A STUDY OF OVERCOMING SOLDER ICICLING AND COPPER WIRE DISSOLUTION IN AN AUTOMATED LEAD-FREE SOLDERING SYSTEM

Showalter, Chad; Sibell, Susan; Jean, Denis; Klimah, Paul; Biggs, Joe
Kester Inc.
Itasca, IL, USA
cshowalter@kester.com

ABSTRACT

Solder icicling and copper dissolution are anything but new phenomena in the soldering industry since the switch from lead to lead-free solder. However, in these common defects there are still industry unknowns in understanding how to correctly plan and execute a Design of Experiment (DoE) to optimize a lead-free process to its full operating potential. In order to increase efficiency and quality of your process and product it is essential that a DoE be conducted when switching from a lead to lead-free alloy. By utilizing common industry solder analysis methods, in conjunction with a robust design of experiments, we have been able to provide three process improvements to a dip soldering application. We were able to show scientific results with data. This allowed us to correlate the results with actual process conditions to bring awareness of how final product quality may change if any of the parameters were increased or decreased from the determined setting.

Key words: DoE Design, copper dissolution, icicling, magnet wire

INTRODUCTION

Dip soldering remains a common attachment method due to its simplicity, robustness, uniformity and low cost for a number of applications [1]. In particular, the soldering of enameled copper wires to a terminal such as required when making transformers, inductors, electromagnets, motors, solenoids and other devices are often performed by dip soldering. This process has historically used high lead content alloys such as the Sn10Pb90 or Sn05Pb93.5Ag1.5 which have low metals cost, liquidus points in the range of 300^{o}C, and low copper dissolution rates [2].

During the dipping operation, the part is first dipped typically into a high rosin content heat stable flux, and then dipped into the pot of molten solder. The molten solder itself is used to burn off the enamel insulation which is commonly a polyamide or polyimide layer, of the copper and then solder the copper wire to the terminal. The polyimide insulation requires a high temperature for removal, often in the range of 350 - 500^{o}C depending on the specific coating used [2].

Once soldered, the devices are commonly packaged to protect the fine copper wire from damage. Solder icicling of the terminals can cause issues with various types of outer packaging configurations such as plastic casings surrounding solenoid coils or component covers. More importantly, solder icicling is a key indicator that something in the process must be investigated before an inevitable failure occurs.

Copper dissolution is one failure mode that can many times be associated with solder icicling. Copper dissolution is essentially the reduction in the copper wire diameter, due to various factors that may include; prolonged exposure to the molten solder, elevated temperature of the solder pot, and solder alloy type [3]. This decrease in wire diameter inherently places the product at risk from a reliability standpoint.

In order to best understand the factors effecting the quality and efficiency of a process and product it is essential that a properly designed and executed DoE be conducted when switching from a lead to lead-free alloy. By utilizing common industry solder analysis methods, in conjunction with a robust design of experiments, three statistically significant process were able to be determined and understood for a particular dip soldering application. This mode of analysis has given rise to the ideal conditions required to reduce copper dissolution and solder icicling, thus highlighting the importance of conducting a structured DoE when making a major change in any process.

APPLICATION BACKGROUND

In a dip soldering application, an icicling defect was noticed when moving from a high lead alloy (Sn05Pb93.5Ag1.5) to lead free solder SAC305 (Sn96.5A3.0Cu0.5). The application consisted of dip soldering a fine gauge Magnet Wire, with a thermal class of 180^{o}C, to a terminal on a solenoid component using a ROM1 high rosin content alcohol based flux. The terminals could be one of two alloys: 1) Phosphor Bronze or 2) brass. Both terminal base metals were tin plated and assumed to have equivalent wetting. During the initial testing, an icicling defect was noticed as displayed in Figure 1. The icicles were long enough to affect the lid sealing performed at a later step in the operation.

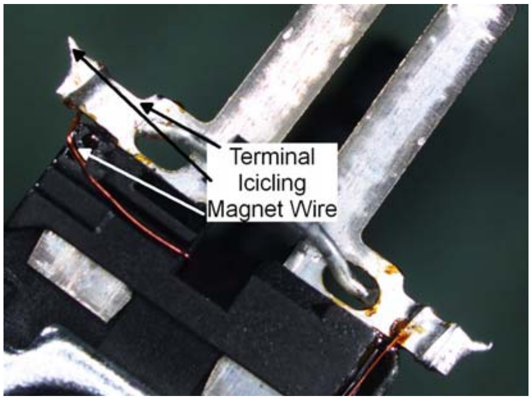


Figure 1. Solenoid Component With Icicle

The magnet wire in use requires a temperature of 390°C for 5 seconds in order to burn off the enamel insulation layer based on the technical literature available. Customer had been using a pot temperature of 515°C and a dip time of 5 seconds with the original Sn5Pb93.5Ag1.5 high lead alloy. When the customer trialed the SAC305 alloy at 515°C and 440°C, both trials resulted in unacceptably long icicling.

Copper dissolution due to the significantly higher tin content of the SAC305 is well known problem within the soldering industry [3]. Copper dissolution was verified by cross sectioning of the soldered magnet wire/terminal connection made at 440°C and 515°C. Significantly reduced copper wire thickness was evidenced. Inconsistent wetting of the solder alloy to the terminal was theorized to be the root cause of the icicling.

After discussions with the technical and production teams dedicated to resolving this issue, a decision was made to further investigate the problem and find a workable solution by:

1) Perform experiment to determine the required solder temperature and contact time for removal of the insulation
2) Perform wetting balance testing on the terminal metallization's to better understand their solderability with the ROM1 flux in regards to icicling
3) Perform copper dissolution DoE for further understanding of process window and FMEA for the magnet wire
4) Perform DoE with 2 lead-free alloys to determine optimal soldering process

MAGNET WIRE INSULATION REMOVAL EXPERIMENT

A time and temperature study was performed to establish the required temperature and time for the solder to properly cut through and remove the enamel insulation and wet the copper wire. The wire insulation was NEMA rated at 180°C. Testing was performed by using a static solder pot with the ROM1 liquid flux. Solder wetting was graded by visual analysis under microscope. Table 1 shows the insulation removal study results.

Table 1. Insulation Removal Results

Temp (°C)	Time (sec)	Solder Wetting %
260	15	0
320	1	0
320	5	1
320	8	10
320	9	20
320	10	50
320	12	100
385	1	100

Based on the results, it was found that a solder pot temperature of at least 385°C is required to cut through the enamel insulation in less than 1 second solder immersion time. For further testing, a low end temperature of 390°C was used to give a buffer to account for potential temperature fluctuations of the solder pot.

TERMINAL METALIZATIONS WETTING TEST

In initial testing, a difference in solderability between the two possible terminal types was noticed despite both types being tin plated to the same specifications. In order to further understand if there were differences in solder ability, the wetting aspects of the terminals were tested using a wetting balance test. Testing was performed on the phosphor bronze and brass terminals using both the SAC305 and a silver-free tin/copper alloy with dopants for low dissolution (referred to as SnCu-LD). The specific tin/copper alloy was selected due to its known low dissolution capabilities when soldering to copper metallization's [4].

The wetting balance test works by dipping (at a controlled speed that is slower than the maximum wetting speed for a flux type and metallization combination) a terminal into a solder pot (of known temperature and alloy). The terminal is mounted to a force gauge that can measure the force applied to the terminal due to buoyancy, non-wetting, and wetting of the solder. The force is recorded over time and graphed for analysis. An illustration of the expected results in conjunction with the dipping process (wetting condition) is shown in Figure 2. Several important data points can be determined including: wetting time, total wetting time, maximum wetting force and wetting stability.

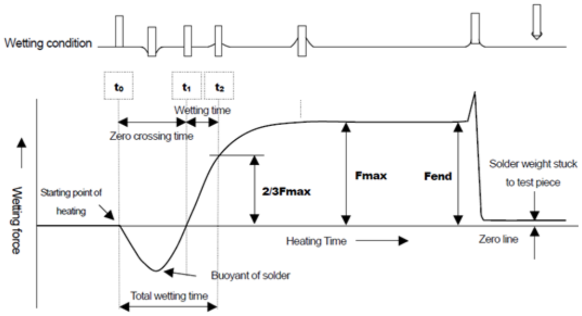


Figure 2. Wetting Balance Test Illustration

For the particular testing performed, the test conditions in Table 2 were implemented.

Table 2. Wetting Balance Test Conditions

Immersion Speed	1mm/sec
Immersion Time	5 sec
Immersion Depth	2mm
Flux	ROM1
Solder Alloy	SAC305, SnCu-LD

All testing was performed in triplicate. Results of the 3 runs were averaged and tabulated below in Table 3. Examples of the resultant wetting curves for 1 run from each test condition are also shown in Figures 3-7. A test temperature of 260C was used to better discriminate the potential differences between lead type.

Table 3. Wetting Balance of Terminal Finishes

Wetting Parameters	Brass Terminal		Phosphor Bronze Terminal	
	SAC305 Solder bath 260°C	SnCu-LD Solder bath 260°C	SAC305 Solder bath 260°C	SnCu-LD Solder bath 260°C
Wetting tim (sec.)	0.341	0.247	0.635	0.662
Total wettin time (sec.)	1.838	4.17	2.330	3.485
Fmax (mN)	2.092	0.903	1.623	1.485
Wetting stability	0.983	0.982	0.977	0.984

Despite the overall wetting time being longer for the SnCu-LD based alloy vs SAC305, the wetting time was shorter for the brass terminal. Therefore, despite it taking longer for the SnCu-LD solder to begin wetting, but once started, it wet faster than the SAC305. This is evidenced in the steeper wetting slope in Figure 4 vs 3. The wetting differences initially experienced between the two terminal types were found to be in fact true. Upon further visual analysis by microscope, exposed base metal was found along the edge of the leads. Tin plating had been performed prior to stamping of the leads which is a common practice for cost reduction. The exposed base metal caused the reduction in solderability evidenced. The exposed edge caused substantial variability between the 3 runs for each combination tested. With sufficient contact time (greater than 4 seconds), both metalizations were solderable and wetting stability remained consistent amongst all the runs with minimal dewetting evidenced.

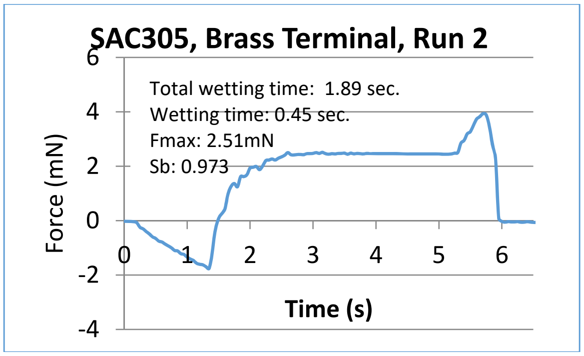


Figure 3. Brass With SAC305 Alloy

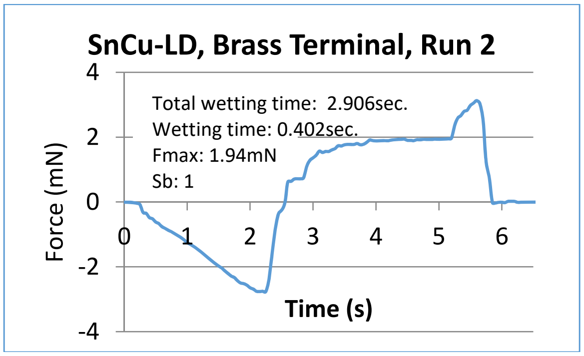


Figure 4. Brass With SnCu-LD Alloy

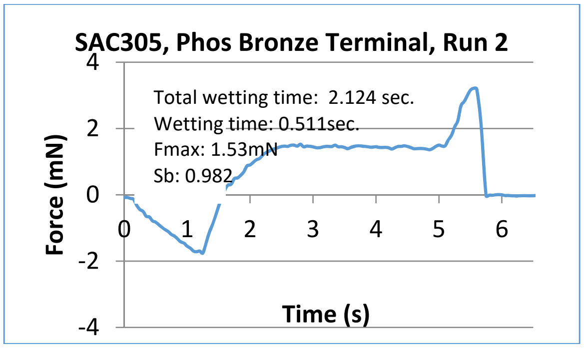


Figure 5. Phosphor Bronze With SAC305 Alloy

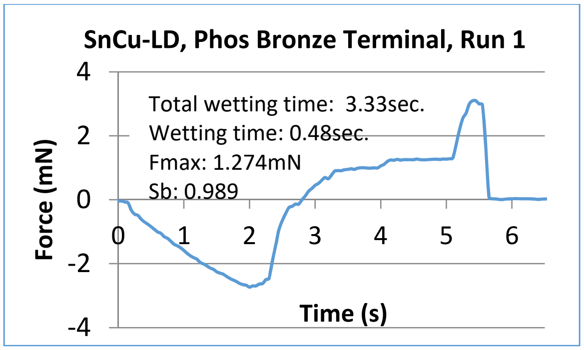


Figure 6. Phosphor Bronze With SnCu-LD Alloy

COPPER WIRE DISSOLUTION DOE

From previous analysis of the initial parts built with the Pb-free alloys, the icicling defect is known to be influenced by the copper dissolution of the magnet wire into the solder alloy. In order to better understand the influencing factors of the copper dissolution, an additional DoE was developed.

The copper dissolution is a function of solder temperature, solder dwell time, solder dynamic and solder alloy. These factors were built into a multilevel factorial DoE of the following design:

DoE Design:

- Multilevel Factorial
- 3 factors
- 1 replicate
- 36 runs
- All terms are free from aliasing

Fix factor:

- ROM1 high rosin alcohol flux

Wire:

- Copper wire diameter: 7.1 mils nominal
- Cross-sectional area: 39.59 mils^2 nominal

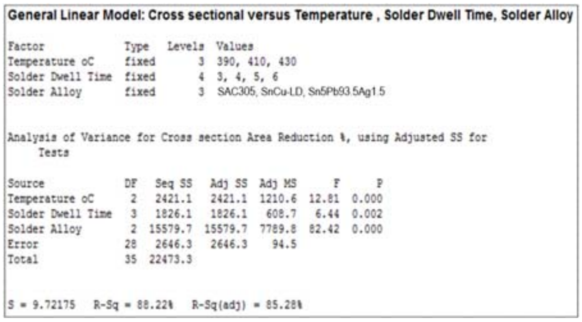
DoE Execution:

- The execution of the DoE was in sequence as shown in the DoE Table 5
- The end of the wire was dipped in the ROM1 flux
- The solder bath was de-drossed prior to dipping the end of the wire in the solder
- The final wire diameter was measured with a digital micrometer

Table 4. Copper Wire Dissolution DoE Design and Results

Run Order	Temperature ºC	Solder Dwell Time Sec.	Solder Alloy	Wire Dia. Mils	Wire Cross sectional Area $Mils^2$	Cross sectional Area Reduction %
1	390	5	SAC305	5	19.635	50.4
2	390	4	SAC305	5	19.635	50.4
3	390	6	SAC305	4.5	15.904	59.8
4	390	3	SAC305	5	19.635	50.4
5	410	5	SAC305	4	12.566	68.3
6	410	6	SAC305	3.5	9.621	75.7
7	410	4	SAC305	4.5	15.904	59.8
8	410	3	SAC305	5	19.635	50.4
9	430	3	SAC305	4.5	15.904	59.8
10	430	6	SAC305	1.5	1.767	95.5
11	430	5	SAC305	2.5	4.909	87.6
12	430	4	SAC305	3.5	9.621	75.7
13	390	4	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
14	390	3	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
15	390	6	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
16	390	5	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
17	410	5	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
18	410	4	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
19	410	3	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
20	410	6	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
21	430	6	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
22	430	3	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
23	430	5	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
24	430	4	Sn5Pb93.5Ag1.5	6.5	33.183	16.2
25	390	3	SnCu-LD	6.5	33.183	16.2
26	390	5	SnCu-LD	5.5	23.758	40.0
27	390	6	SnCu-LD	5	19.635	50.4
28	390	4	SnCu-LD	6	28.274	28.6
29	410	4	SnCu-LD	5	19.635	50.4
30	410	3	SnCu-LD	5.5	23.758	40.0
31	410	6	SnCu-LD	3.5	9.621	75.7
32	410	5	SnCu-LD	4.5	15.904	59.8
33	430	6	SnCu-LD	3	7.069	82.1
34	430	3	SnCu-LD	5	19.635	50.4
35	430	4	SnCu-LD	4.5	15.904	59.8
36	430	5	SnCu-LD	3.5	9.621	75.7

The results were again analyzed using statistical software to determine significant factors. Variance Analysis found that the following factors all had P values below 0.05 which indicate statistical significance: 1) pot temperature, 2) solder dwell time and 3) solder alloy. This is exemplified in the software's data output in Figure 7.



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General Linear Model: Cross sectional versus Temperature , Solder Dwell Time, Solder Alloy

Factor             Type   Levels  Values
Temperature oC     fixed       3  390, 410, 430
Solder Dwell Time  fixed       4  3, 4, 5, 6
Solder Alloy       fixed       3  SAC305, SnCu-LD, Sn5Pb93.5Ag1.5


Analysis of Variance for Cross section Area Reduction %, using Adjusted SS for
    Tests

Source             DF   Seq SS   Adj SS  Adj MS      F      P
Temperature oC      2   2421.1   2421.1  1210.6  12.81  0.000
Solder Dwell Time   3   1826.1   1826.1   608.7   6.44  0.002
Solder Alloy        2  15579.7  15579.7  7789.8  82.42  0.000
Error              28   2646.3   2646.3    94.5
Total              35  22473.3


S = 9.72175   R-Sq = 88.22%   R-Sq(adj) = 85.28%
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Figure 7. ANOVA Result of Significant Factors

The Main Effects plot indicates a correlation between copper dissolution and both pot temperature and solder dwell time as expected. Also seen is the correlation with alloy. The Sn5Pb93.5Ag1.5 alloy has a significantly lower tin content as well as a melt point roughly 75^{o}C higher than the SAC305 and SnCu-LD alloys.

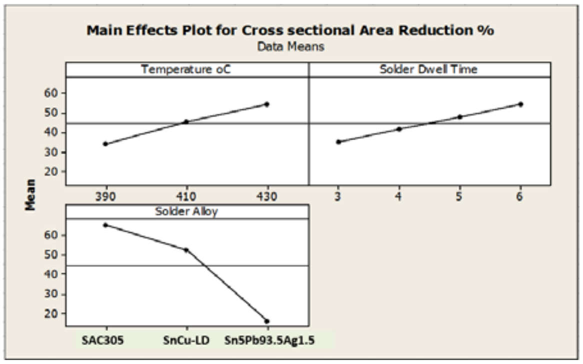

Figure 8. Main Effects Plot of Significant Factors

The specification for the end assembly is that the copper wire diameter must not decrease by more than 50%. It was determined that 3 seconds was adequate to provide a proper solder intermetallic and yet not excessively degrade the wire diameter. At 3 seconds and 390oC, the SnCu-LD alloy was able to maintain final copper wire diameter equivalent to the original Sn05Pb93.5Ag1.5 alloy (16% decrease in diameter for both vs 50% for SAC305).

OPTIMIZATION DoE FOR ICICLING DEFECT

For the final solder icicles optimization DoE, all of the previously tested factors were included: 2 terminal lead alloys, 2 lead free solder alloys, 2 solder dwell times, 2 solder bath temperatures and 4 replicates. Table 5 shows the DoE design and results for the solder icicles. The goal was to determine the optimum time and temperature to get proper soldering and minimize both copper dissolution and icicling. Icicle length was determined by using a micrometer and manually measuring the distance between the end of the terminal and the end of the icicle. The 3 second dwell time was set as the minimum allowed time to guarantee proper intermetallic formation.

Table 5. DoE Design and Results for Icicling

Run Order	Lead Alloy	Solder Alloy	Solder Temp °C	Solder Dwell Time Sec	Icicle Length mm
1	BRASS	SAC305	390	3	1.6
2	BRASS	SAC305	430	3	1.17
3	BRASS	SAC305	390	5	1.29
4	PH-BR	SnCu-LD	430	5	0
5	PH-BR	SnCu-LD	430	3	0.42
6	PH-BR	SnCu-LD	390	5	0.5
7	PH-BR	SnCu-LD	390	3	0
8	BRASS	SAC305	390	5	1.28
9	PH-BR	SAC305	390	3	0
10	PH-BR	SAC305	430	3	0.32
11	PH-BR	SnCu-LD	430	5	0.29
12	BRASS	SnCu-LD	430	5	0
13	PH-BR	SAC305	430	5	0.15
14	PH-BR	SAC305	430	3	0.36
15	PH-BR	SAC305	430	5	0
16	PH-BR	SnCu-LD	390	3	0
17	BRASS	SnCu-LD	430	3	0.71
18	BRASS	SnCu-LD	430	5	1.3
19	PH-BR	SAC305	390	5	0
20	PH-BR	SnCu-LD	430	5	0
21	PH-BR	SnCu-LD	390	5	0
22	PH-BR	SAC305	390	5	0
23	BRASS	SnCu-LD	390	5	0.151
24	BRASS	SAC305	430	5	1.29
25	PH-BR	SAC305	430	5	0.14
26	BRASS	SnCu-LD	430	5	0
27	BRASS	SAC305	390	5	1.27
28	BRASS	SnCu-LD	430	3	0
29	PH-BR	SnCu-LD	390	5	0
30	PH-BR	SAC305	390	3	0
31	BRASS	SAC305	430	3	0.91
32	BRASS	SAC305	430	5	0.52
33	PH-BR	SnCu-LD	390	3	0
34	BRASS	SAC305	430	3	1.24
35	PH-BR	SnCu-LD	430	3	0.16
36	BRASS	SAC305	430	5	0.35
37	PH-BR	SnCu-LD	390	3	0.24
38	BRASS	SnCu-LD	390	5	0
39	PH-BR	SAC305	430	3	0.54
40	BRASS	SnCu-LD	430	5	0.25
41	BRASS	SnCu-LD	430	3	0.53
42	BRASS	SAC305	430	3	1.04
43	PH-BR	SnCu-LD	430	5	0.15
44	PH-BR	SnCu-LD	430	3	0
45	PH-BR	SnCu-LD	430	3	0
46	BRASS	SnCu-LD	390	3	0
47	BRASS	SAC305	430	5	0
48	PH-BR	SAC305	430	5	0
49	BRASS	SnCu-LD	390	5	0.44
50	BRASS	SnCu-LD	390	5	0.43
51	PH-BR	SAC305	390	3	0.13
52	BRASS	SnCu-LD	390	3	0
53	BRASS	SnCu-LD	430	3	0
54	BRASS	SAC305	390	3	1.48
55	PH-BR	SAC305	430	3	0.36
56	BRASS	SAC305	390	5	0.22
57	PH-BR	SnCu-LD	390	5	0
58	BRASS	SAC305	390	3	0.83
59	PH-BR	SAC305	390	5	0.1
60	PH-BR	SAC305	390	5	0
61	BRASS	SnCu-LD	390	3	0.4
62	BRASS	SAC305	390	3	1.4
63	PH-BR	SAC305	390	3	0
64	BRASS	SnCu-LD	390	3	0.66

Pictures of all test runs have not been included. Examples of a short and long icicle can be found in Figures 9 respectively.

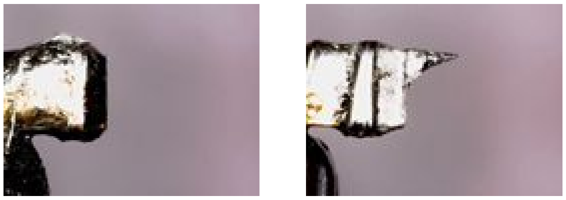

Figure 9. Example of Short and Long Icicle Defect

Analysis was again performed using statistical software. A Pareto chart of the standardized effects using the icicle length as the response can be found in Figure 10. The 4 factors and interactions to the right of the red line are statistically significant. These are: 1) Terminal alloy, 2) Solder alloy, 3) the interaction of the terminal and solder alloys and 4) to a lesser extent the interaction between the solder alloy and dwell time. In the Main Effects Plot in Figure 11, the red points are the center points of the DOE. Use of center points allows determination of if the relationship is linear or non-linear. When looking at the Main Effects plot, we see that both the phosphor bronze terminal and SnCu-LD gave significantly lower responses to icicle length. Pot temperature was negligible (as expected since this was not statistically significant in the Pareto chart). The extended dwell time also gave a reduction in icicle length.

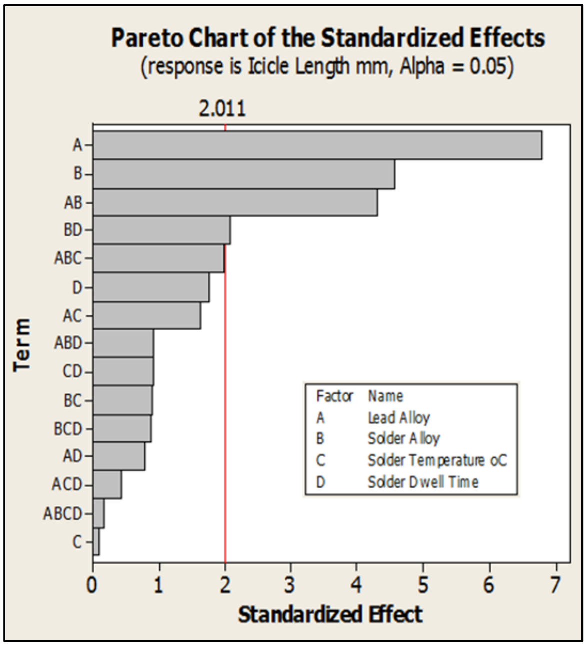

Figure 10. Pareto Chart of Icicling Optimization

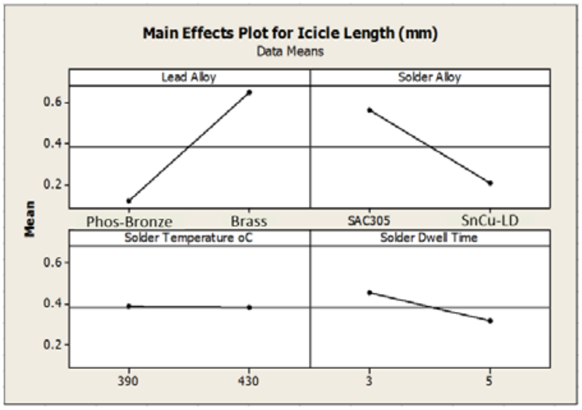

Figure 11. Main Effects for Icicling Optimization

CONCLUSIONS

Complete wetting of the terminal, including the exposed base metal on the stamped edges, is required for the elimination of the solder icicles. Any oxides on the surface of the base metal of the terminal to be soldered will act as a barrier and will prevent wetting and adherence of the solder to the terminal. The oxide need to react chemically with the compound material in the liquid flux. Using the wetting balance test, the solderability of the 2 terminal finishes was determined and found to be solderable when sufficient dwell time is allowed.

The copper dissolution was found to be a function of solder temperature, solder dwell time, and solder alloy. A solder dwell time of three seconds of the copper wire in SnCu-LD solder bath alloy at 390oC had the same cross sectional area than the Sn5Pb93.5Ag1.5 solder alloy (16% reduction for both) but the SAC305 under the same conditions dissolved 50% of the cross sectional area of the copper wire. At increased temperatures (430 oC) the benefit of the SnCu-LD wire was less due to the temperature being an exponential factor to the dissolution rate.

The terminal base alloy, the solder alloy, the interaction between the solder alloy and the terminal base alloy, and the interaction between the solder alloy and the solder dwell time were statistically significant factors in the formation of solder icicling. The SAC 305 alloy exhibited solder icicling on both terminal materials when subjected to a solder pot temperature of 430oC.

The optimum settings for minimizing the solder icicles and copper wire dissolution for this application were found to be:

- Solder alloy: SnCu-LD
- Dip solder pot temperature: 390^{o}C
- Solder dwell time: 3 seconds
- ROM1 rosin based alcohol flux

Phosphor-Bronze terminal alloy

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