Designed Experiment to Determine the Reliability of Various Commercial Plating Baths and the Key Factors Affecting Whisker Formation

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Abstract

In order to develop a reliable lead-free substitute for its products, FCI assembled a global team of engineers to design and run a series of statistically designed experiments. These experiments were designed to provide maximum information about pure tin-plating baths, plating process control, whisker drivers and mitigators, and the effects of environment on whiskers.

The eight main input variables for this DOE included; tin baths-3 levels, nickel thickness-2 levels, topcoat type-2 levels, topcoat thickness-2 levels, preconditioning-2 levels, aging environment-3 levels, aging duration-7 levels, and observed stress zones-4 levels. We also collected some data on no nickel versus nickel. Our test vehicle was a surface mount R/A header (Bergstik®).

The response variables included whisker density, whisker length, solderability, and solder joint reliability. We used total whisker length for data analysis but also measured "effective whisker length" for comparison. Our experimental constants included all raw materials, equipment, tooling, and processes necessary to make the test samples.

We statistically analyzed all results that were collected monthly over a six-month period and were able to draw conclusions about which input variables significantly retarded or promoted whisker growth. This included all sample input variables, sample observation points, and environments. We were also able to determine solder joint reliability in SMT applications. All results will be presented as well as plans for continued investigations.

Background

As FCI was fully committed to the lead-free effort, we needed to select the best globally available bath(s) to use for reel-to-reel electroplating. Bath selection must be based not only on propensity to whisker but also bath maintainability (ease of processing), technical support, cost, and deposit performance. Based on two years of preliminary investigations, we selected matte pure tin as our coating of choice. See References 1-3 for background. In addition to selecting the best commercial tin baths, there were other questions to answer. There were questions regarding optimum tin thickness and nickel underplating requirements/advantages. There were questions regarding how to test for whiskers and, of course, what conditions promote whisker growth.

Bath maintainability was studied extensively in a separate DOE (Reference 4). In that DOE we established and validated the operating limits for the same matte pure tin baths as were evaluated in this DOE. Results showed that all three baths had wide operating windows to produce acceptable coatings.

FCI is a member of the Connector Collaboration Team consisting of Tyco Electronics, FCI, Molex, and Amphenol which started early in 2003. Due to the lack of industry standards and test methods, the Collaboration Team objectives were to work together to offer the best solutions for customers and minimize their cost impact. An important element of the collaboration was to develop common test methodologies so that data presented to customers would have consistency regardless of which company generated the data. The resulting test methodologies developed by the Collaboration Team were adopted by FCI and used throughout its research on lead substitutes. This DOE employed those methodologies. A summary of the Collab Team work is found in Reference 5.

Purpose

The purpose of this DOE was to identify at least two lead-free baths (pure matte tin) to be used worldwide by FCI and its qualified plating vendors. Selection will be based on performance, operability, and availability. Also, determine the optimum tin thickness and the nickel underlayer thickness. Determine the effects of preconditioning, aging method, and time, on whisker formation and growth. Determine the effects of post-plating bending and mechanical damage on performance. Generate sufficient samples and data to obtain statistically valid results.

I. Experimental Design

As mentioned previously, we had a large number of input variables to analyze. We also wanted to insure that our results were statistically valid. So, we used an experimental design to structure the plating runs to prepare samples for the subsequent environmental exposures. Plating runs were replicated to determine the degree of experimental error-especially for whisker formation. The following three sections outline test sample generation, input and response variables and constants, and metrology for the experiments.

A. Test Sample Generation

We chose a standard Bergstik® SMT Header, 2x5 positions, p/n 95278-101, for our test vehicle. Test samples were duplex plated with the various candidate pure tin baths as well as the standard 90/10 tin-lead control bath.

The general sample preparation process was as follows. First, reels of square rolled wire were stamped into pins and attached to bandoliers. Next, pins were duplex plated with gold in the contact area and the various tins and tin-lead on the SMT end. Next plated pins were assembled with housings to make the 2x5 headers. During assembly, the pins were bent to form the SMT legs. The bend R/t ratio was approximately 0.9. In order to view the SMT bend areas adequately with the SEM for whiskers, all samples had to be slightly modified. The pins were carefully pushed partially thru the housing to expose more of the SMT end of the pin. As the housing is designed to retain pins by an interference fit, the electroplated coatings were scratched as the pins were partially pushed out.

The resulting sample preparation enabled us to evaluate 4 “stress zones” on each pin. These zones are depicted in Figure 1. The Flat Zone was our baseline to compare coatings without any mechanical stress. The Bend Zone had compressive stress. The Pin Tip Zone was a high current density area and was shaped before plating by a trim and swage operation. The trim and swage operation imparted stresses to the substrate material. The Scrape Zone had mechanical scratches in the topcoat caused by the plastic housing repositioning. After sample preparation, all parts were tested as described in the following sections.

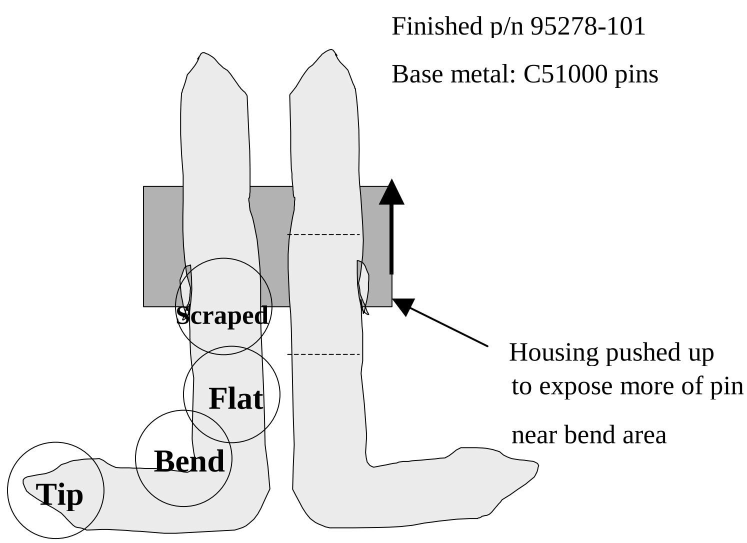


Figure 1. Bergstik® Header Test Samples with the Four Zones

B. Input & Response Variables & Constants

We had a large number of independent variables each with several levels to control. These are summarized in Table 1 below.

Table 1. Identity of Input Variables in Statistical Model for ANOVA of Full Data Set

	Description of Input Variable	Levels	Values
1	Pre**c**onditioning method (**C**)	2	None, Thermal Shock (TS)
2	**A**ging method	3	Dry Heat (DH), Heat & Humidity (HH), Room Temp (RT)
3	Duration of aging (**M**onth)	7	0, 1, 2, 3, 4, 5, & 6 Months
4	**P**lating type	2	Sn, Sn-Pb
5	**P**lating **B**ath **B(P)**	4	Vendor "A", "B", "C", & 90/10 SnPb control
6	Nominal **N**ickel thickness	2	1.27 µm, 2 µm
7	Nominal top **L**ayer thickness	2	2 µm, 4 µm
8	**S**tress zone	4	Bend, Tip, Scrape, Flat

Our primary response variables included; solderability, solder joint reliability, whisker density, and whisker length. Solderability was evaluated on the as-plated pins. Solder joint reliability was evaluated on finished parts mounted onto PWB's. Whisker density and whisker length were evaluated via SEM.

The "constants" for producing the samples included: raw material lot, stamping die and press, terminal part number, plating line and speed, semi-brite nickel at fixed current density, tin bath current density, molded housings, assembly machine, and finished p/n. All parts were plated and assembled at the FCI plant in Besancon, France, with participation by the bath suppliers during the plating trials.

C. Metrology/Equipment/Test Details

We used the following test procedures and equipment for our evaluations.
SEM at variable magnifications for whisker examination-density & length
Test Chambers for TS, DH, and HH testing at the following conditions:

Thermal Shock: 500 cycles; -55°C to +85°C, 10 minute dwell at temperature
Dry Heat: 50+/- 5°C for 6 months
Heat & Humidity: 52+/-5°C and 90% +/-5% Relative Humidity for 6 months
Room Temperature: 23+/-5°C for 6 months

II. Experimental Procedures

A. General Flow and Plating Trial Design

Figure 2 below shows the general test flow for sample preparation and testing.

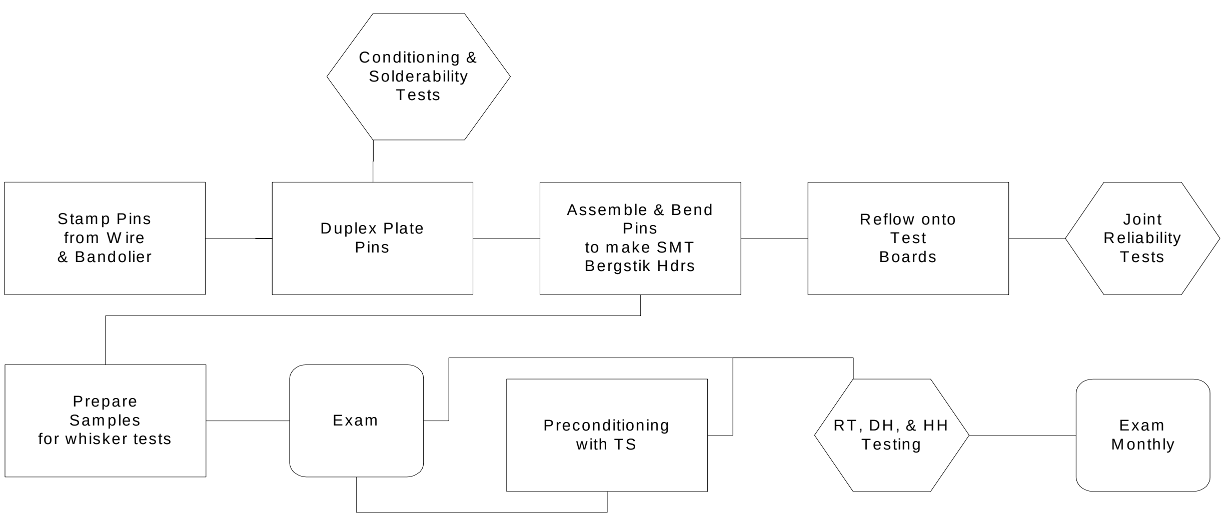


Figure 2. General Test Sample Flow

The plating runs were designed for randomness and replication. Table 2 below shows the plating run details and sequence of runs.

Table 2. Sequence of Plating Trials

Plating Run	Plating Type	Plating Bath	Nominal Thickness / µm	
			Ni Underplate	Top Layer (Sn or Sn-Pb)
A1	Sn	Bath “A”	1.27	2
A2	Sn	Bath “A”	2	4
A3	Sn	Bath “A”	1.27	2
A4	Sn	Bath “A”	1.27	4
A5	Sn	Bath “A”	2	4
A6	Sn	Bath “A”	1.27	2
A7	Sn	Bath “A”	2	4
A8	Sn	Bath “A”	2	2
B1	Sn	Bath “B”	2	2
B2	Sn	Bath “B”	1.27	2
B3	Sn	Bath “B”	2	2
B4	Sn	Bath “B”	1.27	4
B5	Sn	Bath “B”	1.27	4
B6	Sn	Bath “B”	2	2
B7	Sn	Bath “B”	1.27	4
B8	Sn	Bath “B”	2	4
C1	Sn	Bath “C”	2	4
C2	Sn	Bath “C”	2	2
C3	Sn	Bath “C”	1.27	4
C4	Sn	Bath “C”	2	2
C5	Sn	Bath “C”	1.27	4
C6	Sn	Bath “C”	2	2
C7	Sn	Bath “C”	1.27	2
C8	Sn	Bath “C”	1.27	4
D1	Sn-Pb	90/10 SnPb Control Bath	2	4
D2	Sn-Pb	90/10 SnPb Control Bath	2	4
D3	Sn-Pb	90/10 SnPb Control Bath	1.27	4
D4	Sn-Pb	90/10 SnPb Control Bath	2	2
D5	Sn-Pb	90/10 SnPb Control Bath	1.27	2
D6	Sn-Pb	90/10 SnPb Control Bath	1.27	2
D7	Sn-Pb	90/10 SnPb Control Bath	1.27	2
D8	Sn-Pb	90/10 SnPb Control Bath	2	4

After plating and assembly, samples were prepared and subjected to the preconditioning and aging conditions to promote whisker growth. Whisker formation and growth were assessed by counting the number of whiskers appearing over each zone of the plated surface and by determining the maximum whisker length. Whisker count and maximum whisker length were analyzed as independent responses. Many of the recorded data indicated that no whiskers were observed; these were encoded as zero (0) values. In addition to single values, the recorded whisker length data included ranges of values (e.g., “20 – 140 µm”) and upper limits of the values (e.g., “< 5 µm”); the former were encoded as the maximum of the range, and the latter were encoded as the stated upper limit. Since very short whiskers were deemed irrelevant, reported values of maximum whisker length less than or equal to 5 µm were ignored, i.e., they were coded as zero values. An example data matrix, Table 3 below, shows an example of the raw data and combinations of preconditioning and aging done in series. Half the population was subjected only to the three aging treatments. The other half of the population had preconditioning followed by one of the three aging treatments. The data was initially only collected in the Bend Zone. At two months, we started to collect data in the other zones as well. Some samples were examined by x-ray diffraction to determine the preferred grain orientations. Baths B and C had preferred orientations of 220. Bath A preferred orientations were 301,411, and 321.

Table 3. Example of Experimental Data

Plating	DH (No TS)		HH (No TS)		RT (No TS)		TS + DH		TS + HH		TS + RT	
Run	Count	Length	Count	Length	Count	Length	Count	Length	Count	Length	Count	Length
B1	0	0	30	9-14	0	0	0	0	35	12-19	0	0
B2	0	0	0	0	0	0	0	0	40	12.8	0	0
B2	0	0	60	19	0	0	0	0	0	0	0	0
B4	0	0	40	11-40	0	0	75	11-40	60	8-24	55	8-13
B5	0	0	5	<4	0	0	65	11-12	35	17-101	45	8.7
B6	0	0	0	0	0	0	0	0	50	12-30	0	0
B7	0	0	15	13-17	0	0	40	11	40	10-51	45	7-15
B8	0	0	20	24	0	0	60	10-15	37	7-19	60	11.9

It's important to define what is meant when reporting "whisker length". We reported "maximum" whisker length as opposed to "effective" whisker length or "normal" whisker length. As one can see in Figure 3 below, maximum length is worst case. For practical reasons (whisker break off/bridging) effective length is generally a better measure.

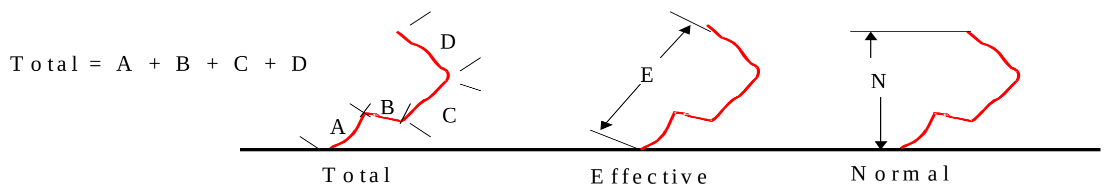


Figure 3. Whisker Length Definitions and Measurement Techniques

B. Statistical Analysis

The whisker count and maximum whisker length data for the entire data set (Bend Zone) were evaluated by analysis of variance (ANOVA) to determine the significance of effects at the 95% confidence level. Data handling and basic calculations were performed using Microsoft Excel 2000. ANOVA was conducted using JMP statistical software, Version 4.0.2.

The experiment was originally designed only to collect and statistically analyze Bend Zone whisker data. However, as the experiment progressed preliminary data examination also indicated that the stress Zones had a significant effect on whiskering. Thus, after two months we started to collect whisker data on the Tip and Scrape Zones and at six months added data from the Flat Zone as a "control". The stress zones were analyzed independently as an entire data set followed up with the "best case" conditions to estimate confidence levels to meet 30µm and 50µm specifications as above. The variability associated with experimental results was evaluated by investigation of variation of observed values among replicate trials. Confidence levels were estimated for meeting specific limits on maximum whisker length (30µm and 50µm) after the most severe treatment for accelerating whisker growth (aging for 6 months in humid heat after thermal shock preconditioning).

III. Experimental Results

Statistical analysis showed the significance of each input variable. Overall, except for nickel thickness, all variables had a statistically significant effect on whisker growth. The details related to each of the variables are shown below. Interactions amongst the variables were also analyzed and a few of the more significant ones included as well.

A. Preconditioning

The main effect of preconditioning was significant for both whisker count and length. Preconditioning with thermal shock was effective in promoting both whisker count and length with average increases by factors of 3.6 and 1.5 respectively when used in series with aging. In other words, using preconditioning in series with aging increased the number of whiskers by nearly 4 and maximum average whisker length by 50%. (The average maximum whisker length is the average taken over many samples using the maximum value for each sample). Table 4 below shows the data.

Table 4. Effect of Preconditioning (TS) on Whiskers

Main Effect	Test	Data Count	Avg. Whisker Count	Avg. Max. Whisker Length
C(Preconditioning)	**No**	1341	7.7	9.1
	TS	1341	27.4	13.9

B. Aging Method

The main effect of aging method was significant for both whisker count and length. But, it depended on the particular aging method. Dry Heat (DH) did not enhance either whisker count or growth. Room Temperature (RT) aging had some minor effect on count and growth. Heat & Humidity (HH) by far was the most severe aging method for acceleration of whisker formation and growth. As one can see in Table 5 below, HH aging increased whisker length by a factor of 20 over DH and nearly 7 over RT aging.

Table 5. Effect of Aging Method on Whiskers

Main Effect	Test	Data Count	Avg. Whisker Count	Avg. Max. Whisker Length
A (Aging method)	**DH**	894	11.3	1.4
	HH	894	28.0	28.8
	RT	894	13.4	4.3

C. Aging Duration (Months)

The main effect of aging duration was significant for both whisker count and length. This is as expected since the purpose of aging is to promote these time related phenomena. The average values of both maximum whisker length and whisker count increased regularly with aging duration. The trend in whisker count was approximately linear with duration implying that whisker initiation continued throughout the test duration; however, the average whisker count started at a relatively high level (more than half the final average) implying that a majority of the whisker initiation occurred during sample production and preconditioning. The average whisker length also increased with time as can be seen by the deltas one month to the next. See Table 6 below. The deltas from three months onward continue to decrease showing that the rate of whisker growth with time was decreasing but had not yet, on the averaged, stopped. The average increase at six months was about 2 micrometers.

Table 6. Effect of Aging Duration on Whiskers

Main Effect	Month	Data Count	Avg. Whisker Count	Avg. Max. Whisker length	Delta
M (Month)	**0**	216	12.7	0.9	-
	1	264	13.1	1.4	0.5
	2	270	14.6	2.6	1.2
	3	444	15.7	9.7	7.1
	4	474	18.0	13.7	4.0
	5	498	20.7	17.4	3.7
	6	516	21.7	19.5	2.1

D. Plating Type

The main effect of plating type (tin versus tin-lead) was significant for both whisker count and length. Surprisingly, the lead-free (pure tin) coating exhibited substantially lower tendency toward whisker formation than did the standard tin-lead coating with an average whisker count lower by a factor of approximately 5. However, the lead free coating exhibited greater whisker growth with an average maximum whisker length approximately 5 times that for the tin-lead coating. See Table 7.

Table 7. Effects of Plating Type (Sn versus SnPb) on Whiskers

Main Effect	Test	Data Count	Avg. Whisker Count	Avg. Max. Whisker Length
P (Plating type)	**Sn**	2142	10.2	13.6
	Sn-Pb	540	47.0	2.9

E. Plating Bath

The main effect of plating bath at five months was not statistically significant. But, at six months a slight difference was noted. For the pure tin coatings, resistance to whiskering (both initiation and growth) was best (lowest average whisker count and length) for the Bath "C", worst for the Bath "B", and intermediate for Bath "A". Subsequent to this, we used data from Bath A and Bath C for our "best case" analysis. Table 8 below shows the performance of each tin bath and compares with the tin-lead bath. As you can see in Table 8 below, there's not much difference between the three tin baths. But, as a group, they are much different than the tin-lead bath.

Table 8. Effects of Plating Bath on Whiskers

Main Effect	Test	Data Count	Avg. Whisker Count	Max. Avg. Whisker Length
B(P) (Plating Bath)	**Bath "A"**	672	10.4	13.5
	Bath "B"	702	12.1	14.8
	Bath "C"	768	8.2	12.7
	SnPb	540	47.0	2.9

F. Nickel Underplate

The main effect of nickel underplate thickness was statistically insignificant for both whisker count and length. This tends to imply that the specified thickness of the nickel underplate is not important for whisker avoidance within the tested range of thickness. See Table 9 below.

Table 9. Effects of Nickel Thickness on Whiskers

Main Effect	Test	Data Count	Avg. Whisker Count	Avg. Max. Whisker Length
N (Ni thickness)	**1.27 µm**	1422	15.3	12.2
	2 µm	1260	20.1	10.7

We conducted a few side experiments to examine the effect of nickel versus no nickel underplate on the Bergstik®. The data wasn't included in the statistical analysis but Table 10 below gives an indication of the beneficial effects of a nickel underlayer. As a follow-up, we'll do some more work to examine the effects of nickel thicknesses in the range of 0.6µm

Table 10. Effects of Nickel versus No Nickel Underplate

		TS + DH		**TS + HH**		**TS + RT**	
Bath A	**Plating**	**Count**	**Length**	**Count**	**Length**	**Count**	**Length**
A8	**2 Ni, 2 Sn**	**0**	**0**	**0**	**0**	**0**	**0**
A0	**0 Ni, 2 Sn**	**95**	**10-32**	**92**	**10-41**	**105**	**12-34**

G. Top Layer Thickness

The main effect of top layer thickness was statistically significant for whisker count but not for whisker length. The thicker coatings (4 µm) exhibited greater whisker count than the thinner coatings (2 µm) with an average increase by a factor of approximately 3. Although not statistically significant, the trend in whisker length was similar with substantially longer whiskers (by a factor of 1.8 on the average) for the thicker coatings. This tends to imply that limiting the topcoat thickness to the lower level of the tested range) is desired for suppression of whiskering. See Table 11 below.

Table 11. Effects of Top Layer Thickness on Whiskers

Main Effect	Test	Data Count	Avg. Whisker Count	Avg. Max. Whisker Length
L (Top Layer thickness)	2 µm	1482	9.8	8.6
	4 µm	1200	27.2	15.1

H. Significant Interactions Amongst the Input Variables

Many of the interactions were statistically significant because the statistical tests were very powerful due to the large extent of the data. Since the effects of factors associated with testing (aging duration, preconditioning, and aging method) are clear from the investigation of input variables, only significant interactions associated with sample characteristics and processing (plating type, plating bath, nickel underplate thickness, and top layer thickness) were investigated further. Interactions between the Stress Zones and various input variables were also analyzed and reported later in the Stress Zone section. The interaction of plating type with top layer thickness was significant and is shown below in Figure 4.

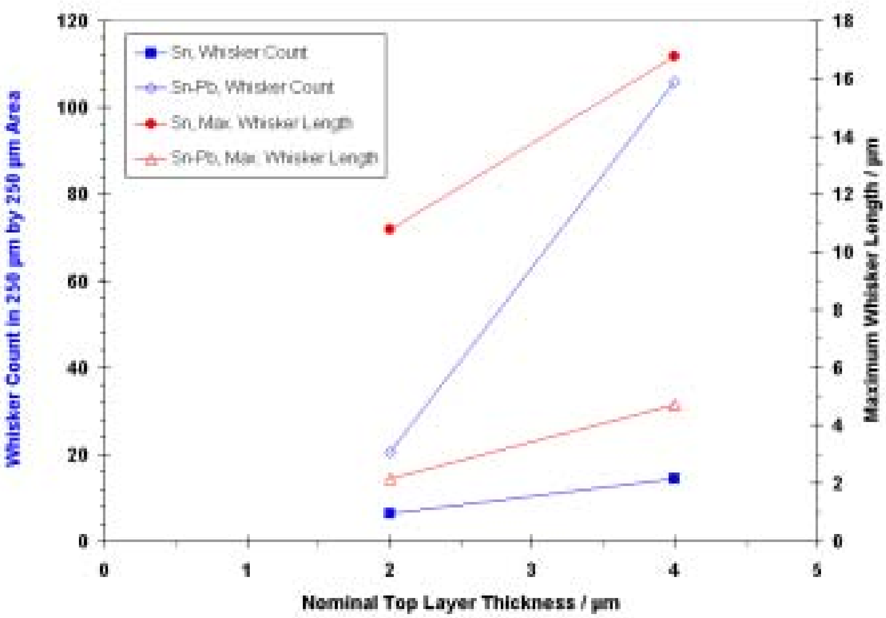


Figure 4. Subset Averages for Interaction of Plating Type and Top Coating Layer Thickness

Both whisker count and length increased with increasing thickness of both tin and tin-lead plating. The significance of the interaction of plating type and top layer thickness resulted from relatively larger increases in whisker count for tin-lead and in whisker length for pure tin. Thinner layers of both tin and tin-lead are preferred for suppression of whiskering.

I. Confidence Levels for Maximum Whisker Length after Aging ("Best Case" Sample Plating Conditions)

Confidence levels were estimated for meeting specific limits on maximum whisker length after application of the treatment that was most effective in promoting whisker growth: aging for 6 months in humid heat after preconditioning with thermal shock. These estimates were made only for thin (2 µm) tin coatings plated from the selected baths (Baths A & C). Maximum whisker lengths of 30 micrometers and 50 micrometers were the limits for which confidence levels were estimated. Maximum whisker lengths were strongly dependent upon stress area. Therefore, the estimates were differentiated by stress area. This first analysis of the full data set only included the bend zone. Data analysis from the other stress zones is reported later in this document.

The observed average values and standard deviations of maximum whisker length from the reduced data subset (thin tin from 2 baths with 6 months aging in humid heat after thermal shock preconditioning) are listed in Table 12 for the various stress areas. Thickness of nickel underplate (statistically insignificant) and identity of tin-plating bath were ignored (i.e., data was combined for all levels of these variables).

Table 12. Average and Standard Deviation of Maximum Whisker Length in Bend Area

	Data Count	**Maximum Whisker Length / micrometer**	
		Average	**Standard Deviation**
Bend	8	10.1	16.4

The confidence levels are estimated on the basis of Student's t distribution using the observed average (assumed exact) and two (2) separate estimates of variability: 1) the observed standard deviation (few degrees of freedom) as given in Table 13; and 2) the constant transformed variation value (standard deviation divided by the square root of the average) from the full data set (many degrees of freedom), 3.49 $\mu m^{1/2}$. These estimates of confidence level are given in Table 13 below. Using worst-case environment (TS + HH, 6 months) and worst-case measurements (total whisker length), we predict meeting the 50µm specification 100% of the time. We compared total whisker length versus effective whisker length for two baths at 6 months. We calculated that the effective length measurements were 20% to 30% less than the total length measurements. Thus, we'd expect higher confidence levels using effective length in the statistics.

Table 13. Estimated Confidence Levels for Meeting Maximum Whisker Length Limits (Thin Tin, 2 Baths, 6 Months, Humid Heat, Thermal Shock Preconditioning)

Estimate of Variation from	**Stress Area**	**Average**	**Standard**	**Estimated Confidence Level**	
				< 30 µm	**< 50 µm**
Observed Std Deviation	**Bend**	10.1	16.4	87%	98%
S . 3.49 µm$^{1/2}$	**Bend**	10.1	11.1	96%	99.98%

IV. Analysis of Stress Zones

Our original DOE intent was to examine the Bergstik® samples only in the Bend Zone as that area represented the "preconditioning" most commonly required as a precursor to aging tests. However, as the monthly examinations progressed, we realized that other factors besides the original seven input parameters were having a strong influence on whisker growth. Therefore we decided to expand our examination to four zones: flat, bend, scrape, and pin tip. Refer again to Figure 2, which graphically shows the locations of the four zones. A more detailed description of each zone with some accompanying photos follows. The initial investigations of the effects of stress are reported in Reference 6. Reference 6 examines the effects of deposit stress, total hydrogen and oxygen in the deposit, impurities in the deposit, and mechanical stresses induced after plating.

A. Flat Zone

The "Flat Zone" was included to enable us to get an "apples-to-apples" comparison of the three commercial plating baths without any external or internal influences. The flat zone is post plated. There are no substrate forming operations either before or after plating to impart any stress. There are no scrapes or other mechanical damage to influence results. Figure 5 shows a typical flat zone.

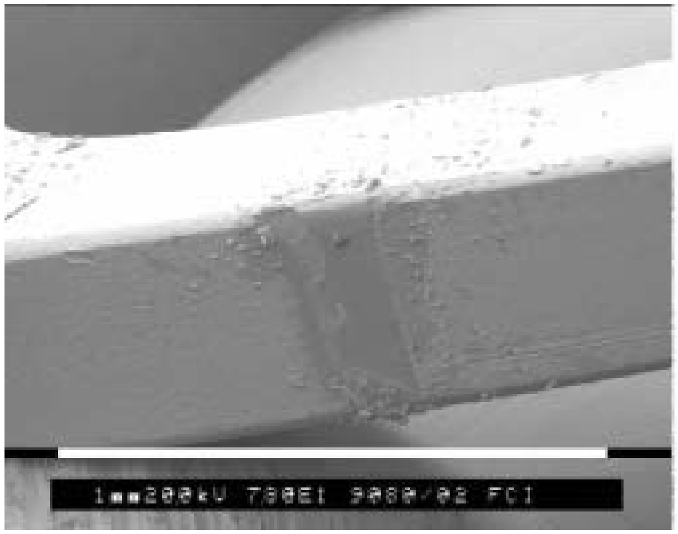


Figure 5. SEM photo of Flat Zone

B. Bend Zone

The "Bend zone" was our initial zone of focus because the plated coatings were subjected to bending to impart compressive stress as a precursor to aging. Data from the bend zones was used initially to compare the three plating baths in order to select one or two for our use. Upon further analysis of the bend zones we discovered that pure mechanical bending was not the only stress inducer. As part of the forming operation at assembly, a small diameter mandrel is positioned in the bend area and the pins are bent over the mandrel to provide the SMT bend. The result is some minor mechanical deformation in the bend area. A typical bend area can be seen in Figures 6 and 7. Notice the position of the whisker in Figure 7.

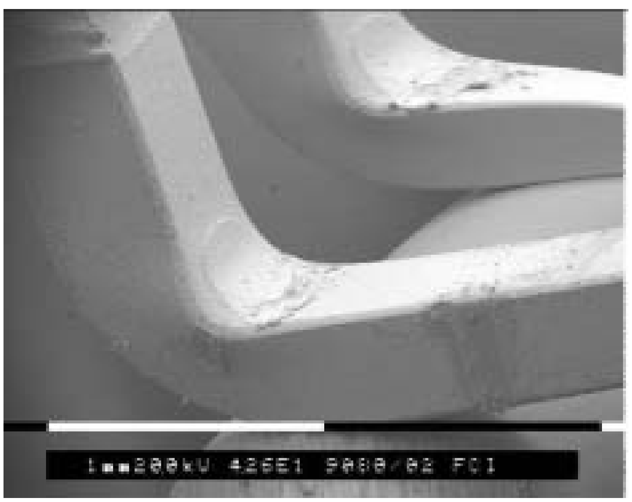


Figure 6. Bend Zone

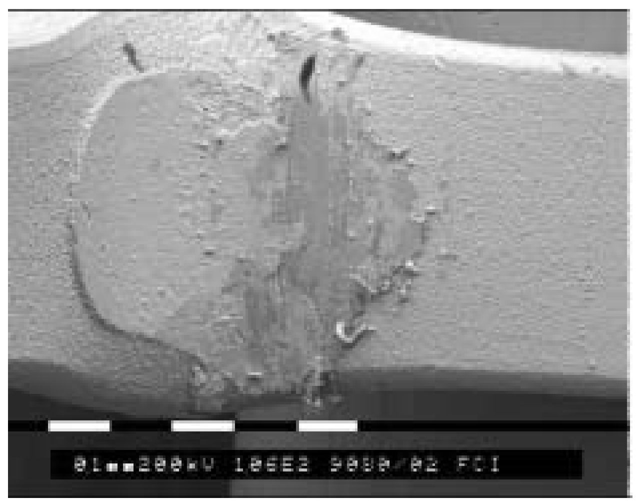
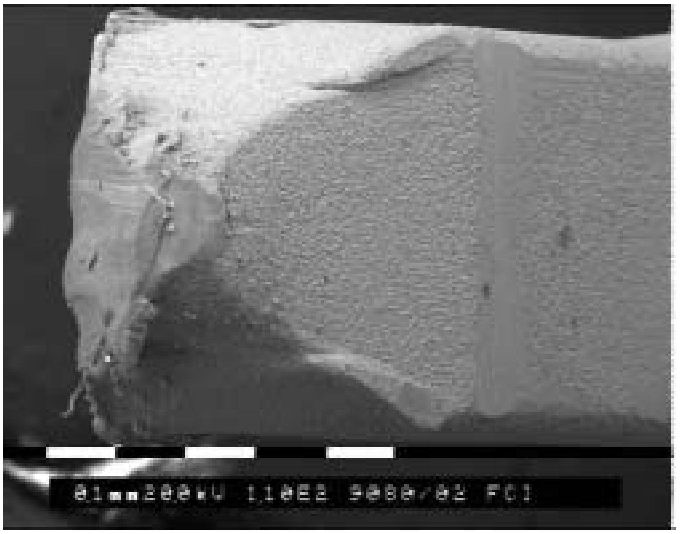


Figure 7. Whisker in Bend Zone

C. Pin Tip Zone

The "Tip Zone" was added because initially we expected to see the influence of significant amounts of preplated stress caused by the trimming and swaging to form the pin tip. What we discovered was that the amount of whiskers on the trim and swage tip sides were minimal. The majority of whiskers were growing on the one tip side that was mechanically scraped during the pin SMT leg forming. Apparently during forming, the tool used to actually bend the pins is rolled up and over the pin tip. This action results in mechanical deformation to the plating on one side of the pin tip. Figures 8 and 9 below illustrate the findings. Once again, in Figure 9 the whisker is growing out adjacent to the mechanically damaged area. This was the same observation as on the Bend Zone.



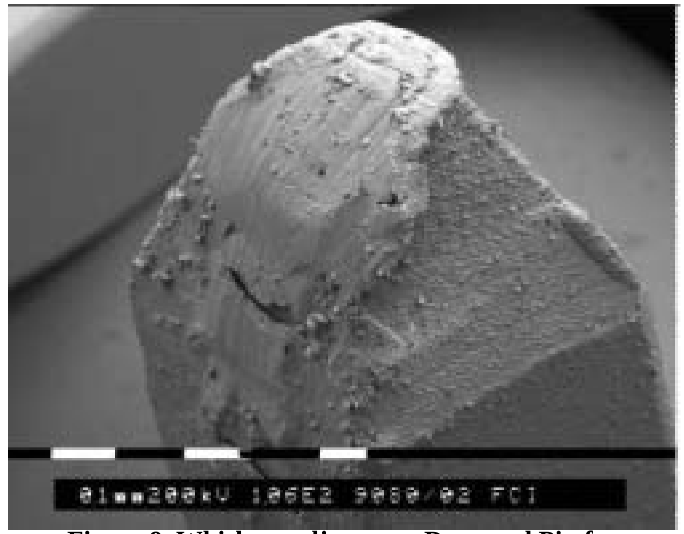
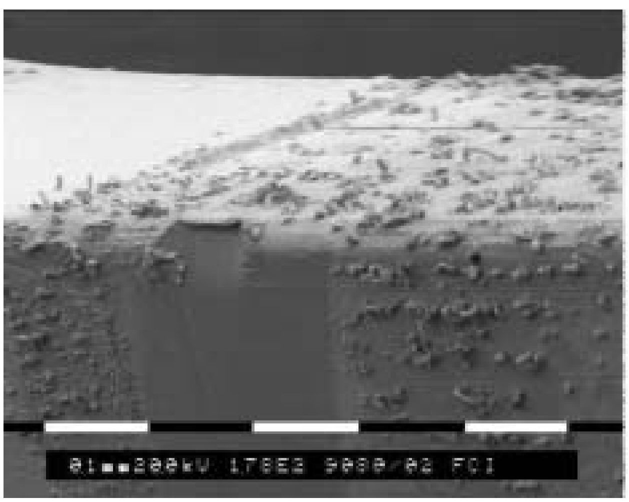


Figure 8. Pin Tip **Figure 9. Whiskers adjacent to Damaged Pin face**

D. Scrape Zone

The "Scrape Zone" was artificially created, as mentioned previously, by the sample preparation process. The result of pushing the pins partially out of the plastic housing was to mechanically deform the plating – deep scrapes. A typical example of the scrape zone can be seen in Figure 10. This is a remarkable photo showing both the scrape zone (right side) and the flat zone (left side). The contrast is striking. No whiskers on the flat zone but gross whiskering on the scraped zone. Upon further examination of the scraped zone, we noted that the whiskers lined up exactly with the scrapes and were adjacent to the scrapes as were the whiskers in the tips and bend zones. Figure 11 shows the whisker detail in the scrape zone.



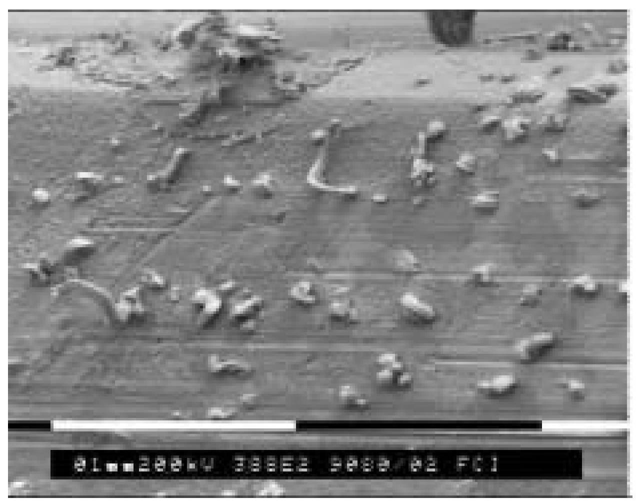


Figure 10. Scrape Zone **Figure 11. Whiskers in Scrape Zone**

E. Results of Stress Zone Analysis

As mentioned previously, the Stress Zones seemed to have a significant impact on whiskers so we did a statistical analysis by Zone. The resulting data analysis once again provided the same results as the 6-month study for most of the input variables. Preconditioning (TS), aging method (HH), and tin layer thickness (thick) all significantly promoted whisker growth. Nickel thickness and the three pure tin plating baths did not significantly affect whiskering. What we discovered in this analysis was the significant difference between pure tin and SnPb and the significant difference between the stress zones. Overall, the SnPb samples have significantly higher density of whiskers (OSE's) but much shorter whiskers. The SnPb coating results did not vary by stress zone, as did the pure tin samples. For pure tin, results indicated that if the coating deposit is relatively undisturbed and properly applied, then whiskering is minimal. However, when there are significant amounts of coating mechanical deformation (scraping) then whiskering is much more prevalent. The scrape zone was the worst followed by the tip zone. The tip zone whiskering was primarily limited to the surface mechanically damaged during the assembly bending operation-not the trim-swage operation. Table 14 below summarizes the four-zone data analysis.

Table 14. Subset Averages for Input Variables, Full Data Set, Stress Zones

Main Effect		**Data Count**	**Subset Average**	
			Whisker Count	**hisker Length / µm**
C (Preconditioning)	**No**	354	9.3	11.7
		354	23.1	16.8
A (Aging thod)	**DH**	236	9.5	1.2
	HH	236	29.4	37.4
	RT	236	9.7	4.1
S (Stress Zone)	**Flat**	192	28.6	5.1
	Bend	192	7.3	4.1
	Tip	156	12.9	19.7
	Scrape	168	15.2	32.3
P (Plati ype)	**Sn**	564	10.9	17.0
	S	144	36.8	3.3
B(P) (Platin th)	**B**	186	10.3	15.6
	Bath “B”	186	13.3	19.4
	Bath “C”	192	9.3	16.2
	SnPb	144	36.8	3.3
N (Ni thickness)	**1**	372	14.9	15.05
		336	17.6	13.35
L (Top Layer thickness)	**2 µm**	384	11.4	10.82
	4 µm	324	21.8	18.30

Interactions amongst the input variables were also analyzed and several were significant. The significance of the interaction of stress area and plating type resulted from opposite trends among stress areas between tin and tin-lead coatings (in opposite ways for whisker initiation and growth). Dependence of whisker initiation on stress area was minimal for tin but very large for tin-lead, which had a large average whisker count in the flat area and small average whisker counts in the bend and scraped areas. Dependence of whisker growth on stress area was minimal for tin-lead but very large for tin, which grew long whiskers in the scraped area (and to a lesser extent in the tip area) but not in the flat or bend areas. Consequently, applied stress appears to favor whisker growth rather than whisker formation in tin coatings (and suppressing whisker formation in tin-lead coatings). See Figures 12 and 13 below for graphs.

As part of our overall lead-free program, we conducted another DOE (unpublished) “Matte Pure Tin Assembly Evaluation” in which we examined the tendency of whiskering through typical assembly operations such as terminal bending and stitching. Results showed that with proper care, parts could be made without the mechanical damage that caused the whiskering in this DOE. The learning’s associated with these DOE’s are being incorporated into our manufacturing operations.

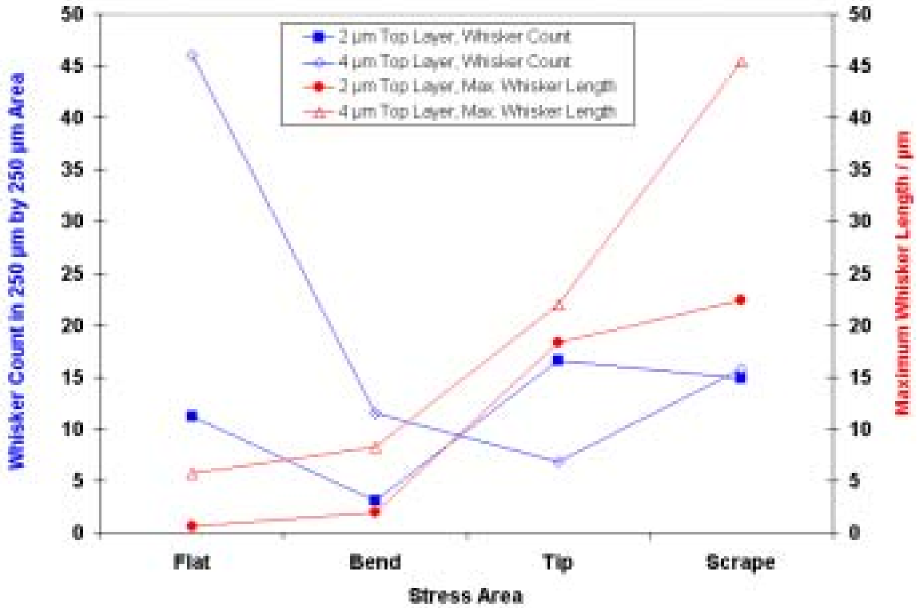


Figure 12. Subset Averages for Interaction of Stress Area and Top layer Thickness

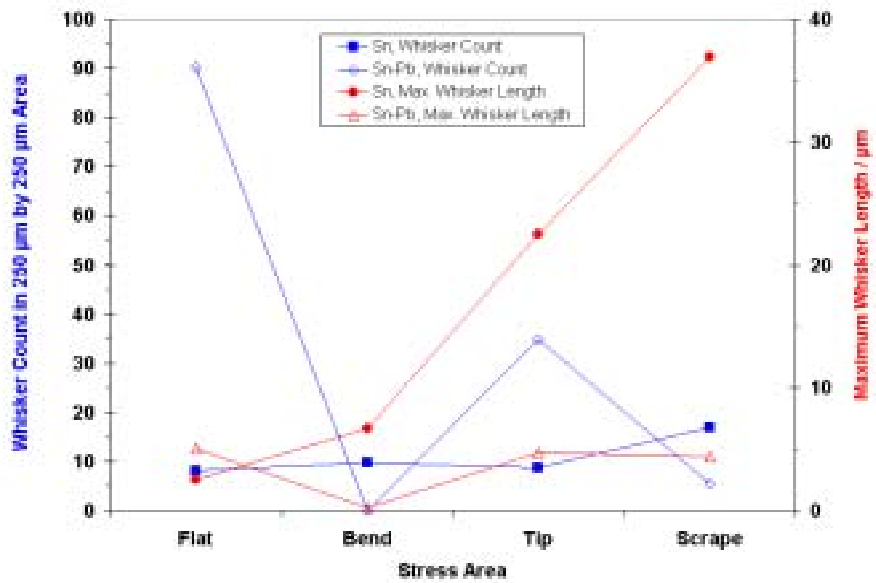


Figure 13. Subset Averages for Interaction of Stress Area and Plating Type

F. Best Conditions Analysis versus Four Zones

In similar fashion to the basic study, we analyzed the four zones limiting the data set to the "best plating conditions", i.e. Baths "A" and "C", and thin tin topcoat and nickel. Results are summarized below in Table 15. Once again, the TS preconditioning and HH aging significantly promoted whisker growth. Once again, nickel thickness was not significant. The scraped area followed by the pin tip had the most and longest whiskers and significantly more than in the flat and bend zones.

Table 15. Subset Averages for Main Effects, Thin Tin from 2 Baths, Stress Zones

Main Effect	Value	Data Count	Subset Average	
			Whisker Count	Max. Whisker Length / µm
C (Preconditioning)	No	96	3.7	9.2
	TS	96	8.6	15.9
A (Aging method)	DH	64	0.0	0.0
	HH	64	18.3	36.3
	RT	64	0.2	1.5
S (Stress area)	Flat	48	0.04	0.0
	Bend	48	1.6	1.7
	Tip	48	8.6	18.9
	Scrape	48	14.6	29.8
B (plating Bath)	Bath "C"	96	5.5	11.7
	Bath "A"	96	6.8	13.5
N (Ni thickness)	1.27 µm	96	6.5	12.49
	2 µm	96	5.9	12.70

G. Statistical Variability and Confidence Levels

Our plating trials included replicates to estimate the statistical variability of the data. The Table 16 below shows the rms standard deviation for the conditions of interest.

Table 16. Observed Average and Standard Deviation of Maximum Whisker Length by Stress Area (Thin Tin, 2 Baths, 6 Months, Humid Heat, Thermal Shock Preconditioning)

Stress Area	Data Count	Maximum Whisker Length / micrometer	
		Average	Standard Deviation
Flat	8	0.0	0.0
Bend	8	10.1	16.4
Tip	8	82.6	46.8
Scrape	8	95.2	23.5

After calculating standard deviations, we were again able to estimate confidence levels for meeting 30µm and 50µm specifications under worst-case environmental conditions-TS + HH, six months and total whisker length. Table 17 below shows that under normal conditions, we can expect to meet a 50µm specification. We can likely meet a 30µm as well using effective whisker length as the criteria.

Table 17. Estimated Confidence Levels for Meeting Maximum Whisker Length Limits (Thin Tin, 2 Baths, 6 Months, Humid Heat, Thermal Shock Preconditioning)

Estimate of Variation from	Stress Area	Average	Standard Deviation	Estimated Confidence Level	
				< 30 µm	< 50 µm
Observed Standard Deviation	Flat	0.0	0.0	100 %	100 %
	Bend	10.1	16.4	87 %	98 %
	Tip	82.6	46.8	15 %	25 %
	Scrape	95.2	23.5	1 %	5 %
Constant Std. Dev. / Avg. 3.55 $\mu m^{1/2}$	Flat	0.0	0.0	100 %	100 %
	Bend	10.1	11.3	96 %	99.97 %
	Tip	82.6	32.2	5 %	16 %
	Scrape	95.2	34.6	3 %	10 %

V. Solder Joint Reliability

A separate DOE was conducted to evaluate solder joint reliability using the same Bergstik® samples as in the Bath DOE. Just a summary of the results will be presented here. The input variables were the same four baths, 5 PWB pad platings (SnPb, AuNi, Sn, OSP, & Ag), and 4 TS levels (0, 250, 500, & 1000 cycles). Constants were: 95Sn4Ag0.5Cu paste and reflow profile (235C peak). Response was 45-degree angle pull strength. Overall, all test samples performed as well as or better than the tin-lead controls. The typical failure mode was separation of the pad from the board. Typical pull strengths ranged from 12 to 29N.

VI. Solderability

A separate DOE was also conducted to evaluate solderability using the as-plated pins used to make the Bergstik® Headers. Input variables again included the same four baths, two solder pot baths (60/40 SnPb and 96Sn/4Ag), and aging (none, 8 hours steam, 16 hours dry heat). Constants were the procedure-NFA 89400, pot temperature (235C), and flux (Actiec 5 multicore). Responses included time to wet, wetting force, and some "dip-and-look". An acceptance criterion is based on wetting force, which is related to wetting angle. As can be seen in Table 18 below, solderability for the lead substitutes is the same as tin-lead as-plated but not quite as good after aging.

"Dip-and-look" testing produced better results and compared favorably with the requirements of IPC/JEDEC-STD-002B. Similar results were obtained by Hilty as reported in Reference 7.

Table 18. Solderability Results Rated per NFA 89400

SnPb Pot	No aging	Steam Age	Dry Heat
Sn Pb plated	Excellent	Excellent	Good
Bath "A"	Excellent	Good	Acceptable
Bath "B"	Excellent	Acceptable	Unacceptable
Bath "C"	Excellent	Acceptable	Acceptable
SnAg Pot	**No aging**	**Steam Age**	**Dry Heat**
SnPb plated	Excellent	Excellent	Excellent
Bath "A"	Excellent	Excellent	Excellent
Bath "B"	Excellent	Good	Acceptable
Bath "C"	Excellent	Good	Good

VII. Conclusions

As a result of our experimental work we conclude the following.

- Statistical analysis and a properly designed experiment are powerful tools to examine and understand whisker phenomena
- When stating whisker length requirements, its important to define the measurement methodology-total, effective, or normal length.
- Preconditioning by bending before aging only had a minor effect on whiskering. Preconditioning by exposure to 500 cycles of Thermal Shock (TS) produced whiskers 50% longer after aging as compared to no preconditioning before aging.
- Heat and Humidity aging was clearly the most severe environment for propagation and growth of whiskers. HH aging increased whisker length by a factor of 7 versus Room Temperature aging and by a factor of 20 versus Dry Heat aging.
- The combination in series of 500 cycles TS followed by HH aging was very effective to grow whiskers.
- Whiskers were still growing at six months but the rate of growth was decreasing after three months. Average whisker growth at six months was about 2μm.
- Tin-lead clearly outperformed pure matte tin in that average maximum whisker length was one-fourth that of pure tin at six months. On the other hand, tin-lead had nearly five times as many propagation sites (OSE's) as pure tin.

- Of the three commercial baths tested, all performed similarly regarding tendency to form whiskers. Only at six months aging did any statistical differences occur. Overall, several commercial pure matte tin baths are suitable for commercial application.
- In the nickel range tested (1.27 – 2.0µm) there was no difference in topcoat performance.
- In the topcoat range tested (2.0 – 4.0µm) thinner was better.
- Mechanical damage to the pure tin topcoat had a significant impact on whiskering. Whiskers tended to emanate immediately adjacent to scraped surfaces.
- Statistically examining data from plating replicates enabled calculation of standard error and confidence levels to meet certain maximum whisker length specifications. Given the "worst case" environmental conditions (TS + HH) and "best case" plating thicknesses (thin nickel, thin tin) and using "total whisker length", the data predicts being able to meet a 50µm specification nearly 100% and a 30µm specification 96% of the time. These predictions apply to as plated surfaces and "normal" post-plating bending operations.
- Reliability predictions are based on the stated accelerated environmental conditions of TS followed by HH. We have no correlation as yet between these acceleration factors and actual field environments.

VIII. Future Experimental Work

Future work as a result of this DOE includes several general areas. First, we plan to follow-up and collect whisker data at 9 and 12 months to determine a longer-term trend. Second, we plan to complete the follow-up board reflow work we started on the Bergstik® samples from this DOE. We want to see what happens to parts with whiskers that subsequently go thru board reflow. Also, we want to compare the whiskering of "as-assembled" parts versus parts assembled and reflowed onto boards. Third, we plan to develop a FEA model to simulate the mechanical damage and subsequent whisker growth on pure tin coatings. Forth, summarize the DOE's for solderability and joint reliability. Finally, we plan to evaluate the effects of nickel thickness in the range of 0.6 micrometers on whiskering and solderability.

IX. Acknowledgements

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