		19, 40	

	WIO		19	145
S4	WI	149		149
	WO	95	39	
	WIO	39	(149)	149
S5	WI	95		149
	WO		39, 95	
	WIO		95	149
S6A	WIO		42, 96	
S6B	WI		96, 96	
	WO		96	150
	WIO		150	150
S7	WI		42, 42	
	WO		42	150
	WIO			150, 50
U1	WI	39	39	
	WO		18, 18	
	WIO	92	39, (144)	
U2	WI	19	19	
	WO	19	19, (40)	
	WIO	93	145, (145)	

⁽¹⁾ Data from reference 10 for comparison

3.3 COATING THICKNESS

The average coating thickness achieved on the samples are detailed in Table 3.

Table 3: Average conformal coating thicknesses

Coating	Thickness (μm)
S1	15
S2	20
S3	488
S4	19
A1	6
A2	18
A3	20
A4	11
P1	15
P2	9
P3	18
P4	38
P5	57
P6	42
P7	19
U1	79
U2	13

4 DISCUSSION

4.1 COMPARISON OF COATINGS

A graphical comparison of the whisker in (WI) results is given in Figure 10. Similar comparisons for whisker out (WO) samples are given in Figure 11, and for whisker in/out (WIO) samples in Figure 12. For each sample condition, two of the concertinaed assemblies were tested, A and B.

These comparisons clearly show that if a coating is applied to both surfaces, then the ability of the coating to prevent shorting whiskers is significantly improved. However, this was still insufficient in 42% of the samples in preventing intermittents or shorts occurring during the 150 day test period. For whisker in samples, 70% of samples exhibited intermittents or shorts. This figure is the same for the whisker out samples.

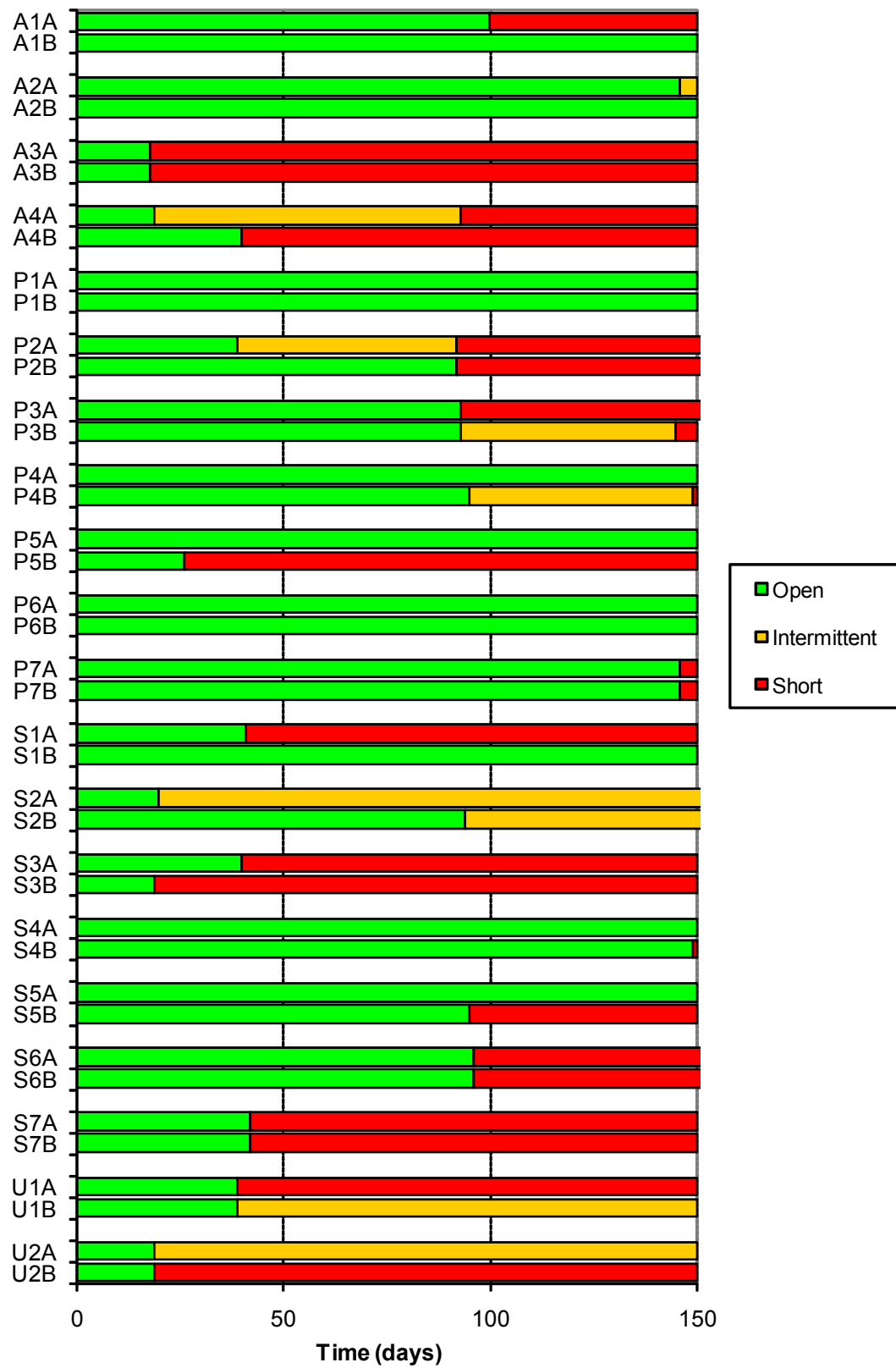


Figure 10: Electrical Measurements of Whisker In (WI) Samples

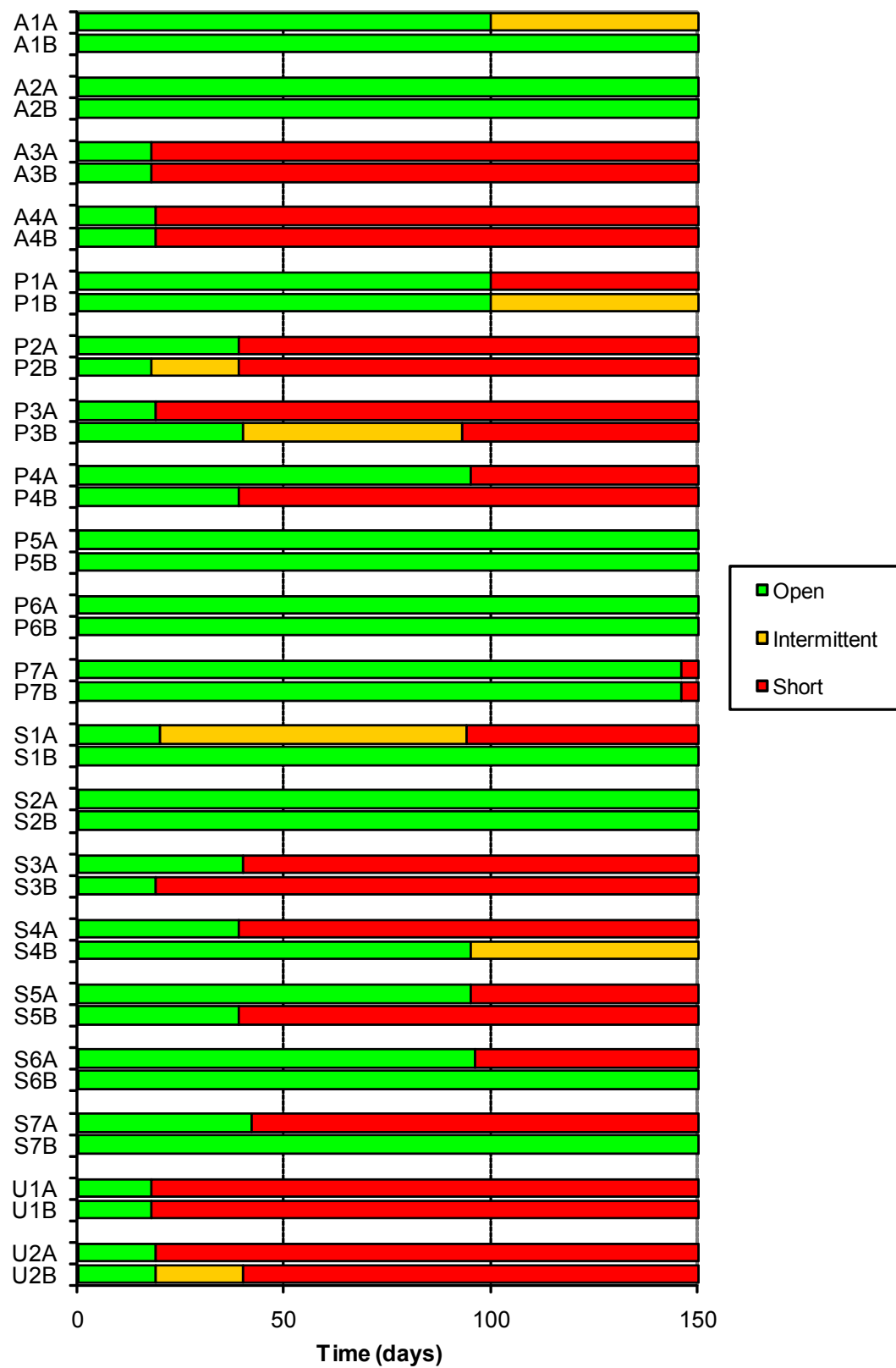


Figure 11: Electrical Measurements of Whisker Out (WO) Samples

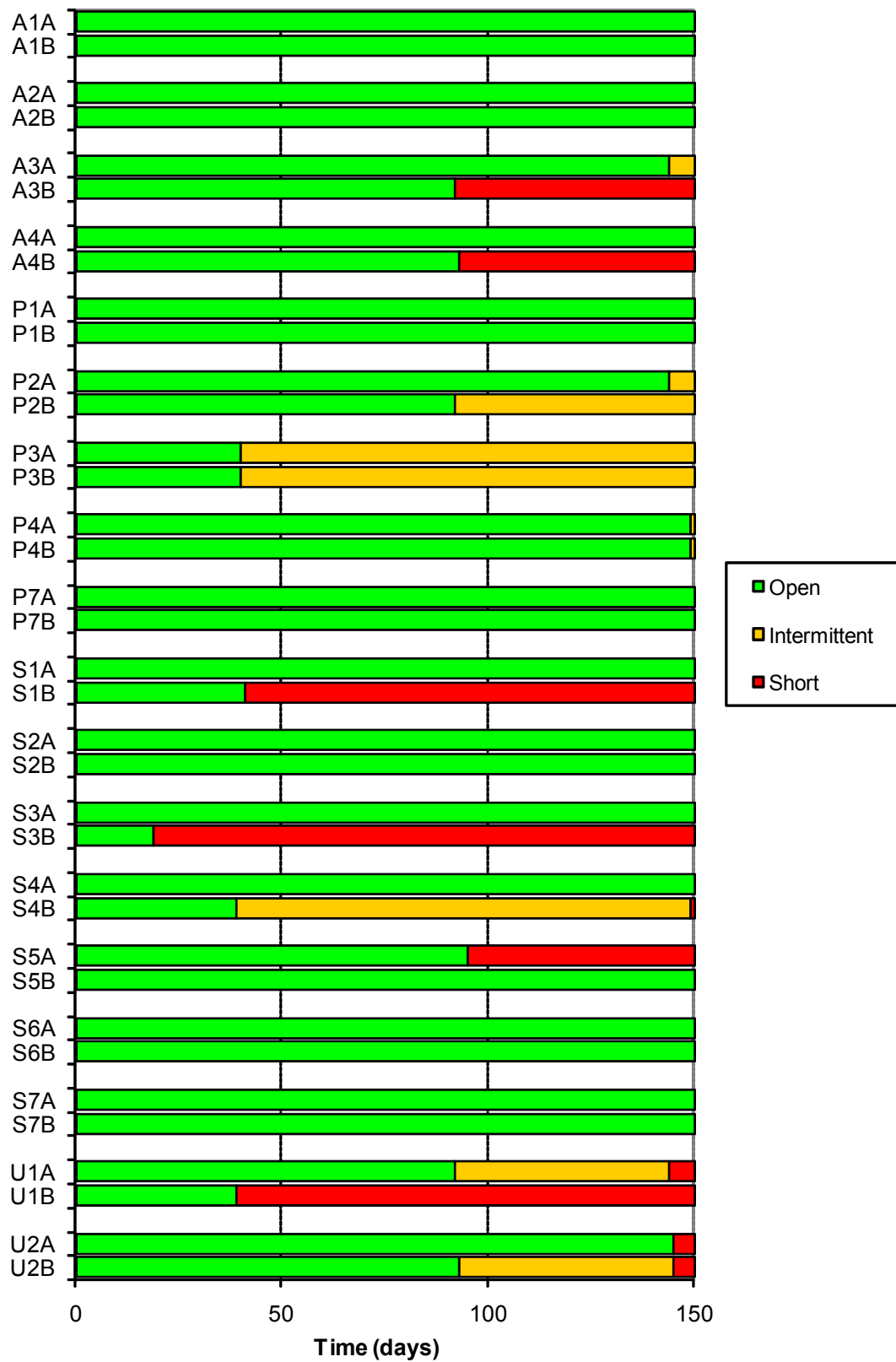


Figure 12: Electrical Measurements of Whisker In/Out (WIO) Samples (data from reference 10 for materials A1 and P1 added for comparison)

4.2 ACRYLIC COATINGS

A summary of performance of the four acrylic conformal coatings is given in Table 4. All coatings developed shorts/intermittents and edge whiskers during testing. Typical edge whiskers are shown in Figure 13. Two materials exhibited whiskers erupting through coating. Typical erupting whiskers can be seen in Figure 14 to Figure 20.

Table 4: Summary of acrylic coating performance

	A1	A2	A3	A4
Whiskers In Shorts	Intermittent	Intermittent	Yes	Yes
Whiskers Out Shorts	Intermittent	No	Yes	Yes
Whiskers In/Out Shorts	Intermittent	No	Intermittent	Intermittent
Edge Whiskers	Yes	Yes	Yes	Yes
Erupting Whiskers	Yes	No	Yes	No

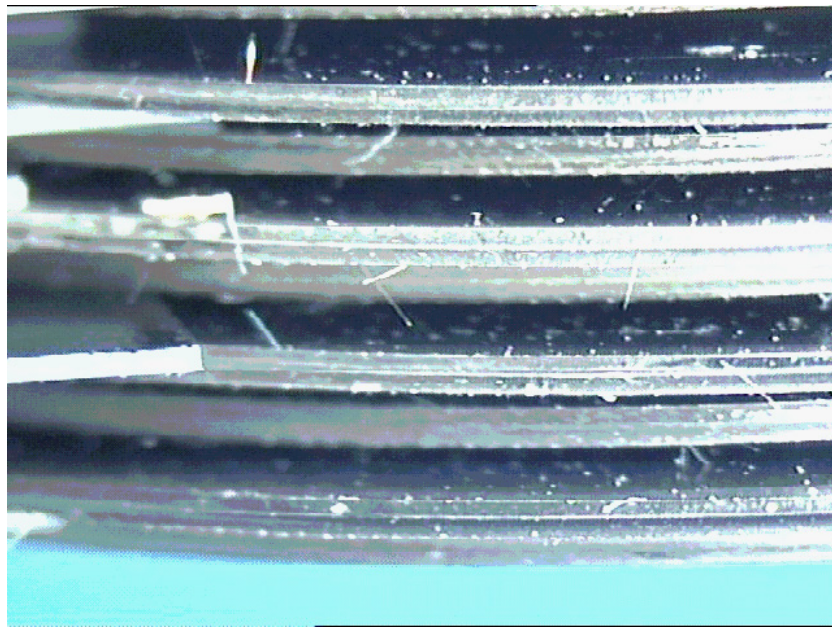


Figure 13: Typical edge whiskers on acrylic coating (both plates coated)



Figure 14: Typical erupting whisker (~150 μm in length) on acrylic sample.

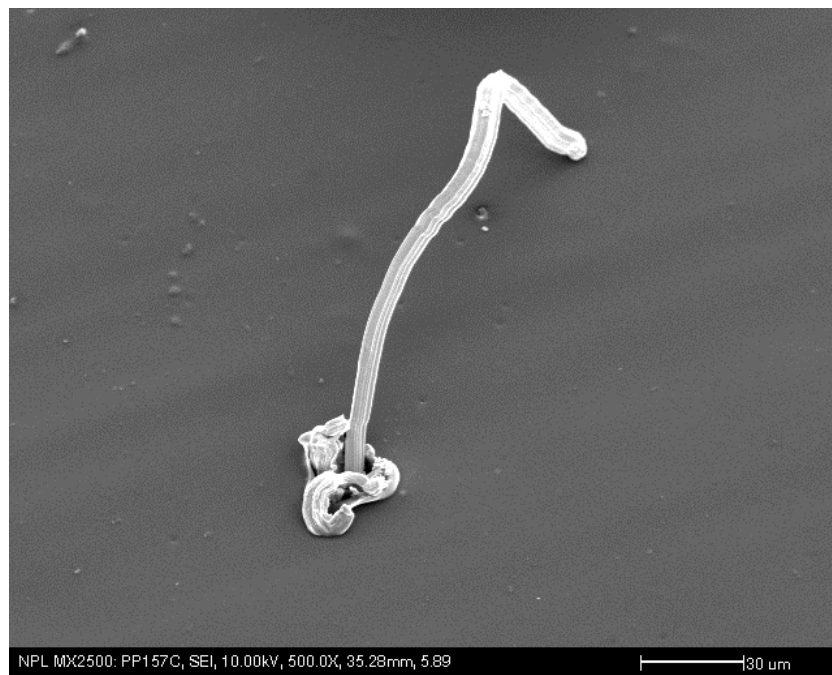


Figure 15: Typical erupting whisker (~200 μm in length) on acrylic sample.



Figure 16: Typical erupting whisker (~250 μm in length) on acrylic sample.

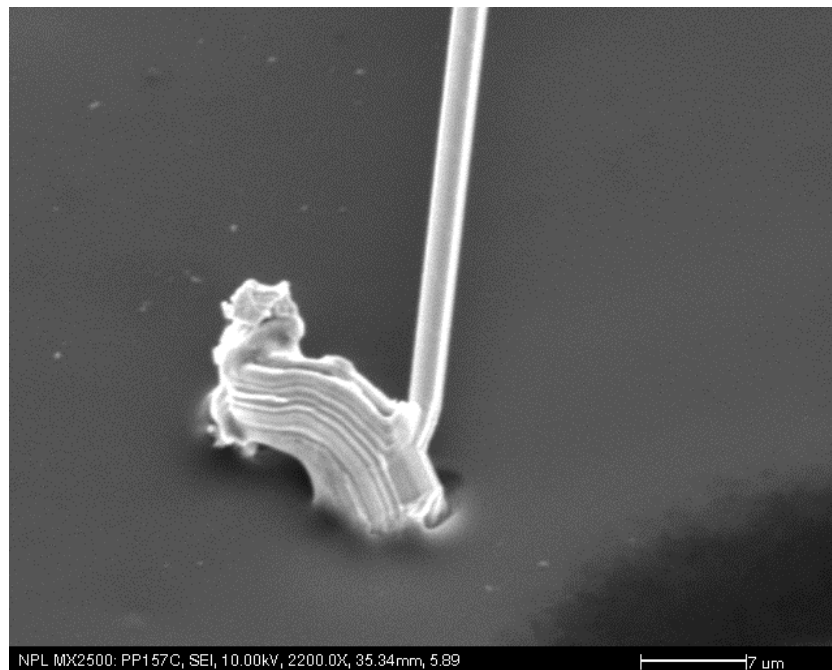


Figure 17: Root of erupting whisker shown above



Figure 18: Typical erupting whisker (~300 μm in length) on acrylic sample.



Figure 19: Root of erupting whisker shown above

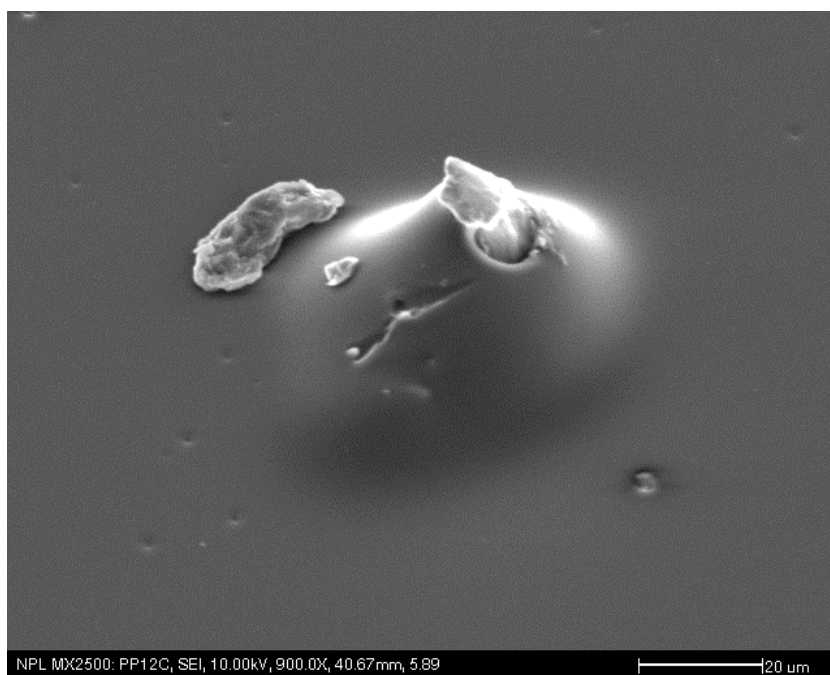


Figure 20: Typical emerging whisker (~20 μ m in length) on acrylic sample

4.3 POLYURETHANE COATINGS

A summary of performance of the five different polyurethane conformal coatings is given in Table 5. Three of the five materials exhibited edge whiskers, whilst all polyurethane materials developed shorts or intermittents during testing. Typical edge whiskers are shown in Figure 21. No erupting whiskers were noted on polyurethane samples. With the data in Figures 10 and 11 it is not possible to draw conclusion on whether the different hardnesses of the P4/5/6 coatings had a significant effect.

Table 5: Summary of polyurethane coating performance

	P1	P2	P3	P4/5/6	P7
Whiskers In Shorts	Intermittent	Yes	Yes	Intermittent	Intermittent
Whiskers Out Shorts	Yes	Yes	Yes	Yes	No
Whiskers I/O Shorts	No	Intermittent	Intermittent	Intermittent	No
Edge Whiskers	No	Yes	Yes	Yes	No
Erupting Whiskers	No	No	No	No	No

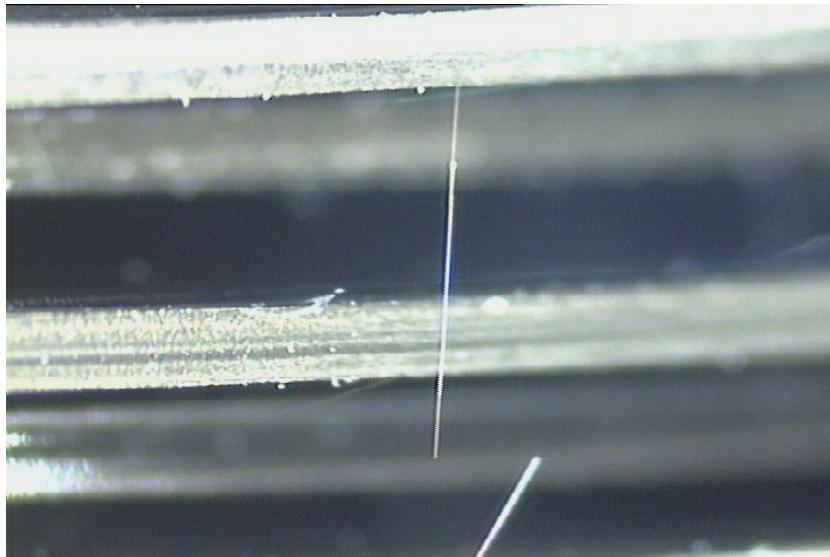


Figure 21: Typical edge whisker on polyurethane coating (both plates coated).

4.4 SILICONE COATINGS

A summary of performance of the seven different silicone conformal coatings is given in Table 6. All silicone coating materials examined exhibited edge whiskers, and all materials developed shorts or intermittents during testing. Typical edge whiskers are shown in **Figure 22**. No erupting whiskers were noted during visual inspection of the silicone samples. It should be noted that samples S6 and S7 were only coated on one side of the plate. This necessitated the assembly of the samples has flat sheets, and therefore inspection of the coated surface was not possible.

During SEM inspection, erupting whiskers were noted from a damaged or incomplete area of coating, as shown in Figure 23. In other areas, a number of whiskers had deformed the coating without penetrating through it (tenting whiskers). Examples of these can be seen in Figure 24 and Figure 25. On whisker-in samples, a number of surface dimples were seen and in several cases, there were indications of penetrating whiskers deforming the silicone coating away from the whisker. Examples of this are shown in Figure 26 and Figure 27.

Table 6: Summary of silicone coating performance

	S1	S2	S3	S4	S5	S6	S7
Whiskers In Shorts	Intermittent	Intermittent	No	Intermittent	Intermittent	Yes	Yes
Whiskers Out Shorts	Intermittent	No	No	Intermittent	No	Yes	Yes
Whiskers in/out shorts	Intermittent	No	Intermittent	Intermittent	Intermittent	Intermittent	No
Edge Whiskers	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Erupting Whiskers	No	No	No	No	No	N/A	N/A

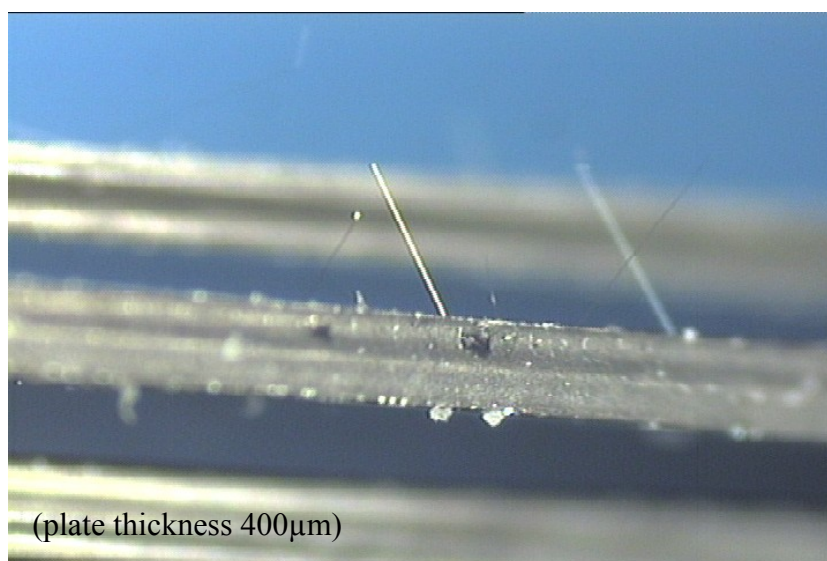


Figure 22: Typical edge whiskers on silicone coating (both plates coated)

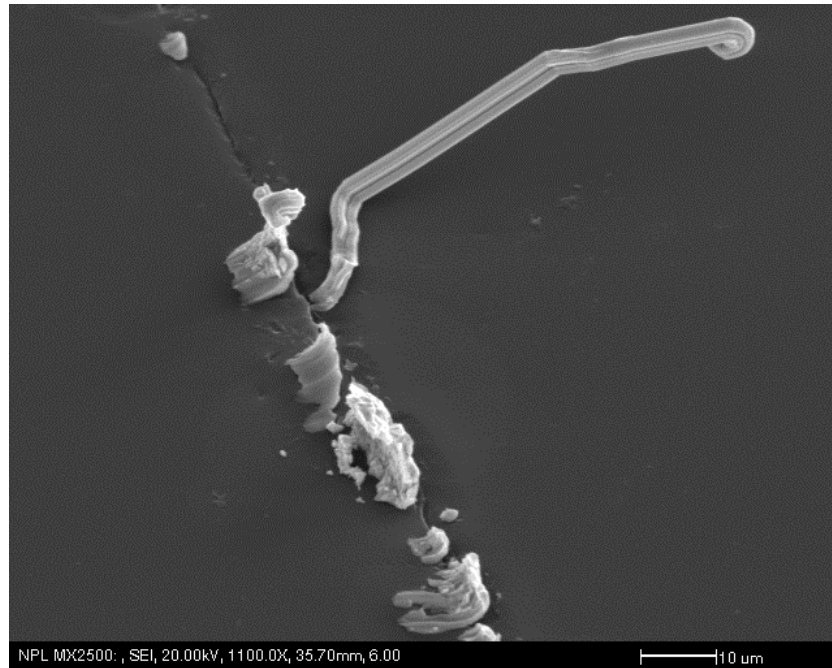


Figure 23: Erupting whisker from damaged area of silicone coating

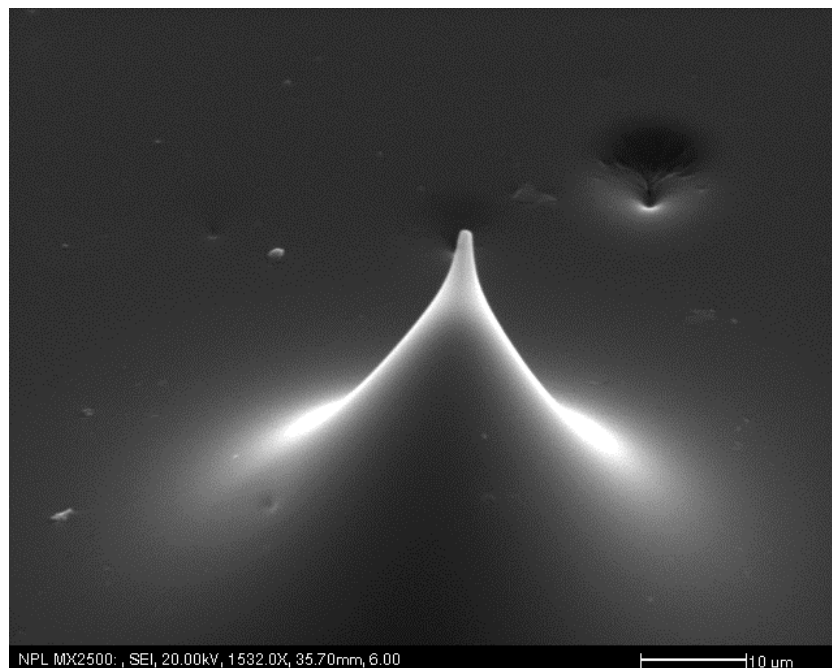


Figure 24: Tented whisker on silicone coating

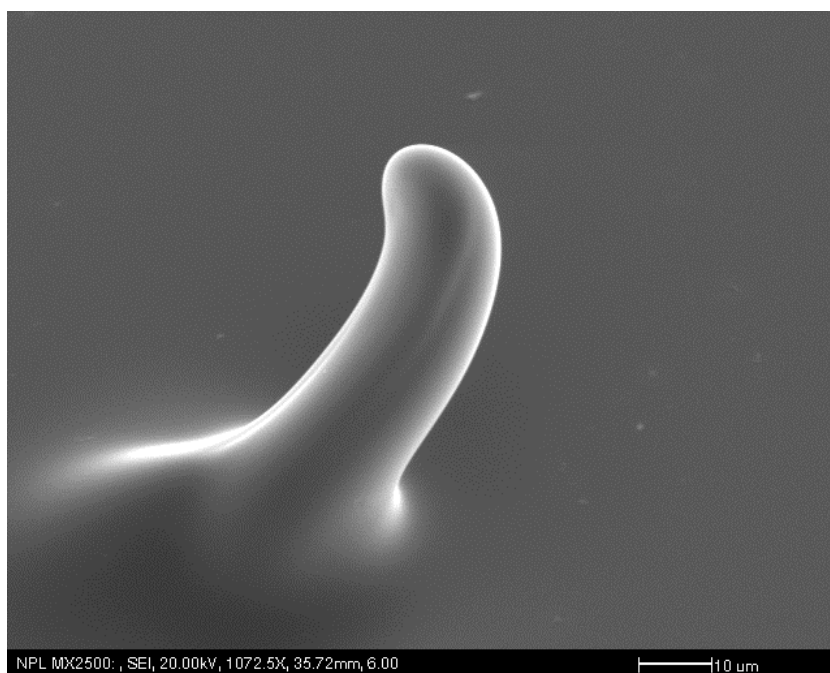


Figure 25: Tented whisker on silicone coating

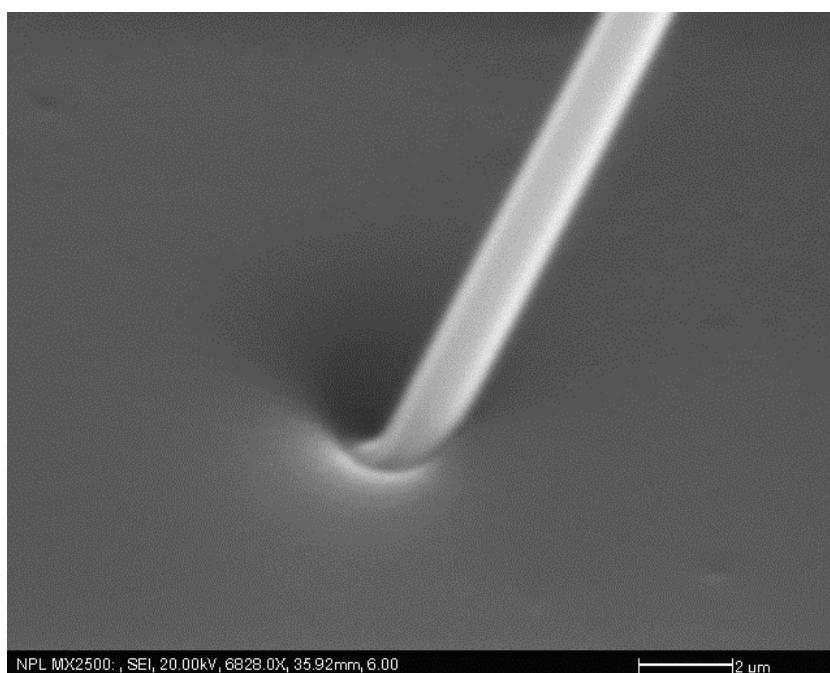


Figure 26: Penetrating whisker on silicone coating

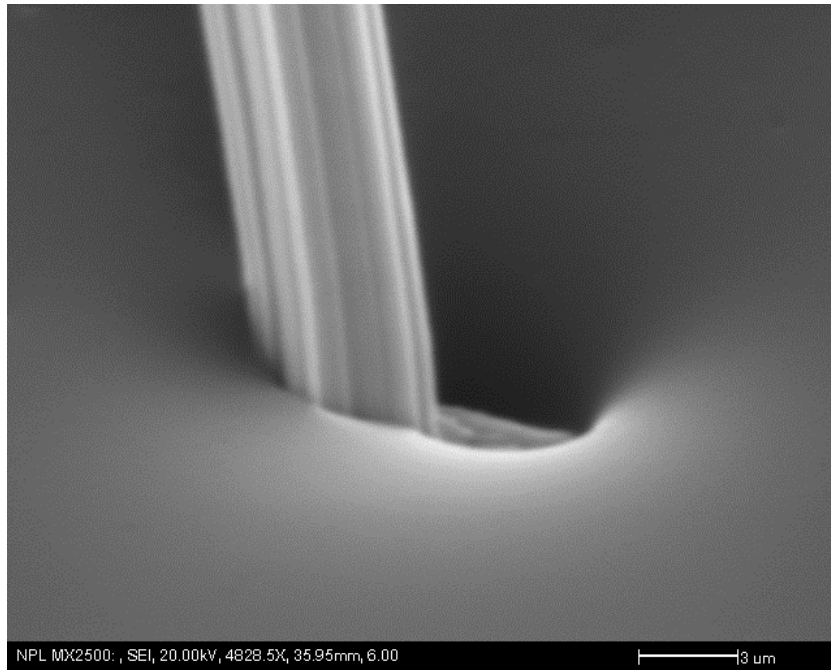


Figure 27: Penetrating whisker on silicone coating

4.5 URETHANE ACRYLATE COATINGS

A summary of performance of two different urethane acrylate conformal coatings is given in Table 7. Both materials examined exhibited edge whiskers, and developed shorts or intermittents during testing. Typical edge whiskers are shown in Figure 28. No erupting whiskers were noted on urethane acrylate samples. No erupting whiskers were noted during visual inspection.

During SEM inspection, an erupting whisker was noted as shown in Figure 29. On the edge of one sample, a whisker was noted that appeared to penetrate under a coating, emerging back through the coating a short distance later. This is shown in Figure 30.

Table 7: Summary of urethane acrylate coating performance

	U1	U2
Whiskers In Shorts	Intermittent	Yes
Whiskers Out Shorts	Yes	Yes
Whiskers In/Out Shorts	Intermittent	Yes
Edge Whiskers	Yes	Yes
Erupting Whiskers	No	No

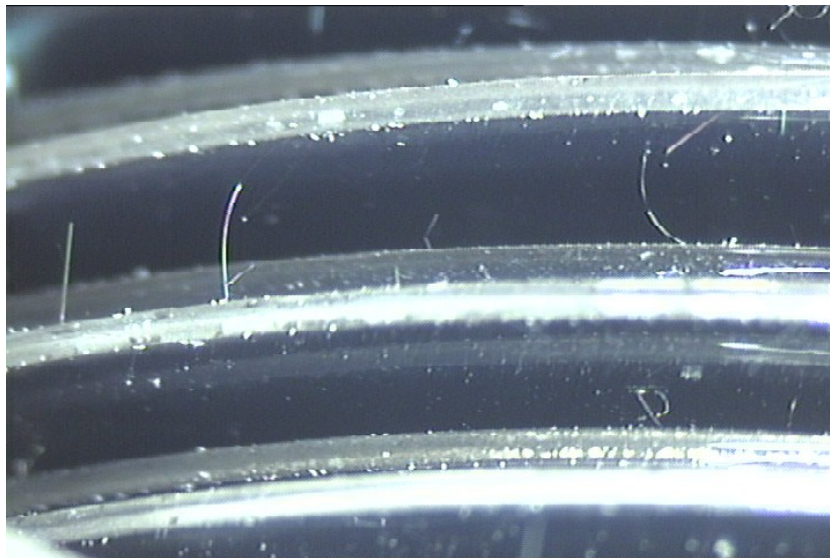


Figure 28: Typical edge whisker on urethane acrylate coating (both plates coated)

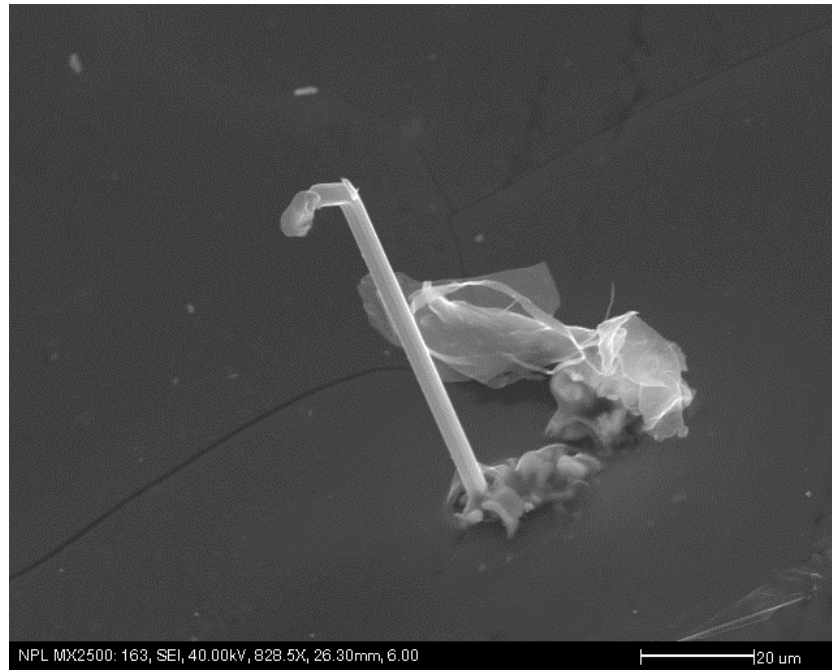


Figure 29: Erupting whisker (~50 μm in length) on urethane acrylate sample.

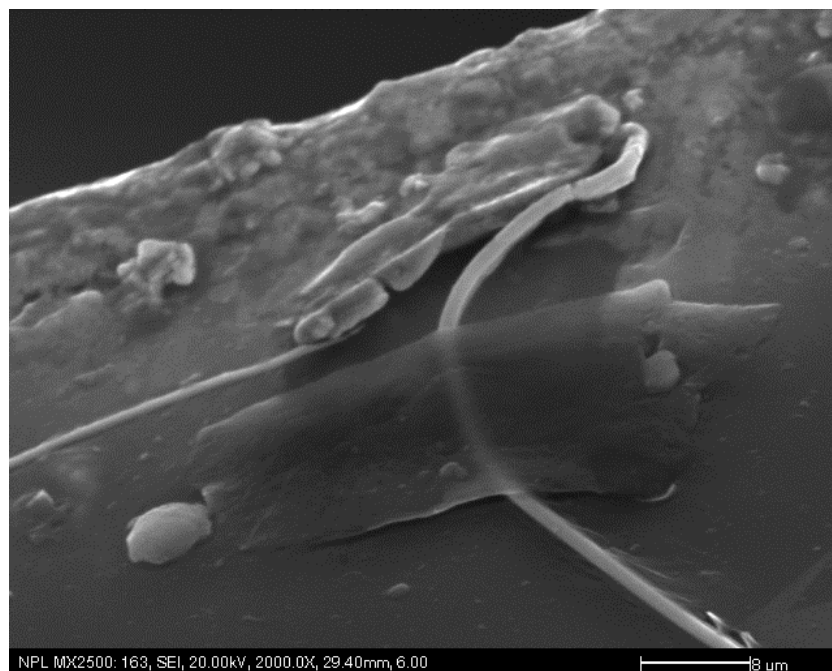


Figure 30: Possible penetrating and emerging whisker on urethane acrylate sample

5 CONCLUSIONS

The technique devised using interdigitated electroplated discs has been proven to successfully determine the relative ability of conformal coatings to mitigate against Sn whisker growth. All the control samples without conformal coatings developed whiskers of sufficient length ($>250\text{ }\mu\text{m}$) to cause electrical shorts between two adjacent isolated plates. The electrical monitoring system was able to detect these shorts and the current in the detection circuit was restricted to a level sufficient to prevent destruction of the whiskers. The control samples all exhibited electrical shorts within 14 days, some within as few as 3 days, allowing for a relatively rapid i.e. 150 day evaluation of the Sn whisker mitigation benefits of conformal coatings. Longer term testing would be required to ensure the coated samples remained whisker free.

All four types of coatings tested, acrylics, polyurethanes, silicones and urethane acrylates, have been shown to suppress the formation of whiskers where coating quality was good, compared to uncoated samples, in up to 150 days of testing. Visual inspection of the external plates of the samples indicated that only 2 coatings of 18 tested showed whiskers erupting through the coating. Both coatings with erupting whiskers were acrylic coatings. Subsequent SEM examination of electrically failed samples also found an erupting whisker on a urethane acrylate coating and on a damaged silicone coating.

Whiskers penetrating out from under coatings were found extensively in areas where the coating was thinner, or there were other coverage issues. All the coatings evaluated except two of the polyurethane coatings exhibited whisker growth from under coated plates in the region of the plate edges. Coating coverage was an issue with a majority of coatings evaluated. From this work no conclusions can be drawn as to whether hardness has an effect on mitigation with polyurethane coatings.

Where both plates of the samples were coated, five of the coatings evaluated did not exhibit electrical shorts at any time during the 150 days of testing. These were one acrylic, two polyurethane and two silicone coatings.

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