Impact of Inert Atmosphere Quality on Wettability of Printed Wiring Board (PWB) Finishes for Surface Mount Soldering Applications

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Executive Summary

An investigation was conducted to assess the impact of reflow soldering inert atmosphere quality on the wettability of various printed wiring board surface finishes. A design of experiments (DOE) was used with four critical process parameters (solder alloy, number of reflow passes, inert atmosphere quality, pwb surface finish) selected for investigation. The following conclusions were reached:

- An inert atmosphere quality of 1000 ppm O2 provides acceptable wetting characteristics applicable for reflow soldering processes using ENIG, immersion silver or immersion tin pwb surface finishes using a Sn63Pb37 solder alloy.

- An inert atmosphere quality of 100 ppm O2 provides acceptable wetting characteristics applicable for reflow soldering processes using ENIG, immersion silver or immersion tin pwb surface finishes using a SAC305 solder alloy.

The following recommendations were made:

- Process trials/functional testing should be conducted to determine whether printed wiring assemblies with surface mount pitch component pitches greater than 25 mil and no BGA/CSP component types are suitable for reflow soldering with an no inert atmosphere.

- Process trials/functional testing should be conducted to determine whether printed wiring assemblies with surface mount pitch component pitches less than 25 mil and/or BGA/CSP component types are suitable for reflow soldering with an inert atmosphere quality of 1000 ppm O2.

- Conversion of a reflow profile utilizing an inert atmosphere quality of 150-300 ppm O2 should be done on an individual printed wiring assembly basis monitoring the soldering process defect levels for a minimum of 3 production lots before making a permanent change to the inert atmosphere quality level.

Background

Rockwell Collins currently utilizes an inert atmosphere of nitrogen for the surface mount reflow soldering processes. The inert atmosphere quality level used is 100-300 ppm O2 content. The use of an inert atmosphere allows the use of less aggressive flux activity levels, promotes favorable solder surface tension, and leads to flux residues that are easier to remove from printed wiring assemblies. However, the use of an inert atmosphere in the surface mount reflow soldering process is a consumable process cost that must be controlled. The Coralville Common Process group requested that AOE review/investigate to determine whether the current inert atmosphere quality level of 100-300 ppm O2 was still applicable. Additionally, it was felt that a better understanding of the effect of inert atmosphere quality level on lead-free soldering processes would be beneficial.

Objective

The objective of the investigation was to determine the impact of reflow soldering inert atmosphere quality on the wettability of various printed wiring board surface finishes.

Procedures

Design of Experiment (DOE) Approach

A number of process parameters were included in the design of experiment approach. Table 1 lists each DOE parameter and its associated variable levels. Two solder alloys were included in the investigation, Sn63Pb37 and SAC305, to assess the impact of the inert atmosphere quality level on both the current Sn63Pb37 reflow soldering process and the anticipated lead-free reflow soldering process of the future. The Sn63Pb37 reflow soldering process utilizes soldering temperatures in the 183°C – 220°C range while the SAC305 reflow soldering process utilizes soldering temperatures in the 221°C – 250°C range. The increased lead-free soldering process temperatures causes additional oxidation of the solder alloys therefore understanding the impact of reducing the quality of the inert atmosphere is important. Typically, a printed wiring assembly is exposed to the reflow soldering process twice: once for the top side and once for the bottom side of the assembly. Understanding the interaction of the number of reflow passes and the inert atmosphere quality were considered critical parameters for the reflow soldering process. All three new generation pwb surface finishes qualified by Rockwell Collins (immersion tin, immersion silver, electroless nickel/immersion gold (ENIG) - were included in the investigation. The surface finishes were applied in accordance with their applicable IPC specification: IPC-4552 (ENIG), IPC-4553 (immersion silver), IPC-4554 (immersion tin). Finally, a range of inert atmosphere quality levels were investigated: the "cleanest" quality level was 100 parts per million (ppm) oxygen content and the "dirtiest" quality level was 10,000 ppm oxygen content. Several test vehicle runs of using no inert atmosphere (e.g. air) were included in the investigation as comparison data points.

Table 1 DOE Parameters and Variable Levels

DOE Parameters	Levels
Solder Alloy	Sn63Pb37, SAC305
Number of Reflow Passes	0, 1, 2
PWB Finishes	Immersion tin, Immersion silver, ENIG
Atmosphere Quality	100 ppm O_2, 1000 ppm O_2, 10000 ppm O_2

Test Vehicle

The test vehicle selected for the investigation was the Dot solderability test vehicle developed by Dr. Chris Hunt of the National Physics Laboratory in England [1]. The Dot solderability test vehicle is ideal for characterizing solder wetting and solder flow interactions with a reflow soldering process. Figure 1 illustrates the Dot solderability test vehicle. A simple solder paste stencil printing procedure is used with the test vehicle with a stencil design composed of 6 tracks of square dots placed with variable pitch as described in the Table 2 and illustrated in Figure 2. The gap between two adjacent stencil openings is increased by about 50 µm in every consequent couple. As the pitch is increasing linearly, the wetting potential can be assessed for each track by observing number of coalesced dots of solder paste. An assessment of "wetting goodness" is made by simply counting the number of non-coalescent dots on the test vehicle after reflow with smaller numbers being the best.

Figure 1 Dot Solderability Test Vehicle

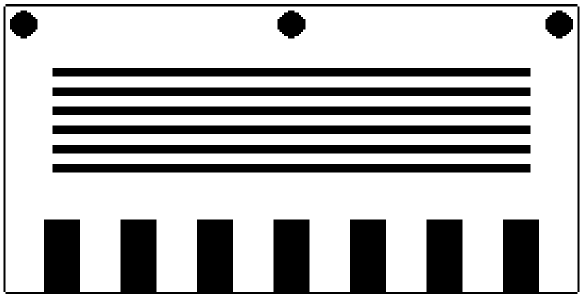
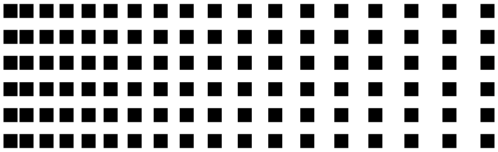


Table 2 Test Vehicle Stencil Pattern Dimensions

Aperture No.	Pitch [mm]	Pitch [mil]	Gap [mm]	Gap [mil]
1	0	-	-	-
2	0.66	26	0.158	6
3	0.71	28	0.211	8
4	0.77	30	0.265	10
5	0.81	32	0.312	12
6	0.86	34	0.364	14
7	0.91	36	0.414	16
8	0.97	38	0.466	18
9	1.02	40	0.516	20
10	1.07	42	0.566	22
11	1.12	44	0.618	24
12	1.17	46	0.668	26
13	1.22	48	0.720	28
14	1.27	50	0.770	30
15	1.32	52	0.820	32
16	1.37	54	0.872	34
17	1.42	56	0.922	36
18	1.47	58	0.974	38
Aperture size	0.5 x 0.5 mm square			
	19.7 x 19.7 mil square			
Increment in Gap ≈ 50 µm				

Figure 2 Solder Paste Stencil Deposit Pattern



In addition to simply using the raw number of coalesced dots of solder paste as a figure of merit, Dr. Hunt also used the following formula as a figure of merit:

$$solderability\ \phi = \frac{126 - \sum_{i=1}^{6} x_i}{126} \cdot 100\%$$

Where xi is number of un-coalesced dots on i-th line and the specific solder paste pattern determines the total possible dots (e.g. the 126 value is paste pattern dependent).

Rockwell Collins obtained the Dot solderability test vehicle electronic Gerber files from Dr. Hunt and had a test panel containing 130 individual test vehicles fabricated in three sets at Collins Printed Circuits (CPC). One set of panels was plated with immersion tin surface finish by CPC and the other two sets were sent to MacDermid for the application of immersion silver and ENIG surface finishes.

Test Vehicle Processing

Test vehicle processing was conducted at the Rockwell Collins Coralville facility. The test panels were processed in random order per the DOE trial run matrix (see Appendix A). The Sn63Pb37 solder paste was Indium SMQ92J and the lead-free solder paste was SAC305 procured from Indium Corporation (Indium 230). A manual solder paste stencil process was used in the investigation (see Figure 3).

Figure 3: Hand Stenciling of Solder Paste

The test vehicles were reflowed in a Heller 1912EXL Convection Reflow Oven. This oven utilized 11 temperature zones for solder reflow. The temperature settings are listed in Table 3. Prior to reflow, the reflow environment was profiled with a test board containing 3 thermocouples to assure correct reflow temperatures were achieved.

Table 3 Reflow Oven Profile

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9	Zone 10	Zone 11
Top Zones	128	127	155	175	185	185	185	193	230	237	204
Bottoms Zones	128	127	155	175	185	185	185	193	230	237	204

The test vehicles were allowed to cool after reflow and then placed in the Electrovert Aquastorm 2000 in-line cleaning system for removal of solder flux residues and other contaminants from the assembly. The in-line cleaner utilized 15% (by volume) Kyzen Aquanox 4520 saponifier in deionized (DI) water. The in-line cleaner is shown in Figure 4.

Figure 4 Electrovert Aquastorm In-line Cleaning System

Test Results

Each test vehicle was examined and the total number of non-coalescent dots recorded. The overall wetting performance of each test vehicle is listed in Appendix A. Figures 5 – 13 illustrate the appearance of various test vehicle combinations.

Figure 5 ENIG: As Received, Air, SAC305 (left) versus Sn63Pb37 (right)

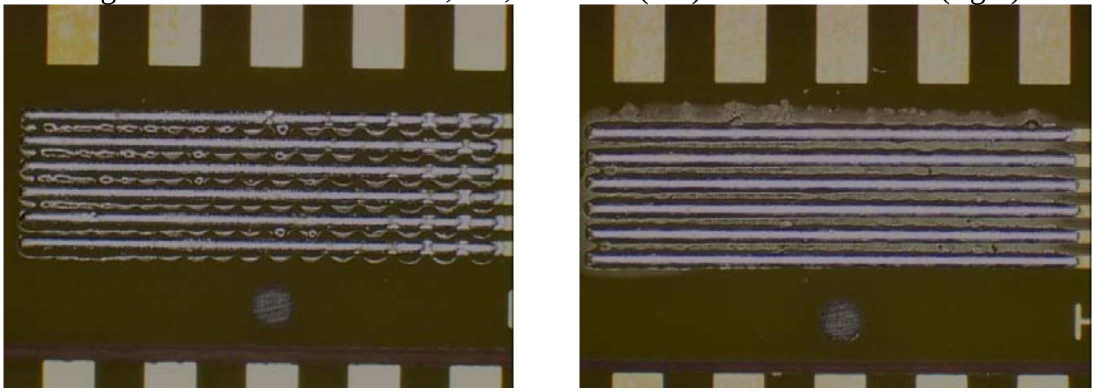


Figure 6 ENIG: One Pass, 10,000 ppm O2, SAC305 (left) - One Pass, 1000 ppm O2, Sn63Pb37 (right)

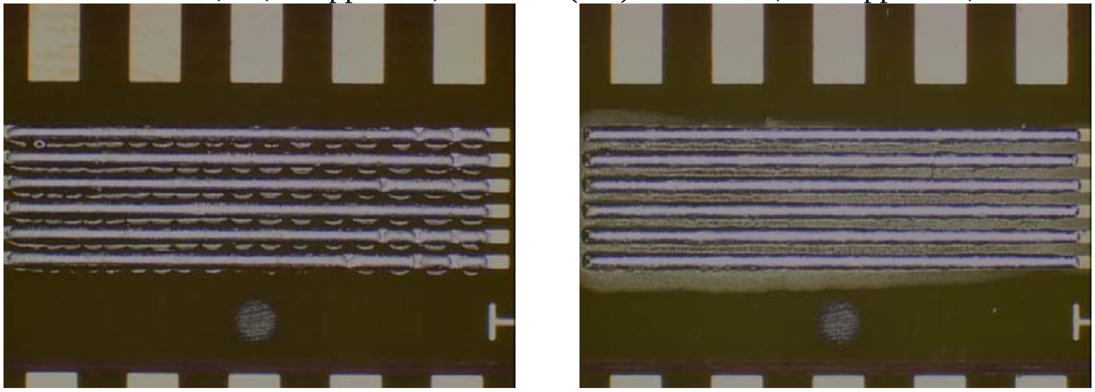


Figure 7 ENIG: Two Pass, 1000 ppm O2, SAC305 (left) - Two Pass, 100 ppm O2, Sn63Pb37 (right)

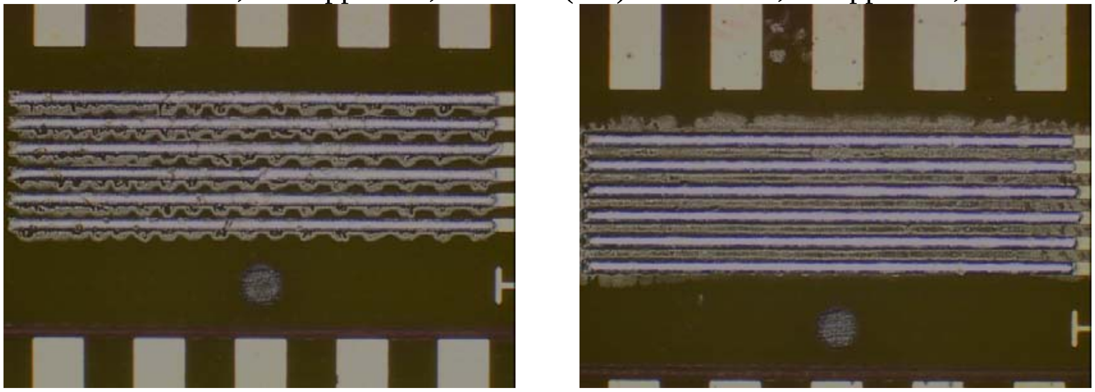


Figure 8 Immersion Silver: As Received, Air, SAC305 (left) versus Sn63Pb37 (right)

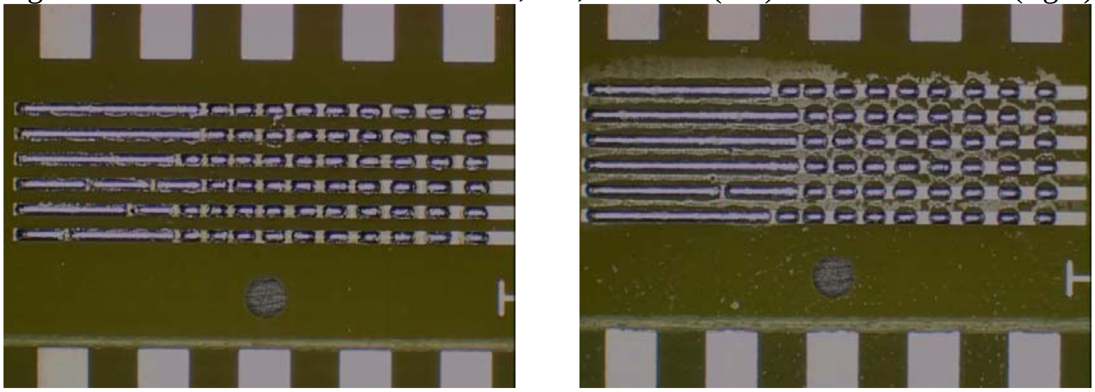


Figure 9 Immersion Silver: As Received, 100 ppm O2, SAC305 (left) -One Pass, 100 ppm O2, Sn63Pb37 (right)

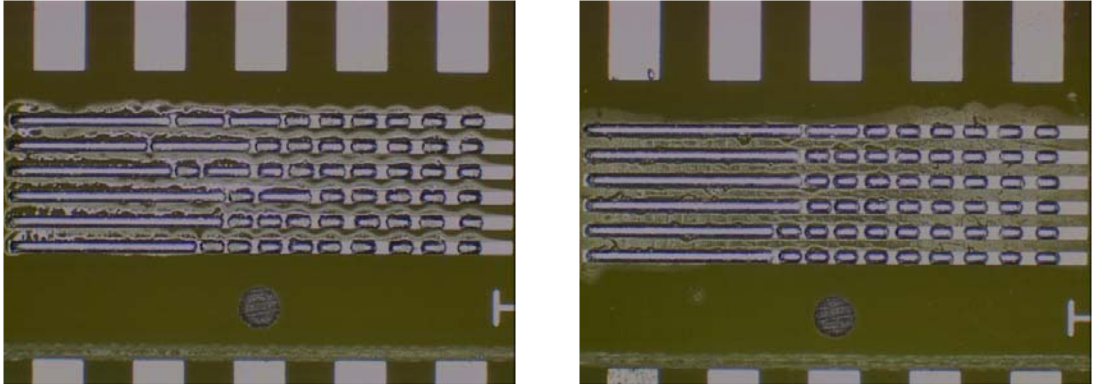


Figure 10 Immersion Silver: Two Pass, 1000 ppm O2, SAC305 (left), Two Pass, 10,000 ppm O2, Sn63Pb37 (right)

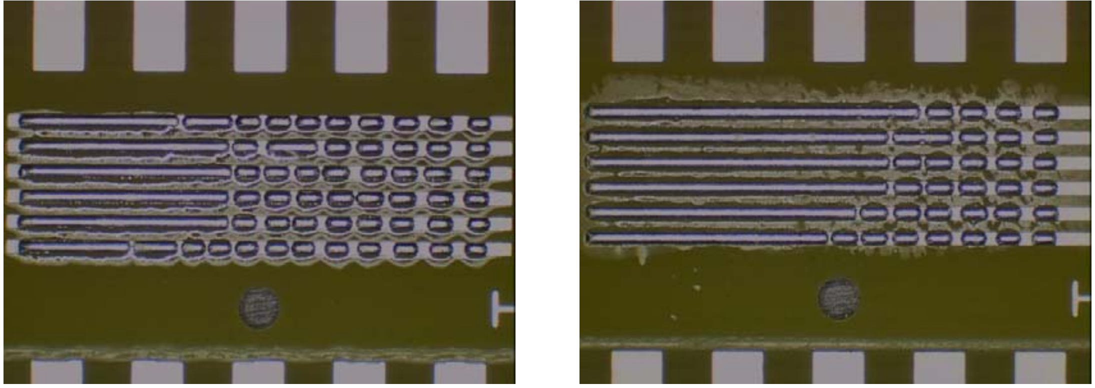


Figure 11 Immersion Tin: As Received, Air, SAC305 (left) versus Sn63Pb37 (right)

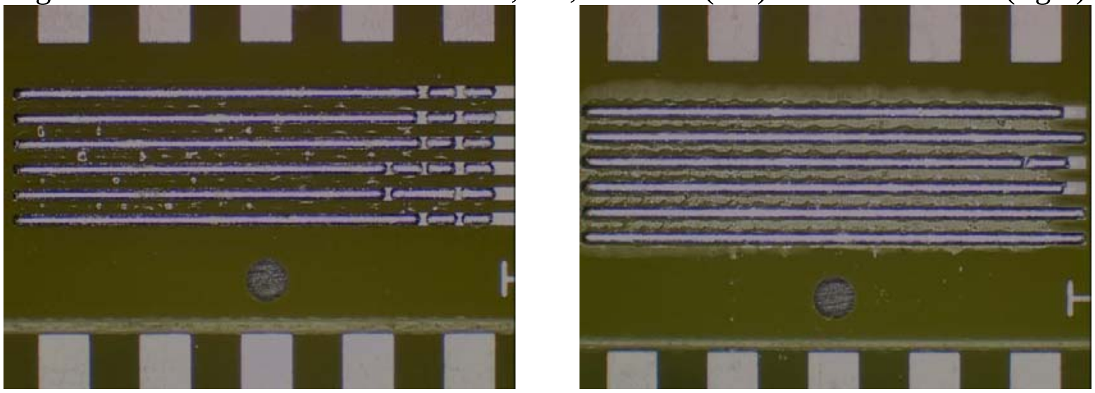


Figure 12 Immersion Tin: As Received, 100 ppm O2, SAC305 (left), As Received, 1000 ppm O2, Sn63Pb37 (right)

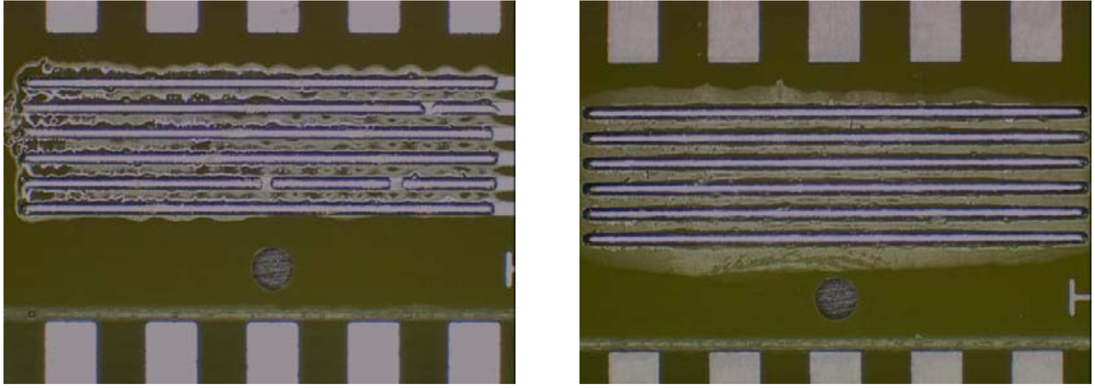
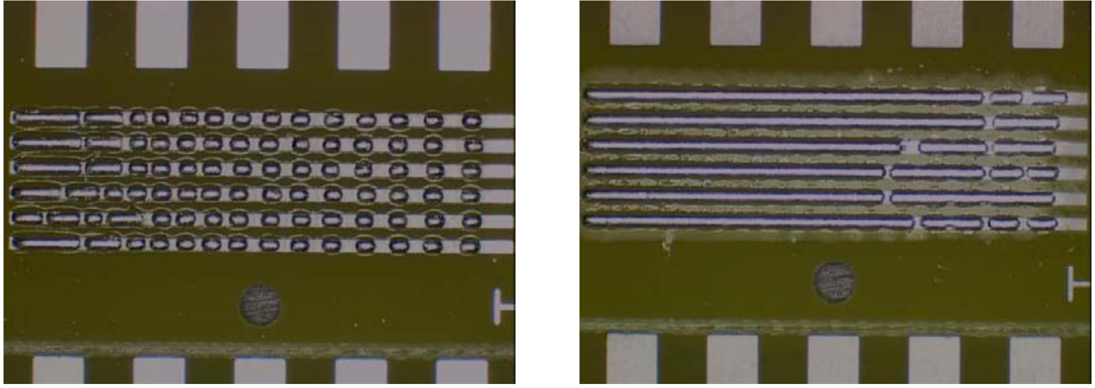


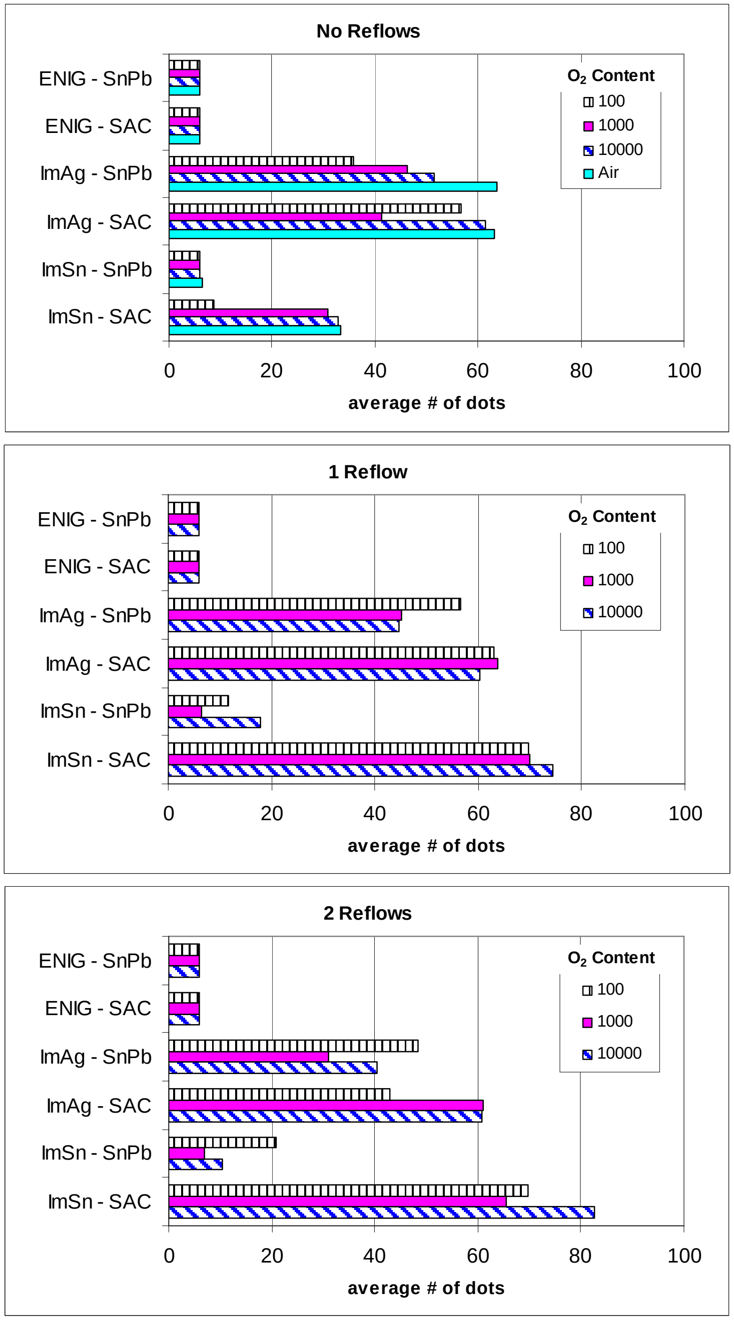
Figure 13 Immersion Tin: Two Pass, 10,000 ppm O2, SAC305 (left), One Pass, 10,000 ppm O2, Sn63Pb37 (right)



Discussion

Figure 14 shows the overall averaged results of non-coalesced dots as a function of surface finish, inert atmosphere quality, and number of reflow passes. The maximum number of dots that could be coalesced for this test was 108 if no dots coalesced (6 rows x 18 pad per row as shown in Figure 2), while the minimum number would be 6 (if all dots coalesced). The fewer the number of dots, the better the wettability performance achieved.

Figure 14 Investigation Statistical Analysis Results



The data analysis revealed the following investigation discussion points:

(1) The ENIG surface finish had the best wetting performance of the three surface finishes tested. The ENIG surface finish had near perfect wetting all combinations of the solder alloy, number of reflow passes and inert atmosphere quality parameters

The fact that the ENIG surface finish had the best performance is not a surprise. The gold plating acts as a sacrificial coating that protects the underlying nickel from oxidation during storage and solder processing. Gold plating does not form an oxide layer and has one of the fastest metallic diffusion rates into tin/lead solder [2]. These characteristics are the basis for the equally good results for the SAC305 solder alloy. However, the ENIG finish has a disadvantage in that the overall solder joint is inherently weaker because of the tin/nickel intermetallic phase in contrast to the tin/copper intermetallic phase that is formed with other pwb surface finishes. The cost of ENIG pwbs can also be higher than other surface finish choices due to the presence of the gold.

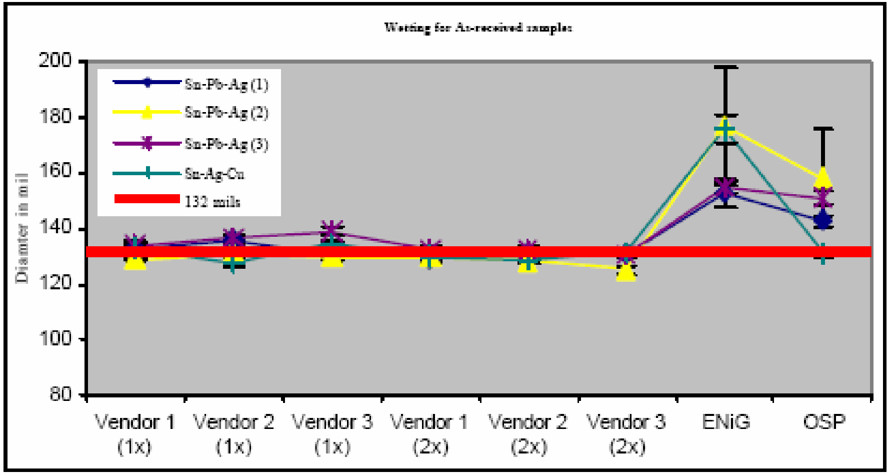
(2) The immersion tin surface finish had better wetting performance with the Sn63Pb37 solder alloy than the SAC305 solder alloy, suffered wetting performance degradation as the number of reflow passes increased and was relatively unaffected by the inert atmosphere quality parameter

The fact that the immersion tin surface finish had degraded wetting performance as a function of the number of reflow passes is also not a surprise. Internal Rockwell Collins investigations and external industry studies [3, 4] have documented the degradation of immersion tin with increased temperature and number of reflow excursions. This lack of thermal process robustness is one of the major reasons for the declining use of immersion tin surface finishes on Rockwell Collins pwbs.

(3) The immersion silver surface finish had the poorest wetting performance of the three surface finishes tested. While the immersion silver finish was relatively unaffected by the solder alloy and number of reflow passes, it was somewhat influenced by the inert atmosphere quality parameters.

The poor performance of the immersion silver surface finish was a surprise. Current use of immersion silver surface finishes on Rockwell Collins pwbs is widespread and few solderability issues have been reported. An investigation conducted by Motorola researchers [5] of immersion silver pwb surface finishes recorded similar behavior to the investigation test results. The Motorola ENIG and OSP finishes exhibited greater solder wetting behavior while the immersion silver exhibiting better solder wetting consistency. Figure 15 illustrates the Motorola wetting data for immersion silver, ENIG, and OSP surface finishes in the as-received condition for lead-free solder alloys. In this figure, a larger diameter size indicates better wettability performance of the surface finish. Thus the ENIG and OSP surface finishes performed better than the immersion silver surface finishes provided by the 3 pwb vendors (note: each vendor provide both standard thickness (1x) and double thickness (2x).

Figure 15 Motorola Wetting Data for As-Received Surface Finishes [5]



Xie et al [6] conducted wettability tests on immersion silver, immersion tin, and ENIG surface finishes subjected to various conditioning treatments. Their investigation utilized a wetting bar test vehicle similar to the dot solderability test vehicle. Their test results showed that the immersion silver surface finish had the poorest wetting performance and required a 100% solder paste pad coverage deposit to achieve complete pad wetting. The immersion tin and ENIG surface finishes required only a 30%-70% solder paste pad coverage deposit to achieve complete pad wetting. Figure 16 illustrates the solder paste pad coverage test vehicle and results.

Figure 16 Wetting Bar Test Solder Paste Pad Coverage Test Vehicle and Results [6]

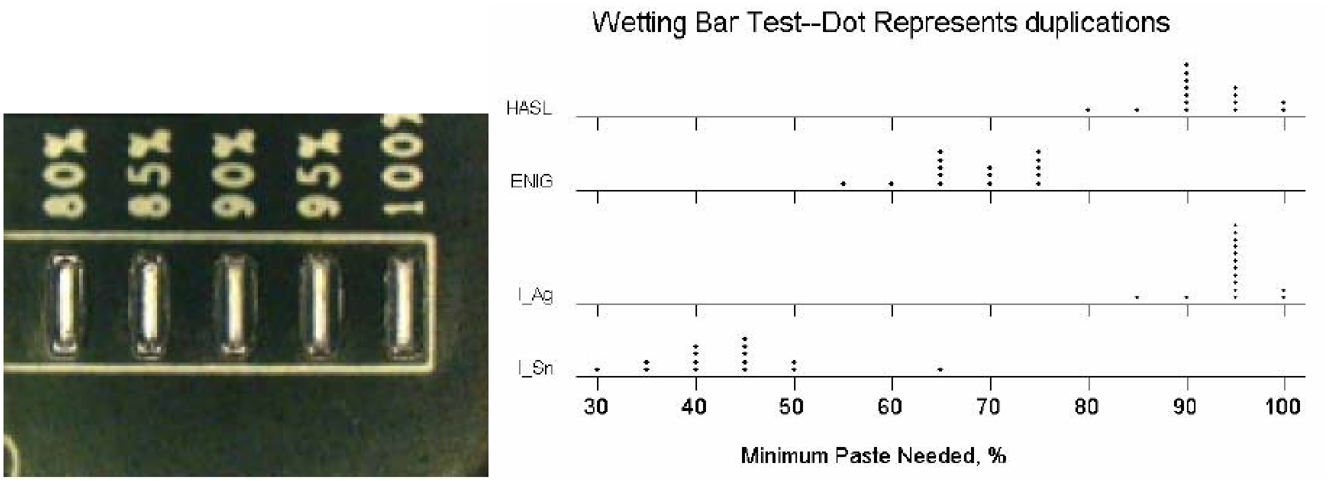


Figure 17 shows a third industry study [7] which found that the immersion silver surface finish had the poorest wetting performance in comparison to OSP, immersion tin and ENIG surface finishes. The study test vehicle used a 40 mil wide x 30 mil high parallel solder paste stripes with gaps varied between 0.1 mm to 0.8 mm (see Figure 17). The number of gaps to bridge was counted in a similar fashion to the non-coalesced dots on the dot solderability test vehicle. Figure 18 illustrates the test results compiled for eutectic tin/lead solder paste.

Figure 17 Parallel Solder Paste Stripe Test Vehicle [7]

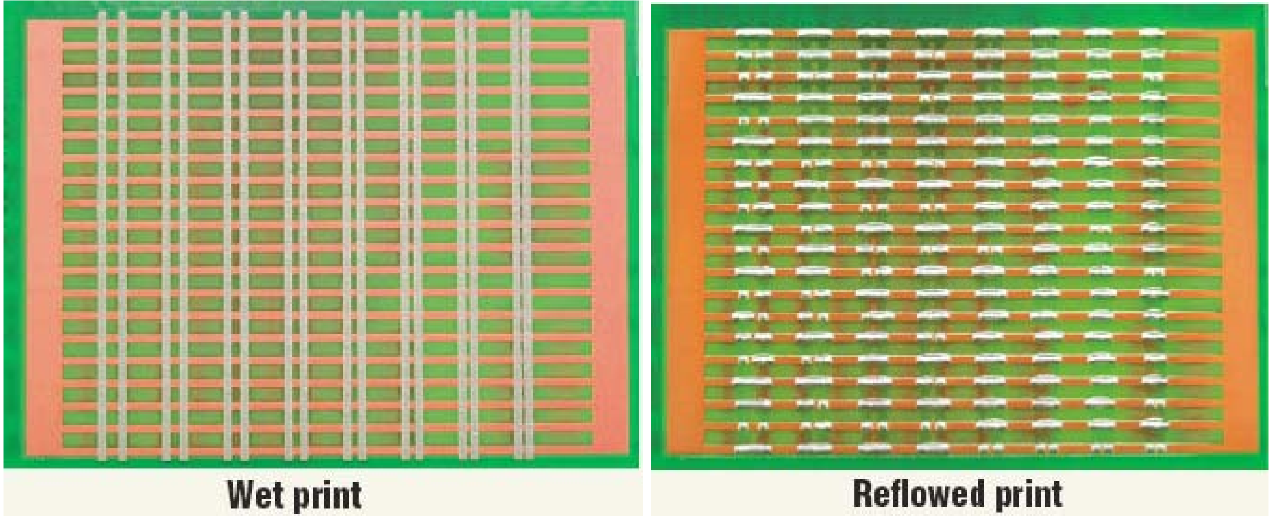
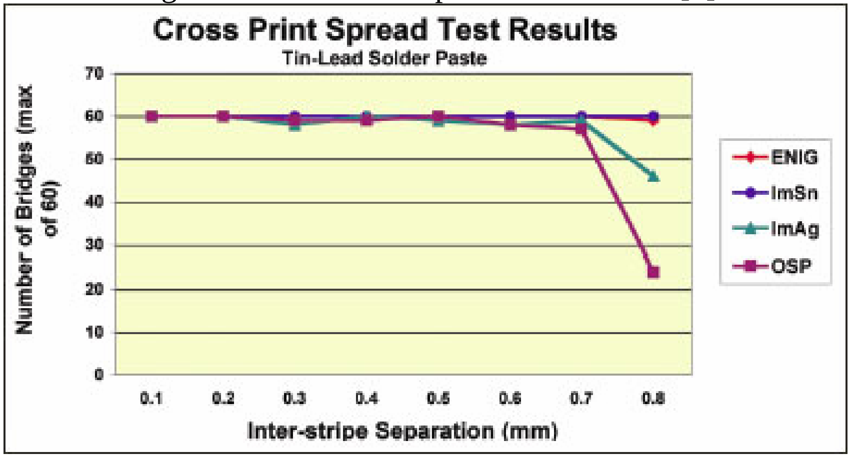


Figure 18 Cross Print Spread Test Results [7]



All three of these industry investigations documented tests show that an immersion silver surface finish does not spread beyond the solder paste deposit in comparison to either immersion tin or ENIG surface finishes. The dot solderability test vehicle test data in the current study documented a similar result.

(4) The use of an inert atmosphere resulted in better wetting performance than soldering in air. The overall best wetting performance, combining all three surface finish choices after multiple reflow passes, resulted in:

a. An inert atmosphere quality of 1000 ppm O2 for the Sn63Pb37 solder alloy
b. An inert atmosphere quality of 100 ppm O2 for the SAC305 solder alloy.

Prior Rockwell Collin investigations [8] have shown that too pure of an inert atmosphere can result in solder surface tension forces that cause defects due to excessive wetting of pwb pads and component terminations. The creation of a “dirty” inert atmosphere by allowing 150-300 ppm O2 contamination results in adequate solder wetting and the creation of better solder joint geometries. The previous work was conducted with fused and hot air solder leveled (HASL) tin/lead pwb surface finishes. The results of the current investigation show that adequate wetting of the ENIG, immersion tin and immersion silver surface finishes was achieved using an inert atmosphere quality of 1000 ppm O2. This result means that a less pure inert atmosphere can be utilized in the reflow soldering process, thus reducing nitrogen consumption. Reducing the inert atmosphere quality to the 1000 ppm level should be done with caution, as it is expected that the interaction of the component termination or an area array (e.g. Ball Grid Array – BGA, or Chip Scale Package – CSP) solderball with the solder paste deposit will have an affect on the overall solder wetting/surface tension characteristics. Additionally, this study documents an initial “line in the sand” for the inert atmosphere quality needed for lead-free reflow soldering processes using a SAC305 solder alloy.

Conclusions

The following conclusions were reached for the testing conducted for this investigation:

- An inert atmosphere quality of 1000 ppm O2 provides acceptable wetting characteristics applicable for reflow soldering processes using ENIG, immersion silver or immersion tin pwb surface finishes using a Sn63Pb37 solder alloy.

- An inert atmosphere quality of 100 ppm O2 provides acceptable wetting characteristics applicable for reflow soldering processes using ENIG, immersion silver or immersion tin pwb surface finishes using a SAC305 solder alloy.

Recommendations

The current practice of using an inert atmosphere quality of 100-300 ppm O2 in the Rockwell Collins reflow oven soldering processes should be evaluated by the cognizant Industrial Engineer on a printed wiring assembly basis. It is recommended that:

- Process trials/functional testing should be conducted to determine whether printed wiring assemblies with surface mount pitch component pitches greater than 25 mil and no BGA/CSP component types are suitable for reflow soldering with an no inert atmosphere.

- Process trials/functional testing should be conducted to determine whether printed wiring assemblies with surface mount pitch component pitches less than 25 mil and/or BGA/CSP component types are suitable for reflow soldering with an inert atmosphere quality of 1000 ppm O2.

- Conversion of a reflow profile utilizing an inert atmosphere quality of 150-300 ppm O2 should be done on an individual printed wiring assembly basis monitoring the soldering process defect levels for a minimum of 3 production lots before making a permanent change to the inert atmosphere quality level.

Acknowledgements

The authors would like to thank Dr. Chris Hunt, NPL, for the test vehicle electronic files and technical discussions, Ross Wilcoxon, Rockwell Collins, for data analysis/manuscript review, and Dave Adams, Rockwell Collins, for manuscript review.

References

[1] Wickham, M., Zou, L., and Hunt, C.: An Assessment of the Suitability of Current PCB Laminates to Withstand Lead-free Reflow Profiles, NPL Report MATC(A)091, April 2002

[2] W. Bader, “Dissolution of Au, Ag, Pd, Pt, Cu, and Ni in a Molten Tin-Lead Solder”, Welding Journal 48, 1969.

[3] D. Hillman et al, “Lead-free Processing Temperature Effects on Immersion Tin Oxidation”, Working Paper WP04-2018, 2004.

[4] J. Lau et al, Electronics Manufacturing with Lead-free, Halogen-free & Conductive-Adhesive Materials, McGraw Hill Publishing, ISBN0-07-138624-6, 2003.

[5] S. Chada and E. Bradley, “Investigation of Immersion Silver PCB Finishes for Portable Product Applications”, SMTAI Conference Proceedings, 2001.

[6] D. Xie et al, “Solderability and Process Integration Studies of Immersion Silver and Tin Surface Finishes”, SMTAI Conference Proceedings, 2002.

[7] EM AISA Magazine, “Quantifying Lead-free Solder Spread”, www.emasiamag.com

[8] D. Hillman et al, “Feasibility Investigation of 0201 Surface Mount Component Implementation”, Working Paper WP05-2008, 2004.

Appendix A

DOE run	finish	reflows	oxygen content	solder alloy	Dots on board	Max dots possible
1	ImAg	0	100	Tin lead	626	1944
1	ImAg	0	100	Tin lead	660	1944
2	ImSn	0	100	Tin lead	109	1944
2	ImSn	0	100	Tin lead	108	1944
3	ENIG	0	100	Tin lead	108	1944
3	ENIG	0	100	Tin lead	108	1944
4	ImAg	1	100	Tin lead	1020	1944
5	ImSn	1	100	Tin lead	208	1944
6	ENIG	1	100	Tin lead	108	1944
7	ImAg	2	100	Tin lead	871	1944
8	ImSn	2	100	Tin lead	373	1944
9	ENIG	2	100	Tin lead	108	1944
10	ImAg	0	1000	Tin lead	831	1944
11	ImSn	0	1000	Tin lead	108	1944
12	ENIG	0	1000	Tin lead	108	1944
13	ImAg	1	1000	Tin lead	813	1944
14	ImSn	1	1000	Tin lead	114	1944
15	ENIG	1	1000	Tin lead	108	1944
16	ImAg	2	1000	Tin lead	651	2268
17	ImSn	2	1000	Tin lead	123	1944
18	ENIG	2	1000	Tin lead	108	1944
19	ImAg	0	10000	Tin lead	926	1944
20	ImSn	0	10000	Tin lead	108	1944
21	ENIG	0	10000	Tin lead	108	1944
22	ImAg	1	10000	Tin lead	804	1944
23	ImSn	1	10000	Tin lead	321	1944
24	ENIG	1	10000	Tin lead	108	1944
25	ImAg	2	10000	Tin lead	727	1944
26	ImSn	2	10000	Tin lead	186	1944
27	ENIG	2	10000	Tin lead	108	1944
28	ImAg	0	100	SAC	850	1620
29	ImSn	0	100	SAC	130	1620
30	ENIG	0	100	SAC	90	1620
31	ImAg	1	100	SAC	1135	1944
32	ImSn	1	100	SAC	1253	1944
33	ENIG	1	100	SAC	108	1944
34	ImAg	2	100	SAC	516	1296
35	ImSn	2	100	SAC	1256	1944
36	ENIG	2	100	SAC	108	1944
37	ImAg	0	1000	SAC	742	1944
38	ImSn	0	1000	SAC	553	1944
39	ENIG	0	1000	SAC	126	2268
40	ImAg	1	1000	SAC	764	1296
41	ImSn	1	1000	SAC	1261	1944
42	ENIG	1	1000	SAC	108	1944
43	ImAg	2	1000	SAC	916	1620
44	ImSn	2	1000	SAC	1181	1944
45	ENIG	2	1000	SAC	90	1620
46	ImAg	0	10000	SAC	1106	1944
47	ImSn	0	10000	SAC	492	1620
48	ENIG	0	10000	SAC	126	2268
49	ImAg	1	10000	SAC	906	1620
50	ImSn	1	10000	SAC	1118	1620
51	ENIG	1	10000	SAC	90	1620
52	ImAg	2	10000	SAC	1042	1620
52	ImAg	2	10000	SAC	780	1620
53	ImSn	2	10000	SAC	1239	1620
54	ENIG	2	10000	SAC	90	1620
A	ImAg	0	Air	Tin Lead	956	1620
B	ImAg	0	Air	Tin Lead	958	1620
A	ImSn	0	Air	Tin Lead	93	1620
B	ImSn	0	Air	Tin Lead	104	1620
A	ENIG	0	Air	Tin Lead	90	1620
B	ENIG	0	Air	Tin Lead	90	1620
A	ImAg	0	Air	SAC	759	1296
B	ImAg	0	Air	SAC	948	1620
A	ImSn	0	Air	SAC	376	1620
B	ImSn	0	Air	SAC	625	1620
A	ENIG	0	Air	SAC	90	1620
B	ENIG	0	Air	SAC	72	1296