Design of Experiments to Assess the Solderability of Various Printed Wiring Board Finishes

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Abstract
There are two main driving forces that are causing the electronics industry to take a look at alternatives to hot air solder leveling (HASL) as a surface finish for printed wiring boards (PWB). First, finer pitch array packages like micro-BGA and chip scale packages are being used in increasing volumes and for a broader variety of devices. With reducing pitches, and thus smaller ball diameters, it becomes necessary to have a predictably flatter surface in order to achieve a consistently more reliable solder joint. The inherent nature of the HASL process to leave inconsistent and uneven topographical profiles of the PWB pad surface, has been well observed and documented. Alternative finishes such as organic solderability preservative (OSP), immersion tin, immersion silver, electroless nickel/immersion gold (ENIG), etc., have been proven to provide the flatness desired – several orders of magnitude flatter than HASL.

The second reason to consider HASL alternatives is the move toward lead-free electronics, particularly in Europe and Japan. With legislation already approved in Europe and a strong focus on environmental marketing in Japan, the demand on PWB fabricators to produce "unleaded" product will no doubt see a marked increase over the next several years. In the United States, organizations such as IPC, the National Electronics Manufacturing Initiative (NEMI), and others have been heavily involved in research activities related to lead-free materials over the last several years. Although the US has not produced any legislative mandates (as of this writing) on the removal of lead from electronics, research activities are ongoing.

Introduction
The purpose of this study was to quantitatively compare a selected group of PWB alternative finishes to HASL in terms of solderability. The finishes chosen for the experiment – immersion tin, immersion silver, and flash gold over nickel, with HASL used as a control and basis for comparison – were picked on the merits of price, availability, and/or compatibility with our processes and business model. OSP and ENIG were not selected for use in this study based on concerns about shelf life, process compatibility, and solder joint reliability.

The method chosen to evaluate solderability was a "spread test" for which a controlled amount of flux was applied, followed by a Sn63Pb37 solder sphere of known diameter (d=0.012" ± 0.0005"), to a statistically valid number of PWB pads. A tacky flux was chosen so as to match the activity level of the flux in the solder paste used in actual manufacturing, and to adequately secure the sphere to the pad. The tacky flux was dispensed automatically with an automated positive displacement-dispensing machine, and the amount was controlled so as to minimize the deposition volume without inhibiting wetting due to insufficient flux. The solder spheres were manually placed in the center of the flux deposit on 0.095" by 0.125" pads using a pneumatic vacuum pencil. The PWBs were then sent through an 8-zone reflow oven using a thermal profile matched to normal manufacturing conditions, verified with a profile recorder.

After the reflow process, the dimensions of the solder deposits were measured in both the X and Y directions using a digital micrometer attached to a microscope, accurate to ±0.0001". The measured X and Y dimensions were then averaged to obtain a "diameter". Since the observed solder spread was fairly uniform (circular), this was a reasonable parameter for estimation of the spread.

The experiment was designed with seven finishes, differing by metallurgy, chemistry, and/or PWB vendor. These included HASL, 2 immersion tin finishes (ImSn1 and ImSn2 at 40-50 µ inches), 3 immersion silver finishes (ImAg1, ImAg2, and ImAg3 at 7-22 µinches), and a flash gold (~ 1-2 µinches) over nickel finish. The thickness measurements were taken using XRF spectroscopy. In addition, another factor introduced was the total number of reflow oven passes, for which one and three were selected. This simulated the "as received" condition (1 pass) as well as two reflow passes and a rework cycle (3 passes). Each of the 14 preconditions had 3 PWBs, with each PWB containing 10 solder spheres for a total of 42 PWBs and 420 solder spheres placed. Measured diameters for the 10 spheres per board were averaged to give a total of 42 data points. The response variable, or variable of interest, was the ratio:

$$\mathbf{D_{avg.} / D_0}$$

$D_{avg.}$ ~ average diameter of the 10 reflowed solder deposits per PWB
D_0 ~ the initial diameter of the solder sphere (0.012")

It is reasonable to suggest that as this ratio increases, the contact angle θ decreases, since the volume of the solder deposit is assumed to be conserved. Wetting is occurring as θ decreases and the spread ratio increases. (See Figure 1.)

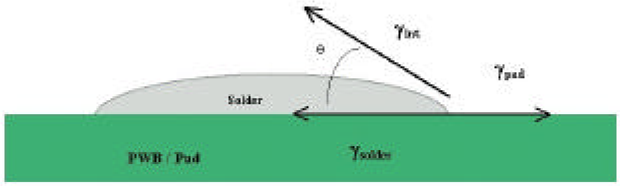

Figure 1 - Wetting Diagram

For solder wetting to occur on the PWB pad, it must be true that

$$\gamma_{pad} > \gamma_{solder} + \gamma_{int.}\cos\theta$$

where the γ terms are the surface tensions of the pad, solder, and flux/solder interface respectively.

Analysis

An analysis of variance (ANOVA) was performed on the 42 ratios obtained, and is shown in Table 1. The surface finish type, number of reflow passes, and interaction were significant at the 95% confidence level.

* $F_{.05,6,28} = 2.45$ and since $F_0 > 2.45$ there is significance
** $F_{.05,1,28} = 4.20$ and since $F_0 > 4.20$ there is significance

Next, a Duncan Multiple Range test was performed on the individual surface finish means (with reflow passes fixed at 3) to verify which means were statistically better than the others. This test did reveal statistically significant differences in the wetting performance of the surface finishes. The order, from highest wetting ability to lowest, is as follows:

ImAg3 > HASL, Au flash,ImAg1,2 > ImSn1, 2

The ImAg3 immersion silver chemistry/vendor showed superior wetting over HASL, with the other immersion silver finishes and flash gold performing as well as HASL. A normal probability plot was also constructed, showing no reason to question assumptions of normally distributed data.

This was followed up by a plot of the residuals for the seven finish types in order to check the variation of the individual data points from their respective cell means. Figure 2 shows rather low variation in the HASL and immersion silver finishes, indicating repeatable results. On the other hand, the immersion tin finishes exhibited a relatively high amount of variation. It should be noted here that data for HASL after 3 reflow passes was not available, so it was estimated to be the same as for 1 reflow pass (conservative with respect to the other finishes). Actually, one would expect the solderability to be diminished at least slightly with each heat (reflow) cycle.

Finally, Figure 3 shows the spread ratio ($D_{avg.} / D_0$) for all finishes at one and three reflow passes. It is interesting to note that the immersion tin finish ImSn1 had a very high spread ratio at the first reflow pass, but degraded significantly after three passes. Likely possibilities for this include copper from the PWB pad diffusing into the tin finish, forming a Sn-Cu intermetallic, which reached the pad surface and inhibited solder wetting. Another possibility for the wetting degradation is oxidation of the pad surface, which would also serve to reduce the surface tension of the pad.

Table 1 - ANOVA

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0
Finishes	2.457	6	0.410	35.921*
Reflow Passes	1.837	1	1.837	161.140**
Interaction	2.103	6	0.351	30.746*
Error	0.319	28	0.0114	
Total	6.716	41		

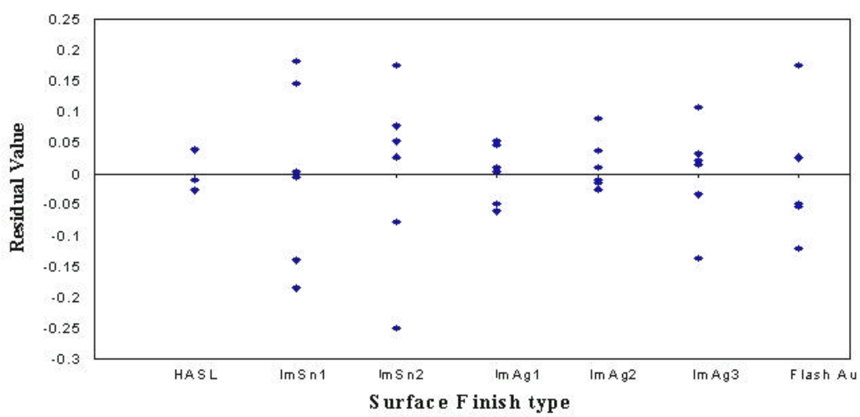

Figure 2 - Residuals Plot

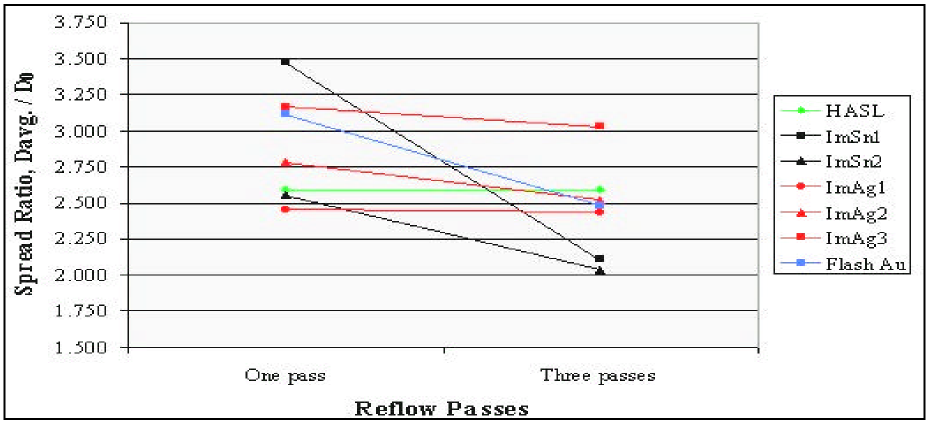

Figure 3 - Spread Ratio Comparison

Meanwhile, ImAg3 exhibited a 17% higher spread ratio than HASL even after 3 reflow passes. This is also conservative, recalling that it was assumed (from a lack of available data) that HASL did not degrade after multiple reflow passes.

Conclusion

Of the finishes evaluated in this experiment, the immersion silver treatment ***ImAg3*** proved to be the best performer; it was 17% better than HASL in terms of the spread ratio, even after 3 reflow passes. In addition, it appeared to have good repeatability in that the residuals were tightly distributed.

The flash gold and other two immersion silver finishes were statistically on a par with HASL after 3 reflow cycles. The immersion silver finishes (ImAg1,2) had particularly tight residual spreads, again indicating very repeatable results.

Both of the immersion tin finishes were somewhat inferior to HASL, in terms of the spread ratio, after 3 reflow passes. It is believed that diffusion of copper through the tin finish was the root cause, and the Sn-Cu intermetallic created would reduce wetting significantly upon reaching the surface. However, another possibility for wetting degradation is the formation of SnO_2 on the pad surface from the air environment and multiple reflow exposures.

The immersion silver finishes performed very well overall in terms of solderability. Since silver does not form intermetallics with copper, much less degradation of the pad surface tension could be expected provided that the Ag layer is uniform. In addition, Scanning Electron Microscopy/Energy Dispersion X-ray (SEM/EDX) analysis showed no evidence of Ag_3Sn intermetallic needles present in the solder joint microstructure. These would tend to embrittle the joint, making it less reliable.

Currently for our PWB vendor base, pricing on a relative scale (where HASL = 1.0) is shown in Table 2.

Table 2 – PWB Vendor Base Pricing on a Relative Scale where HASL – 1.0

Surface Finish	Price Index
HASL	1.00
Immersion Silver	1.10 – 1.15
Immersion Tin	1.10 – 1.20
Gold over nickel	1.10 – 1.20

A subsequent reliability experiment is planned to verify the robustness of solder joints formed with immersion silver and gold PWB finishes under thermal cycling, and after multiple reflow cycles.

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References

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