HOW DOES SURFACE FINISH AFFECT SOLDER PASTE PERFORMANCE?

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ABSTRACT
The surface finishes commonly used on printed circuit boards (PCBs) have an effect on solder paste performance in the surface mount process. Some surface finishes are non-planar like hot air solder level (HASL) which can lead to inconsistencies in solder paste printing. Other surface finishes are difficult to wet during reflow like organic solderability preservative (OSP). What is the overall effect of surface finish on solder paste performance? Which solder paste is best for each surface finish? It is the goal of this paper to answer these questions.

In this work, several different surface finishes were tested in the surface mount process including: HASL, OSP, electroless nickel immersion gold (ENIG), immersion tin, and immersion silver. Several different types of solder pastes were tested along with each surface finish including: lead-free no-clean and water-soluble, and leaded no-clean and water-soluble solder pastes. Each combination of surface finish and solder paste were evaluated for print performance, wetting, solder balling, graping, and voiding. The results of this testing were quantified and summarized. Recommendations pairing the optimal solder paste with each surface finish were given.

Key words: surface finish, solder paste, solder paste printing, wetting, solder balling, graping, voiding

INTRODUCTION
A variety of solderable surface finishes are used on printed circuit boards (Figure 1).

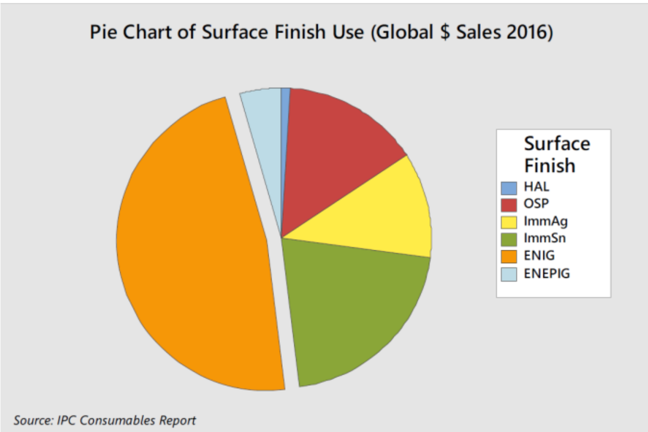

Figure 1: Surface Finishes Used by Sales ($) in 2016 [1]

If surface finishes were not used then soldering would be done to the copper pads. Copper oxidizes very quickly and the oxide thickness grows over time. Copper oxides are very difficult to solder to especially with low activity no-clean fluxes. Solderable surface finishes protect the copper pads and holes while enabling good solderability.

Historically, the most common surface finish was tin-lead (Sn63/Pb37) hot air solder level (HASL). The process used to coat circuit boards with HASL is as follows. The copper is etched to remove oxides, then the circuit board is coated in hot air flux. The circuit board is immersed in molten solder. As the circuit board is removed from the solder hot air is used to "level" the solder making it relatively flat and clearing the holes. Finally, the circuit boards are washed to remove flux residues. Tin-lead HASL has the inherent issue of being non-planar or "bumpy". This can have detrimental effects on printing of solder paste and component placement. Tin-lead HASL is also known to solder very well and is tolerant of multiple soldering cycles. Tin-lead HASL is still commonly used today.

Lead-free HASL is a common finish that has replaced tin-lead HASL in many applications. The process used to coat circuit boards with lead-free HASL is essentially the same as the process for tin-lead HASL. The only exception is the solder alloy that is used. Tin-lead HASL uses Sn63/Pb37 alloy, while lead-free HASL uses tin/copper based alloys like SN100C. Lead-free HASL also has the inherent issue of non-planarity, but solders quite well through multiple soldering cycles. HASL finishes are very durable and hold up well to mechanical damage.

Organic solderability preservative (OSP) is a popular finish due to it's low cost relative to the other surface finishes. The process used to coat circuit boards with OSP is as follows. The copper is cleaned and etched to remove contaminates and oxides. Then the copper is coated with an azole mixture. The excess liquid is removed and the coating is dried. OSP must be handled carefully because it is susceptible to mechanical damage. OSP coated circuit boards must be protected from the air and moisture to prolong shelf life. OSP is flat so it does not have the same issues with non-planarity as HASL. OSP is known to show issues with multiple soldering cycles and is mainly used for cost sensitive applications that require a limited number of soldering cycles.

Electroless nickel immersion gold (ENIG) is a very popular surface finish. ENIG's counterpart electroless nickel

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electroless palladium immersion gold (ENEPIG) is becoming more popular. The process used to coat circuit boards with ENIG is as follows. The copper is cleaned and etched to remove contaminates and oxides. Then the copper is coated with a metallic catalyst, like palladium. Nickel is plated through an electroless plating process which incorporates phosphorous into the nickel deposit. A thin layer of gold is plated onto the nickel deposit through an immersion process where nickel metal is dissolved and replaced by gold metal. ENIG is susceptible to the issue of hyper-corrosion of the nickel which is known commonly as "black pad". ENIG processes have been improved over the years to minimize the risk of "black pad". ENIG is one of the more costly surface finishes. ENIG is a flat finish which promotes good solder paste printing. ENIG is also solderable through multiple cycles and has a long shelf life.

Immersion tin is a popular surface finish used mainly in Europe and Asia. The process used to coat circuit boards with immersion tin is as follows. The copper is cleaned and etched to remove contaminates and oxides. The copper surface is prepared for tin plating through a pre-treatment step, then plated with immersion tin. Copper is dissolved into the plating solution as tin metal is plated onto the circuit board pads. The immersion plating process is self-limiting which limits the maximum thickness of tin. Immersion tin is flat and solders well initially. Lead-free soldering temperatures can damage the finish causing subsequent soldering steps to be challenging. Immersion tin is also susceptible to handling damage because it is relatively thin.

Immersion silver is a finish similar to immersion tin but silver metal is plated over the copper pads. The process used to plate immersion silver onto circuit boards is as follows. The copper is cleaned and etched to remove contaminates and oxides. The copper surface is prepared for silver plating through a pre-treatment step, then plated with immersion silver. Copper is dissolved into the plating solution as silver metal is plated onto the circuit board pads. The immersion plating process is self-limiting which limits the maximum thickness of silver. Anti-tarnish agents are either incorporated into the silver plating step or applied as a final step. Immersion silver is flat and solders well initially but can be tarnished through air exposure and by the heat applied for soldering. Tarnished immersion silver is very difficult to solder. Immersion silver is susceptible to handling damage because it is relatively thin, and must be protected from air and sulfur exposure. Both immersion silver and immersion tin are cost effective finishes.

When choosing a surface finish, there are other characteristics to consider besides print and reflow performance. Here is a list of other characteristics that should be considered with regards to surface finishes [2].

- Solder joint reliability:
  - Surface mount solder joint reliability
  - Ball grid array & bottom terminated component solder joint reliability
  - Plated through hole reliability
- Solderability:
  - Shelf life
  - Solderability after multiple reflow cycles
  - Plated through hole fill after reflow soldering
- Coating characteristics:
  - Complexity of the coating process
  - Flatness of the finish
  - Conductivity for pin probe testing
  - Creep corrosion risk
  - Tin whisker risk

In this work a variety of solder pastes were tested with various surface finishes. Print and reflow characteristics were quantified for each combination of surface finish and solder paste. These results were used to give recommendations for the optimal combinations of solder paste and surface finish.

EXPERIMENTAL METHODOLOGY

The surface finishes used in this work are as follows: tin-lead HASL, lead-free HASL, OSP, ENIG, immersion tin, and immersion silver. The coating thicknesses were measured and are shown below (Table 1).

Table 1: Surface Finish Thicknesses

Surface Finish	Thickness
HASL (Sn63/Pb37)	1.61 - 8.41 µm solder
LF-HASL (SN100C = SnCuNiGe)	2.79 - 3.28 µm solder
OSP	< 2 µm
ENIG	3.05 - 6.10 µm nickel 0.05 - 0.13 µm gold
ITin	1.74 - 1.76 µm tin
ISilver	0.15 - 0.38 µm silver

The solder pastes used for this testing are listed below (Table 2). The codes will be used to refer to these solder pastes throughout the rest of this paper.

Table 2: Solder Pastes Tested

Flux	IPC Flux Classification	Solder Alloy	Code
Water-soluble	ORH0	Sn63/Pb37	WS 63-37
No-clean	ROL0	Sn63/Pb37	NC 63-37
Water-soluble	ORH1	SAC305	WS SAC
No-clean	ROL0	SAC305	NC SAC

The solder powder size used with each solder paste was IPC Type 4 (20-38 µm). The solder pastes chosen are all commercially available products from one manufacturer.

The circuit board used for this testing is called the Print and Reflow (PR) test board and is shown below (Figure 2).

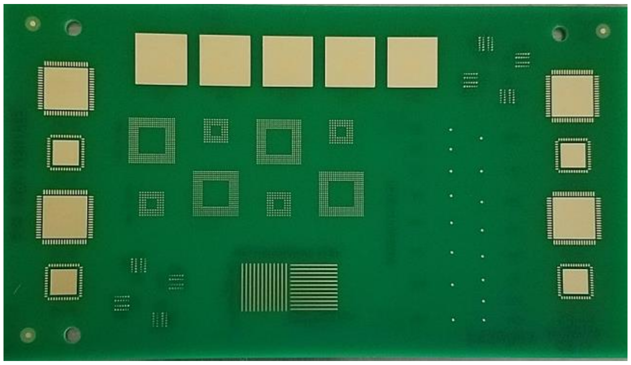


Figure 2: Print and Reflow (PR) Test Board

The PR test board has challenging patterns which allow for quantitative measurement of solder paste performance. These patterns have been used to measure solder paste performance in previous work [3, 4]. The patterns used for printed solder paste volume measurement are 0.4 mm pitch ball grid arrays (BGA). The stencil was 127 µm (5 mils) thick and the apertures were 254 µm (10 mil) rounded squares. These patterns had an area ratio (AR) of 0.50 which challenges the printability of solder pastes (Figure 3).

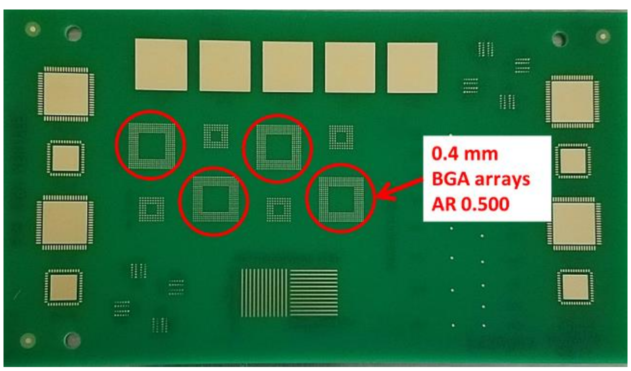


Figure 3: 0.4mm Pitch BGA Arrays Used for Solder Paste Volume Measurement

Additional solder paste printed volume data is gathered from area ratio limit patterns. The stencil apertures are rounded squares ranging in size from 254 µm (10 mil) down to 152 µm (6 mils) and have area ratios of 0.50 down to 0.30 AR (Figure 4).

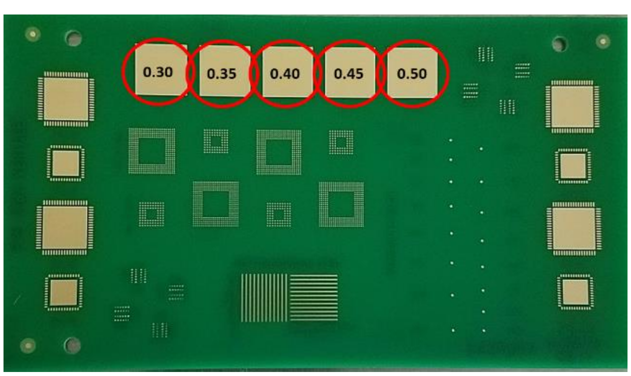


Figure 4: Area Ratio Limit Patterns Used for Solder Paste Volume Measurement

The area ratio limit patterns show the lower limit of printability for solder pastes. Many solder pastes will not print through the smallest 0.30 and 0.35 AR patterns.

A 10-print study was run for each combination of solder paste and surface finish. Printed solder paste volumes were measured and transfer efficiency percentages (TE%) were calculated. Statistical analysis was used to compare and contrast the data sets.

The solder paste print parameters used for this testing are shown below (Table 3).

Table 3: Solder Paste Print Parameters

Printer	Dek Horizon 02
Print Speed	50 mm/sec
Blade Length	300 mm
Blade Pressure	5.0 kg (0.167 kg/cm)
Separation Speed	3.0 mm/sec
Separation Distance	2.0 mm

There are several reflow patterns on the PR test board which allow for quantitative measurement of reflow performance. The characteristics which can be measured are wetting, solder balling, graping, and voiding.

The wetting patterns include 12 parallel lines in both the vertical and horizontal directions. Fifteen solder paste bricks of 0.4 mm width are printed down each line with varying pitch ranging from 0.4 mm at the edges to 0.1 mm in the center of each line (Figure 5).

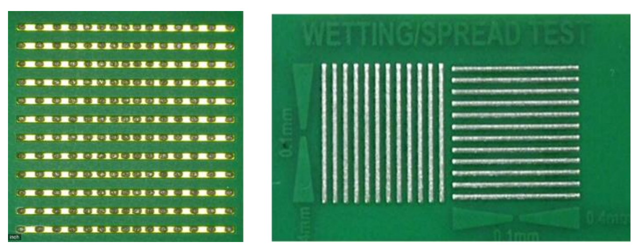


Figure 5: Wetting Reflow Patterns. Printed Solder Paste (Left) and Reflowed Solder (Right)

Ideal wetting is demonstrated by the solder completely covering the entire line. The wetting or spread percentage for each combination of surface finish and solder paste was tallied. The number of gaps that were not covered in solder were counted for each pattern on two circuit boards. The wetting percentage was calculated with the equation below:

$$\text{Wetting \%} = [(\text{Total \# gaps}) / 672] \times 100\%$$

Larger wetting percentages indicate better wetting performance. Ideal wetting is 100%.

Random solder balling was measured using overprint/pullback patterns (Figure 6).

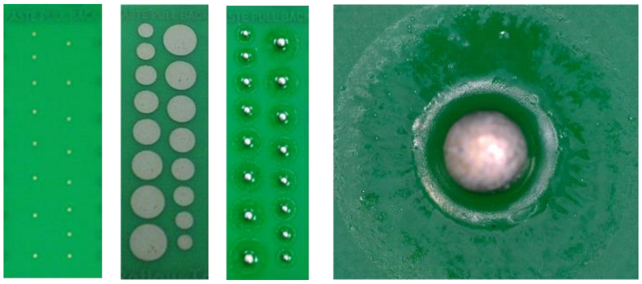


Figure 6: Random Solder Balling Reflow Patterns

The pad size on the circuit board is 0.51 mm (20 mils). The overprint of solder paste onto the pad and surrounding solder mask ranges from 500% to 1250% which equates to stencil aperture diameters of 2.55 mm (100 mils) to 6.35 mm (250 mils). During reflow the solder paste pulls back into one central sphere leaving random solder balls behind in the flux pool. Solder balling performance was measured on two circuit boards and was recorded in three categories as follows:

- The largest % overprint that has 0 solder balls
- The largest % overprint that has < 5 solder balls
- The largest % overprint that has < 10 solder balls

Higher overprint percentages in each category indicate better solder balling performance. Ideal performance is 1250% overprint in each category.

The solder balling performance often varied from one circuit board to another. A judgement call was made and average solder balling performance was recorded. Theoretically surface finish should have a minor effect on solder balling performance. The solder pastes used are the major contributors to solder balling.

Graping was measured using patterns which include solder mask defined (SMD) and non-solder mask defined (NSMD) round and square shaped pads of varying size. The area ratios of the stencil apertures range from 0.60 to 0.35 AR (Figure 7).

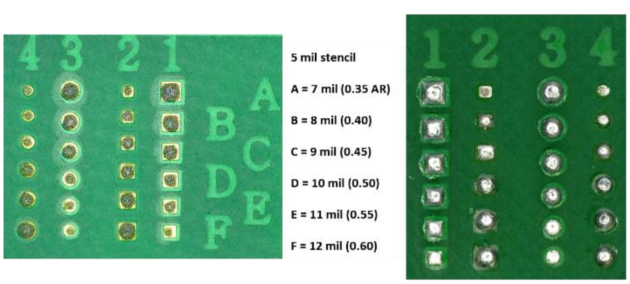


Figure 7: Graping Reflow Patterns. Printed Solder Paste (Left) and Reflowed Solder (Right)

These small solder paste deposits are designed to show graping after reflow. The total number of solder deposits which showed graping were tallied for four patterns on each of two circuit boards. A graping percentage was calculated using the equation below:

$$\text{Graping \%} = [(\text{Total \# graping}) / 192] \times 100\%$$

Lower graping percentages indicate better performance. Ideal performance is 0% graping.

Voiding was measured on the thermal pads of 10 mm body quad flat no lead (QFN) components using a 2D X-ray system. This is similar to testing done in previous work [5, 6]. The solder paste print was broken up into a standard 9-pane cross hatch pattern with 0.51 mm (20 mil) web width and 65% area coverage of the thermal pads (Figure 8).

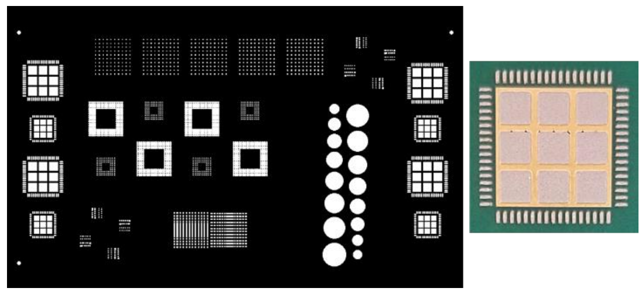


Figure 8: Stencil Design for the Voiding Patterns

Two QFNs were placed per circuit board over the course of a run of ten circuit boards for a total of 20 QFNs. Voiding was measured on the QFN thermal pads and void area % and the largest void % were recorded. Statistical analysis was performed on the voiding data to compare and contrast the data sets. Lower void area and lower void size indicates better performance. Ideal voiding performance is 0% void area and 0% void size.

The reflow profiles used were linear ramp-to-spike type profiles. The reflow profile used for the Sn63/Pb37 solder pastes is shown below (Figure 9).

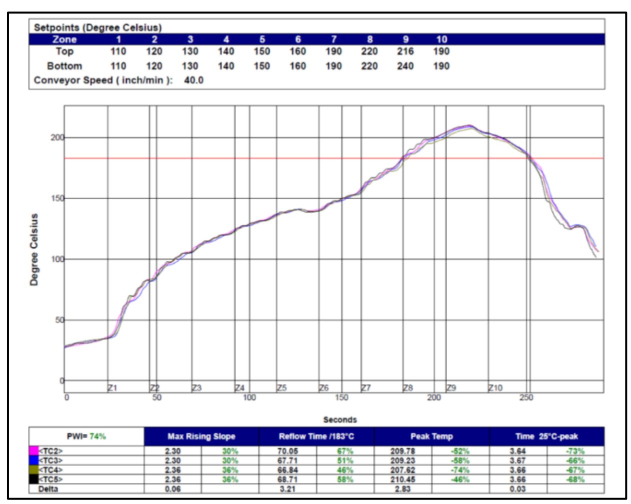


Figure 9: Reflow Profile for the Sn63/Pb37 Solder Pastes

The reflow profile used for the SAC305 solder pastes is shown below (Figure 10).

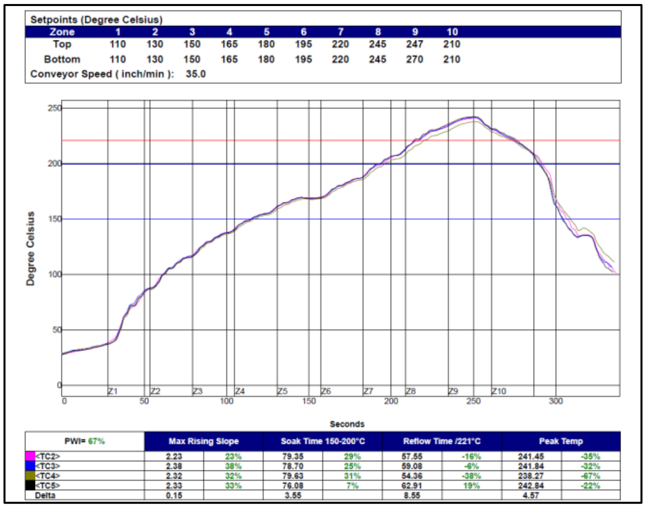


Figure 10: Reflow Profile for the SAC305 Solder Pastes

A summary of the measured parameters in each reflow profile is shown below (Table 4).

Table 4: Reflow Profile Parameters

Parameter	Sn63/Pb37 Profile	SAC305 Profile
Max rising slope	2.3 - 2.4 °C/sec	2.2 - 2.4 °C/sec
Reflow Time	67 - 70 seconds (> 183°C)	54 - 63 seconds (> 221°C)
Peak Temperature	208 - 210°C	238 - 243°C
Time from 25°C to Peak	3.6 to 3.7 minutes	4.1 to 4.2 minutes

Here is a general overview of the testing procedure:

1. Print solder paste onto a circuit board
2. Measure printed solder paste volumes
3. Place 2 QFN components per board
4. Reflow using the appropriate profile
5. Take pictures of the reflowed solder
6. Tally the wetting, solder balling and graping data
7. Measure voiding on the QFN thermal pads
8. Repeat this test procedure to make a total of 10 circuit boards for each combination of surface finish and solder paste

Statistical analysis was done to compare the data sets for printed solder paste transfer efficiency and voiding. The data was displayed in box plot format and Tukey-Kramer honest significant difference (HSD) testing was used to compare the data sets. Tukey-Kramer HSD testing is similar to a Student's T test and is used to determine whether the data sets are significantly different. A 95% confidence level was used in the Tukey-Kramer HSD testing.

RESULTS AND DISCUSSION

Transfer Efficiency Overview

Here is a general overview of the printed solder paste SPI data. The transfer efficiencies varied with solder paste type (Figure 11). This data includes all surface finishes and all patterns grouped together.

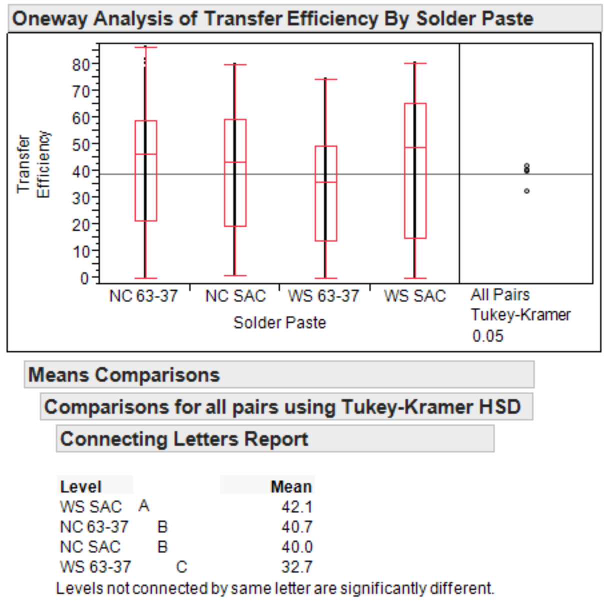
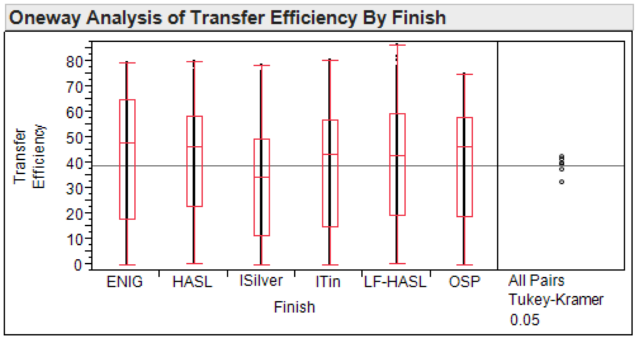


Figure 11: Transfer Efficiency by Solder Paste for All Surface Finishes and Patterns

The box plots for these data sets overlap fairly closely. The Tukey-Kramer HSD connecting letters report assigns letter codes to each data set. If the letter codes are different then the data sets are significantly different with a 95% confidence level. Looking at the connecting letters report (Figure 11), the water-soluble SAC305 solder paste gave the highest transfer efficiency while the water-soluble 63/37 solder paste gave the lowest transfer efficiency. The no-clean 63/37 and SAC305 solder pastes had nearly identical transfer efficiency which were between the two water-soluble solder pastes. This print performance is normal and expected for these solder pastes.

Transfer efficiency was compared for each surface finish (Figure 12). This data includes all solder pastes and all patterns grouped together.



Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Connecting Letters Report

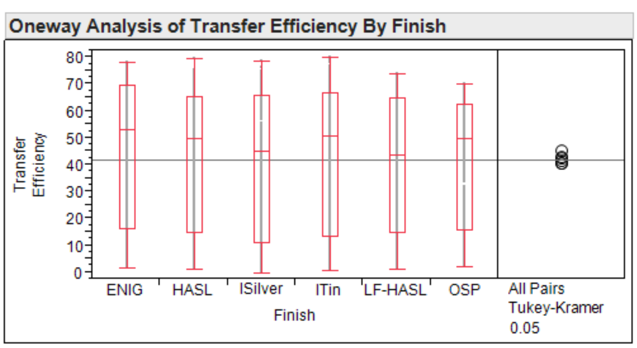
Level					Mean
ENIG	A				42.3
HASL	A				41.6
LF-HASL		B			39.8
OSP		B			39.7
ITin			C		37.4
ISilver				D	32.6

Levels not connected by same letter are significantly different.

Figure 12: Transfer Efficiency by Surface Finish for All Solder Pastes and Patterns

In general, ENIG and HASL (leaded) gave the highest TE percentages. Immersion tin and immersion silver gave the lowest TE percentages. Lead-free HASL and OSP gave TE percentages in the middle of the range.

This general trend of transfer efficiency by surface finish was similar for each of the solder pastes except for the water-soluble SAC305 solder paste (Figure 13).



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Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Connecting Letters Report

Level			Mean
ENIG	A		45.1
ITin	A	B	42.9
HASL		B	42.2
OSP		B	41.6
LF-HASL		B	40.5
ISilver		B	40.4

Levels not connected by same letter are significantly different.

Figure 13: Transfer Efficiency by Surface Finish for the WS SAC Solder Paste and All Patterns

The water-soluble SAC305 solder paste printed nearly equally as well on all of the surface finishes. The ENIG TE was slightly higher than the rest of the finishes. The other surface finishes showed equivalent TE performance with the water-soluble SAC305 solder paste.

Transfer Efficiency for the 0.30 to 0.50 AR Patterns

Here is a closer look at the printed solder paste SPI data for the 0.30, 0.35, 0.40, 0.45, and 0.50 area ratio patterns. These patterns are designed with low area ratios to intentionally challenge solder paste and make the printing process difficult. The transfer efficiency box plots for the area ratio patterns are shown below with the 0.4 mm pitch BGA pattern (0.50 AR) for comparison (Figure 14).

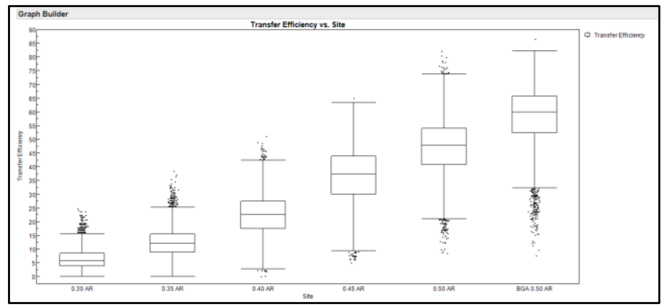


Figure 14: Transfer Efficiency by Area Ratio for all Surface Finishes and Solder Pastes

The median TE values range from about 5% at 0.30 AR up to roughly 50% for the 0.50 AR pattern. For comparison the median TE value for the 0.4 mm pitch BGA (0.50 AR) patterns is roughly 60%. Printing on flat ground pads produces lower TE than printing on the BGA array pads which are copper defined with solder mask clearances.

Transfer efficiency obviously varies with area ratio but some interesting trends can be seen when TE is plotted with respect to solder paste and surface finish.

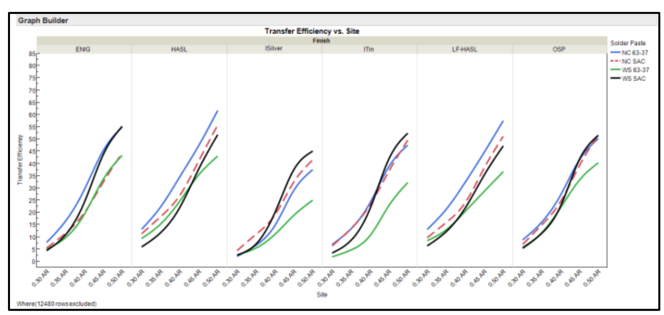


Figure 15: Transfer Efficiency by Area Ratio Broken Out by Solder Paste and Surface Finish

Some surface finishes give close to a linear increase in TE with increasing area ratio, like HASL and LF-HASL. The other surface finishes show a non-linear relationship between TE and area ratio. At area ratios above 0.40 the transfer efficiency increases more quickly with increasing area ratio.

Transfer Efficiency for the 0.4 mm Pitch BGA Arrays

Here is a closer look at the printed solder paste SPI data for the 0.4 mm Pitch BGA Arrays which have a stencil aperture area ratio of 0.50. The TE varied by surface finish for the BGA patterns (Figure 16).

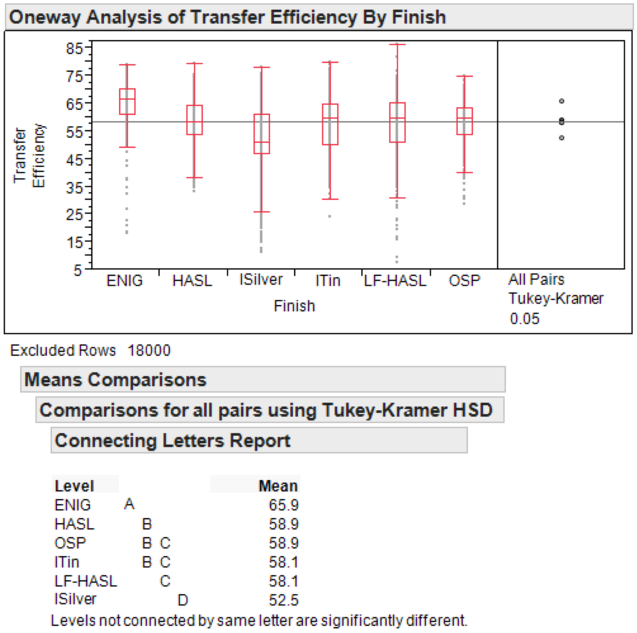


Figure 16: Transfer Efficiency by Surface Finish for all Solder Pastes in the 0.4 mm Pitch BGA Arrays

The same general trends are seen here as was seen above in Figure 12. ENIG gave the highest TE% with HASL (leaded) second while immersion silver gave the lowest TE%. OSP, immersion tin, and lead-free HASL all gave middle TE percentages.

Splitting the print data out by solder paste and surface finish shows some interesting trends (Figure 17).

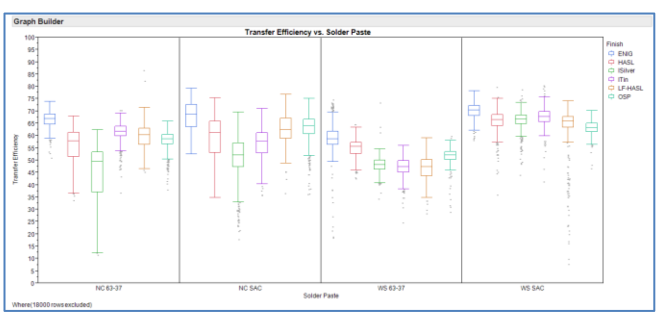


Figure 17: Transfer Efficiency for the 0.4 mm Pitch BGA Arrays by Solder Paste and Surface Finish

The water-soluble SAC305 solder paste gave similar transfer efficiencies for each surface finish. The other solder pastes varied in print performance with surface finish. Immersion silver gave the lowest transfer efficiencies for the no-clean 63/37 and no-clean SAC305 solder pastes. ENIG gave the highest TE for all of the solder pastes.

Analysis of the coefficient of variation (CV) for the TE values for each surface finish is below (Table 5). This data includes all solder pastes grouped together.

Table 5: Coefficient of Variation Analysis (TE) for Each Surface Finish and the 0.4 mm Pitch BGA Arrays

Surface Finish	**Mean TE%**	**Standard Deviation of TE%**	**CV (%)**
ENIG	65.9	6.4	**9.7**
HASL	58.9	7.5	**12.7**
ISilver	52.5	11.2	**21.3**
ITin	58.1	8.8	**15.1**
LF-HASL	58.1	9.3	**16.0**
OSP	58.9	6.3	**10.7**

Only ENIG gave a CV lower than 10% which is the generally accepted upper limit for a process under good control. Immersion silver gave a CV over 20% which is the highest of all the surface finishes. All of the other surface finishes had CV between 10% and 20% which are not ideal. This trend in coefficient of variation follows the trend in transfer efficiency performance for these surface finishes. As TE increases, CV tends to decrease.

Reflow Performance - Wetting

Solder paste wetting or spread was evaluated and summarized for each solder paste (Figure 18). This data includes all surface finishes.

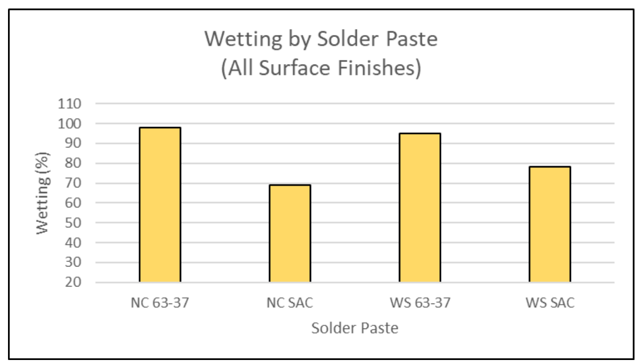


Figure 18: Wetting Average by Solder Paste Including All Surface Finishes

A wetting percentage of 100% is ideal and indicates complete spread of the solder paste. Both the no-clean and water-soluble 63/37 solder pastes had wetting values of near 100%. The water-soluble SAC305 solder paste had a wetting value of 80% and the no-clean SAC305 solder paste had a wetting value of 70%. The lower wetting values shown by the SAC305 solder pastes indicate that they did not spread as well on some of the surface finishes which lowered the overall average.

The wetting data sorted by surface finish is shown below (Figure 19). This data includes all solder pastes.

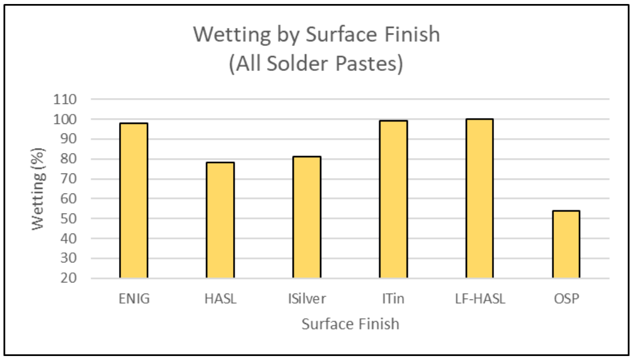


Figure 19: Wetting Average by Surface Finish Including All Solder Pastes

ENIG, immersion tin and lead-free HASL all showed near 100% wetting. Tin-lead HASL and immersion silver showed near 80% wetting. OSP showed 53% wetting. On the average; ENIG, immersion tin and lead-free HASL are easier to wet with a variety of solder pastes. OSP is the most difficult surface finish for solder pastes to wet.

Wetting was broken out for both surface finish and solder paste (Figure 20).

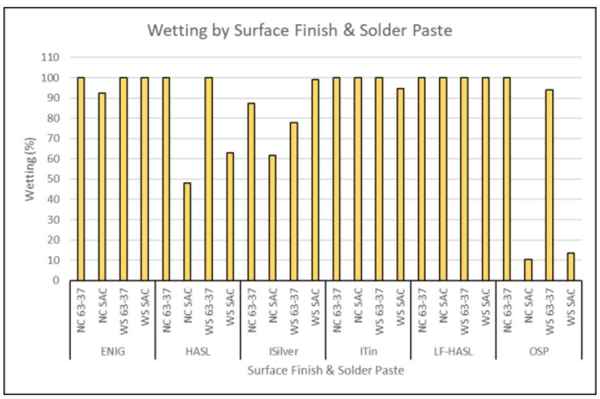


Figure 20: Wetting by both Surface Finish and Solder Paste

ENIG, immersion tin and lead-free HASL had near 100% wetting with each solder paste. Tin-lead HASL had 50% wetting with no-clean SAC305 and 62% wetting with water-soluble SAC305. This indicates that those particular solder pastes were not ideal for wetting the tin/lead finish.

Immersion silver showed 100% wetting with water-soluble SAC305 solder paste and 88% wetting with no-clean 63/37 solder paste. This dropped to 78% wetting with water-soluble 63/37 solder paste, and 62% wetting with no-clean SAC305 solder paste. OSP gave 95 to 100% wetting with water-soluble 63/37 solder paste and no-clean 63/37 solder paste respectively. OSP was difficult to wet with both the no-clean and water-soluble SAC305 solder pastes showing near 10% wetting.

Representative images of wetting performance are shown below (Figure 21).

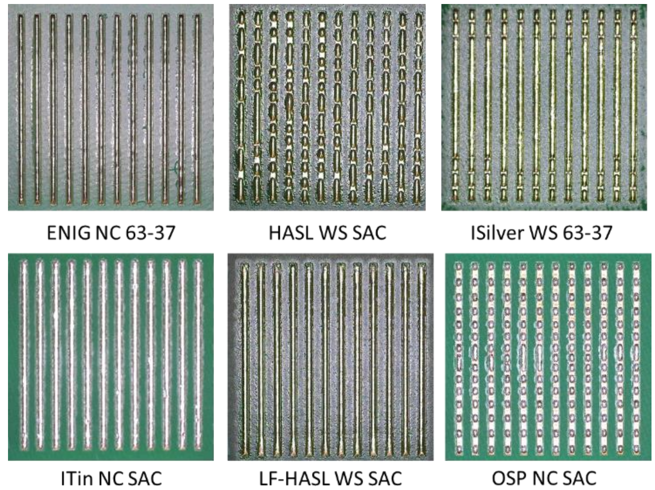


Figure 21: Pictures of Solder Paste Wetting on the Surface Finishes

Generally speaking immersion silver and OSP are more susceptible to oxidation during reflow than the other surface finishes. The reflow profile used for the SAC305 solder pastes may have caused oxidation which limited wetting on these finishes.

Reflow Performance - Solder Balling

Random solder balling was measured by solder paste. The chart below includes the data for all surface finishes (Figure 22).

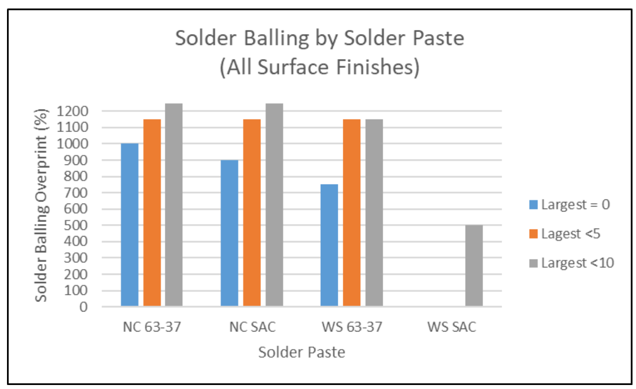


Figure 22: Solder Balling Average by Solder Paste Including All Surface Finishes

Higher overprint percentages indicate better performance in this test. Overprint ratings of 1250% are ideal for each category. Generally speaking, both the no-clean 63/37 and SAC305 solder pastes had very good solder balling performance. The water-soluble 63/37 solder paste also showed good performance. The water-soluble SAC305 solder paste had the worst solder balling performance.

Random solder balling was measured by surface finish including the data for all solder pastes (Figure 23).

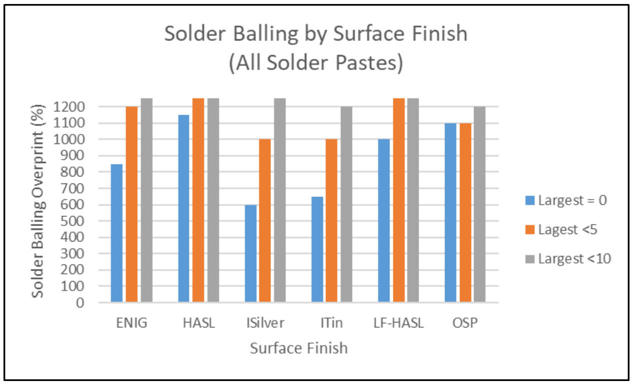
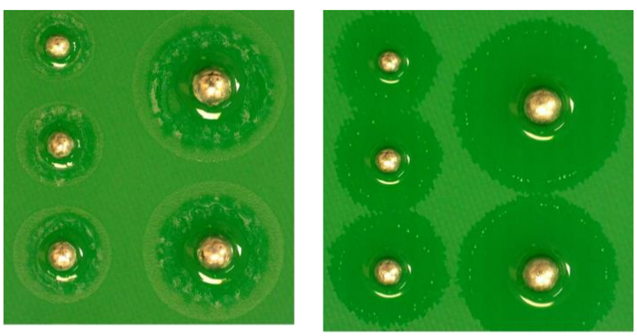


Figure 23: Solder Balling Average by Surface Finish Including All Solder Pastes

Solder balling performance seems to be affected by surface finish. Generally speaking ENIG, tin-lead HASL, LF-HASL and OSP had the best performance. Immersion silver and immersion tin showed worse solder balling performance on the average. This particular test depends upon the ability of the solder paste to pull back off of the solder mask to a small pad covered in the surface finish. It is possible that the processes used to apply immersion silver and immersion tin may have an effect on the solder mask which would limit pull back. Further investigation would have to be done to validate this.

Representative images of solder balling are shown below (Figure 24).



OSP NC SAC

OSP WS 63-37

Figure 24: Pictures of Good (Left) and Poor (Right) Solder Balling Performance

Reflow Performance - Graping

Graping was measured by solder paste. The chart below includes the data for all surface finishes (Figure 25).

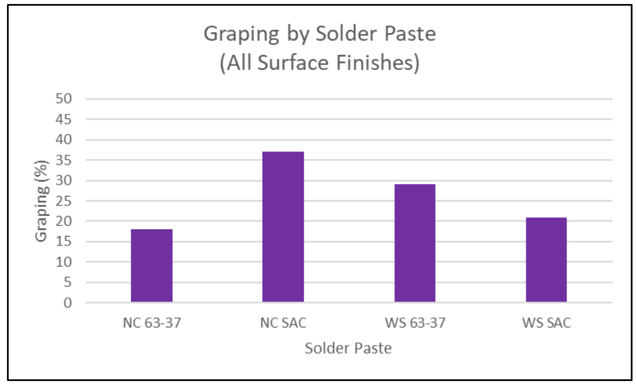


Figure 25: Graping Average by Solder Paste Including All Surface Finishes

Lower graping percentages indicate better performance in this test. The ideal graping value is 0%. No-clean SAC305 solder paste gave the highest graping followed by the water-soluble 63/37 solder paste. The lowest graping was seen with the water-soluble SAC305 and no-clean 63/37 solder pastes.

Graping was measured by surface finish including the data for all solder pastes (Figure 26).

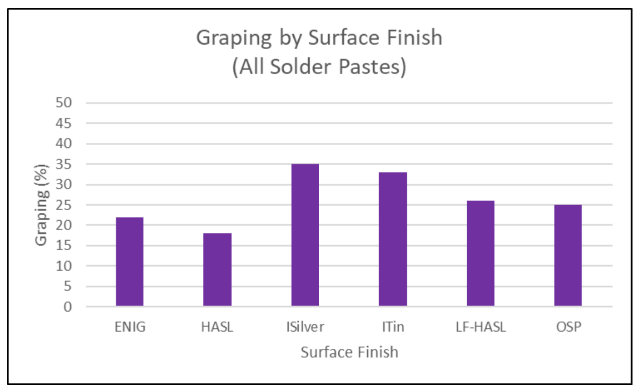


Figure 26: Graping Average by Surface Finish Including All Solder Pastes

Immersion silver and immersion tin gave the highest graping percentages followed by lead-free HASL and OSP. The lowest graping percentages were seen with ENIG and tin-lead HASL.

This test depends upon the ability of the solder paste flux to remove oxides from the solder powder and board pad in order to give complete coalescence of the solder powder into a smooth deposit. The printed solder paste volume also plays a role in this. ENIG and tin-lead HASL finishes gave the highest transfer efficiencies (Figure 12) while immersion tin and immersion silver gave the overall lowest transfer efficiencies. Generally speaking, higher solder paste volumes lead to lower graping values.

Graping broken out by both surface finish and solder paste is shown below (Figure 27).

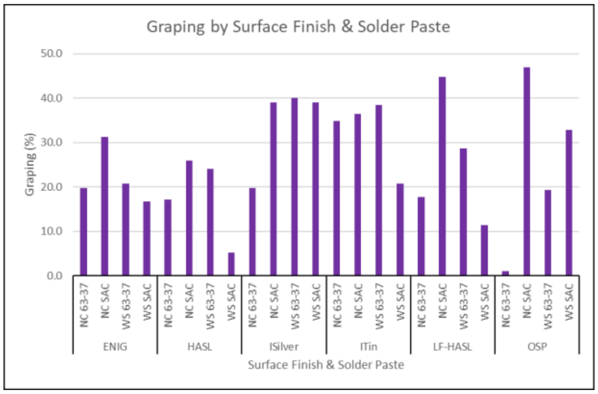
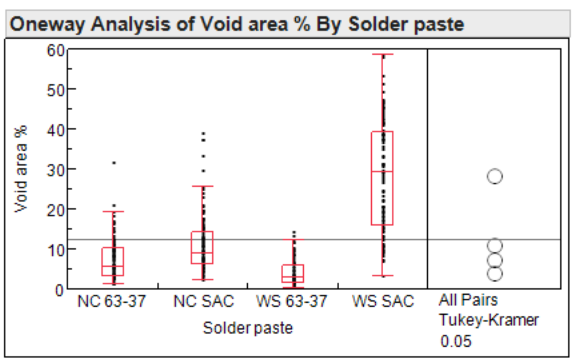


Figure 27: Graping by both Surface Finish and Solder Paste

Some surface finishes give fairly level graping performance regardless of solder paste, like ENIG. The graping for ENIG with NC 63-37, WS 63-37 and WS SAC solder pastes was between 17 and 21%. Other surface finishes like OSP give a range of graping performance based on the solder paste used. OSP with no-clean 63/37 solder paste gave the overall lowest graping (1%) while OSP with no-clean SAC305 solder paste gave the overall highest graping (47%). It is clear that graping performance depends upon both surface finish and solder paste.

Voiding Performance

Void area percentage was measured and sorted by solder paste and includes the data for all surface finishes (Figure 28).



Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Connecting Letters Report

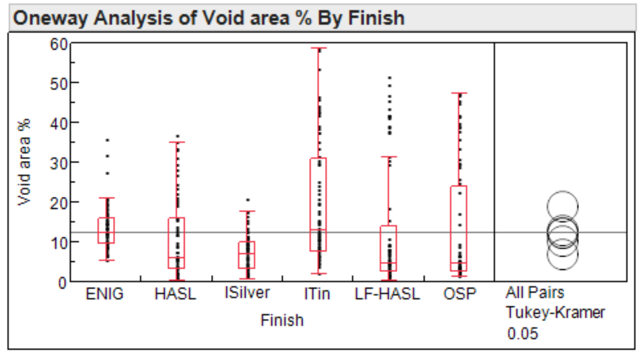
Level					Mean
WS SAC	A				28.3
NC SAC		B			11.2
NC 63-37			C		7.2
WS 63-37				D	4.1

Levels not connected by same letter are significantly different.

Figure 28: Void Area (%) by Solder Paste Including All Surface Finishes

There is a distinct difference in void area for each of these solder pastes. Water-soluble SAC305 solder paste shows higher void area then no-clean SAC305, which is higher than no-clean 63/37, followed by water-soluble 63/37 solder paste which had the lowest void area.

The void area data for each surface finish is shown below (Figure 29). This data includes all of the solder pastes.



Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Connecting Letters Report

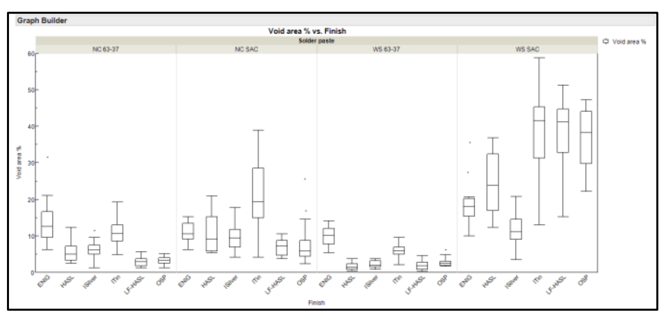
Level				Mean
ITin	A			19.4
ENIG		B		13.2
OSP		B	C	12.7
LF-HASL		B	C	12.5
HASL		B	C	10.7
ISilver			C	7.5

Levels not connected by same letter are significantly different.

Figure 29: Void Area (%) by Surface Finish Including All Solder Pastes

The differences in voiding area by surface finish are not as clear as the difference in voiding area by solder paste. With that said, void area does vary somewhat by surface finish. Immersion tin showed the highest voiding area with all other finishes giving statistically lower void areas. ENIG gave similar voiding to OSP, LF-HASL, and HASL but higher voiding than immersion silver. The void area produced by immersion silver was lower than immersion tin and ENIG, but statistically similar to OSP, LF-HASL and HASL surface finishes.

Void area varied for each surface finish and solder paste combination (Figure 30).



Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Connecting Letters Report

Level		Mean
ITin WS SAC	A	39.3
LF-HASL WS SAC	A	38.4
OSP WS SAC	A	37.1
HASL WS SAC	B	24.7
ITin NC SAC	B C	21.2
ENIG WS SAC	C D	18.4
ENIG NC 63-37	D E	13.7
ISilver WS SAC	E F	11.9
ITin NC 63-37	E F G	11.1
ENIG NC SAC	E F G	11.0
HASL NC SAC	E F G	10.6
ENIG WS 63-37	E F G	9.9
ISilver NC SAC	E F G	9.7
OSP NC SAC	F G H	7.7
LF-HASL NC SAC	F G H I	6.9
ISilver NC 63-37	F G H I	6.2
ITin WS 63-37	F G H I	6.1
HASL NC 63-37	G H I	5.8
OSP NC 63-37	H I	3.3
LF-HASL NC 63-37	H I	3.0
OSP WS 63-37	H I	2.8
ISilver WS 63-37	H I	2.2
LF-HASL WS 63-37	H I	1.9
HASL WS 63-37	I	1.7

Levels not connected by same letter are significantly different.

Figure 30: Void Area (%) by Both Surface Finish and Solder Paste and the Tukey-Kramer HSD Connecting Letters Report

The overall highest voiding was seen with the water-soluble SAC305 solder paste with the immersion tin, LF-HASL, and OSP surface finishes. The overall lowest voiding was seen from the water-soluble 63/37 solder paste with the HASL surface finish. Representative images of voiding from some combinations are shown below (Figure 31).

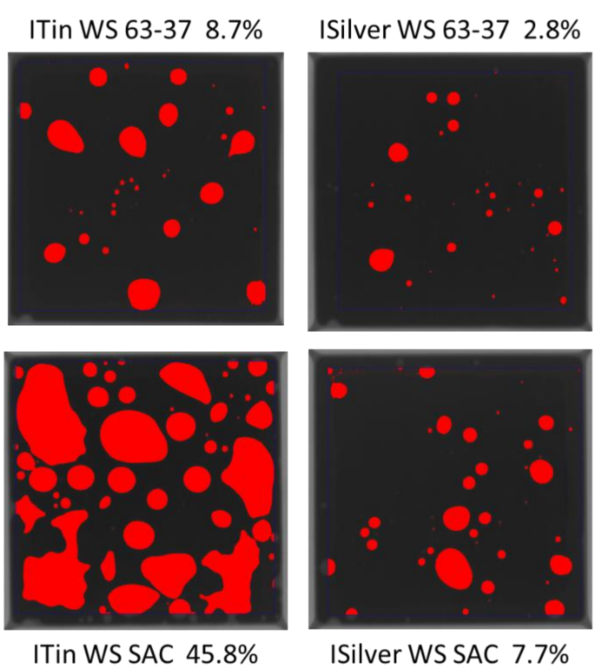


Figure 31: Representative Images of Voiding from Select Surface Finish and Solder Paste Combinations

The voiding images show different voiding behavior for the water-soluble solder pastes with two different surface finishes. The water-soluble 63/37 solder paste gave very low voiding with the immersion silver finish, and moderate voiding with the immersion tin finish. The water-soluble SAC305 solder paste gave very high voiding with the immersion tin finish and much lower voiding with the immersion silver finish. It is clear from the voiding data and images that solder paste and surface finish both play a role in voiding behavior.

Scoring of Each Surface Finish Solder Paste Combination

A scoring system was used to rank the performance of each surface finish and solder paste combination. This scoring system was based upon a scale of 1 to 5. A score of 1 indicates the worst performance in that particular category. Scores of 2 to 4 indicate "middle of the pack" performance. A score of 5 indicates the best possible performance in that category. The raw data from each surface finish and solder paste combination was used and scores were assigned within each category and performance metric (Table 6).

Table 6: Scoring Categories and Performance Metrics for Each Surface Finish and Solder Paste Combination

Category	Performance Metric	Possible Score
Print	Transfer Efficiency % in the 0.4 mm BGA Arrays	5
Print	Coefficient of Variation (TE) in the 0.4 mm BGA Arrays	5
Print	Transfer Efficiency % in the 0.50 AR Pattern	5
Print	Coefficient of Variation (TE) in the 0.50 AR Pattern	5
Reflow	Wetting or Spread %	5
Reflow	Solder Balling	5
Reflow	Graping %	5
Voiding	Void Area %	5
Voiding	Largest Void %	5
	Total Possible Score	**45**

The scoring scales for each category are shown below (Table 7).

Table 7: Scoring Scales for Each Category

	Print 0.4 mm BGA		Print 0.50 AR Pattern		Reflow			Voiding	
Score	TE%	CV%	TE%	CV%	Wetting %	Solder Balling	Graping %	Void Area %	Largest Void %
1	<50	>15	<40	>20	0-20	none	41-50	>25	>5.0
2	51-57	10-14	41-45	16-20	21-40	500-650	31-40	16-25	3.1-5.0
3	58-64	8-9	46-50	11-15	41-60	700-850	21-30	11-15	2.1-3.0
4	65-70	6-7	51-55	8-10	61-80	900-1050	11-20	6-10	1.1-2.0
5	>70	0-5	>55	<8	81-100	1100-1250	0-10	1-5	0-1.0

The raw data that was used for scoring is not included in this paper for brevity. The overall scores were summarized for the surface finishes and solder pastes used (Table 8).

Table 8: Scores Ranking Overall Surface Finish (Left) and Solder Paste (Right) Performance

Surface Finish	Total (180 poss)
ENIG	131
HASL	128
OSP	123
LF-HASL	117
ITin	113
ISilver	107

Solder Paste	Total (270 poss)
NC 63-37	207
WS 63-37	178
NC SAC	174
WS SAC	160

The ENIG surface finish has the highest overall score while immersion silver has the lowest overall score. The no-clean 63/37 solder paste had the highest overall score while the water-soluble SAC305 solder paste had the lowest overall score. These scores apply to the surface finishes and solder pastes used in this battery of tests. If other materials or tests are used then performance may differ.

The overall scoring for each surface finish and solder paste combination are below (Table 9).

Table 9: Total Scores for Each Surface Finish and Solder Paste Combination

Surface Finish	Solder Paste	Print Score (20 poss)	Reflow Score (15 poss)	Void Score (10 poss)	Total (45 poss)
OSP	NC 63-37	15	15	10	**40**
ENIG	NC 63-37	17	14	6	**37**
LF-HASL	NC 63-37	13	14	10	**37**
HASL	NC 63-37	13	14	8	**35**
HASL	WS 63-37	12	13	10	**35**
ENIG	WS SAC	18	11	5	**34**
ITin	NC 63-37	14	11	7	**32**
OSP	WS 63-37	11	11	10	**32**
ENIG	NC SAC	13	11	7	**31**
HASL	NC SAC	13	11	7	**31**
LF-HASL	NC SAC	11	11	9	**31**
ENIG	WS 63-37	10	12	7	**29**
OSP	NC SAC	13	7	8	**28**
ISilver	WS 63-37	8	10	10	**28**
LF-HASL	WS 63-37	5	13	10	**28**
ITin	WS SAC	17	9	2	**28**
ITin	NC SAC	12	11	4	**27**
HASL	WS SAC	13	10	4	**27**
ISilver	WS SAC	13	8	6	**27**
ISilver	NC 63-37	5	13	8	**26**
ISilver	NC SAC	9	10	7	**26**
ITin	WS 63-37	7	11	8	**26**
OSP	WS SAC	17	4	2	**23**
LF-HASL	WS SAC	8	11	2	**21**

The highest scoring combinations included the no-clean 63/37 solder paste along with OSP, ENIG, LF-HASL, and HASL surface finishes. This was followed by the water-soluble 63/37 solder paste with HASL surface finish. Scores near the bottom were for the immersion silver surface finish with water-soluble SAC305, no-clean 63-37, and no-clean SAC305 solder pastes, and immersion tin with the water-soluble 63/37 solder paste. The lowest overall scores were for the water-soluble SAC305 solder paste with the OSP and LF-HASL surface finishes.

There were no perfect scores for printing although some combinations were close. Only OSP with the no-clean 63-37 solder paste had a perfect reflow score, but others were close. Several combinations had perfect voiding scores and they were all with Sn63/Pb37 solder pastes.

Sn63/Pb37 solder pastes tend to perform better than SAC305 solder pastes in these tests. Seven of the top ten scores were given to Sn63/Pb37 solder paste combinations. In contrast to this, seven of the bottom ten scores were given to SAC305 solder pastes. Leaded HASL and ENIG surface finishes each took three of the top ten scores, while immersion silver did not show up in the top ten. Immersion silver took three of the bottom ten scores as did immersion tin. OSP took the highest score and the 2nd to the lowest score. Lead-free HASL took the 3rd highest score and the lowest score. OSP and LF-HASL performance varies widely with the solder paste used.

Here is a general overview of the pros and cons for each surface finish with respect to printing, reflow, and voiding behavior (Table 10).

Table 10: Overview of Surface Finish Performance in Printing, Reflow and Voiding

Surface Finish	Printing	Reflow	Voiding
ENIG	✓	✓	✗
HASL	OK	OK	OK
ISilver	✗	✗	✓
ITin	OK	OK	✗
LF-HASL	✗	✓	✓
OSP	✓	✗	OK

A green checkmark indicates good performance in that area. "OK" indicates average performance. A red "X" indicates less than optimal performance. This summary is intended to be used as a general guideline for performance of each surface finish. A green checkmark does not guarantee optimal performance of that surface finish. Similarly, a red "X" does not indicate failure to perform. These pros and cons are simply general observations about the strengths and weaknesses of each surface finish based upon the results of this work.

CONCLUSIONS

A range of solder paste and surface finish combinations were tested for print, reflow, and voiding performance. Differences in performance were shown and quantified. If one has the freedom to choose the surface finishes and solder pastes used then it is recommended to choose a combination that works well together. The no-clean 63/37 solder paste tends to work well with most surface finishes. If a lead-free solder paste is required, then a no-clean SAC305 solder paste is a good choice for most surface finishes. The ENIG, and leaded HASL surface finishes tend to work well with most solder pastes. The immersion silver and immersion tin surface finishes did not perform as well as the other surface finishes. The OSP and lead-free HASL surface finishes showed a wide range of performance depending upon the solder paste used. It is important to know the limitations of the solder pastes and surface finishes in order optimize performance.

FUTURE WORK

Several combinations of surface finish and solder paste will be explored in more detail. An expanded range of lead-free solder alloys will be evaluated. Print speeds and blade pressures will be varied over a wide range. Reflow performance will be measured after thermally aging the circuit boards with 1 reflow cycle to simulate what happens on the 2^{nd} side of a double-sided surface mount PCB. Reflow profiles will be varied to include long soak and high peak temperatures. This work will be summarized and presented at future technical conferences.

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