# Quantifying the improvements in the solder paste printing process from stencil nanocoatings and engineered under wipe solvents

**Conference Paper** · November 2014

DOI: 10.1109/IEMT.2014.7123073



**9 authors**, including:

Mike Bixenman
Kyzen Corporation


Joe Perault
Sensata Technologies Inc.


Eric Lee Hanson
Aculon Inc.

# QUANTIFYING THE IMPROVEMENTS IN THE SOLDER PASTE PRINTING PROCESS FROM STENCIL NANOCOATINGS AND ENGINEERED UNDER WIPE SOLVENTS

Chrys Shea, Shea Engineering Services
Mike Bixenman, T.C. Loy and Debbie Carboni, Kyzen
Brook Sandy-Smith and Greg Wade, Indium
Ray Whittier, Vicor Corporation
Joe Perault, Parmi
Eric Hanson, Aculon

**Abstract**
Over the past several years, much research has been performed and published on the benefits of stencil nano-coatings and solvent under wipes. The process improvements are evident and well-documented in terms of higher print and end-of-line yields, in improved print volume repeatability, in extended under wipe intervals, and in photographs of the stencil's PCB-seating surface under both white and UV light. But quantifying the benefits using automated Solder Paste Inspection (SPI) methods has been elusive at best. SPI results using these process enhancements typically reveal slightly lower paste transfer efficiencies and less variation in print volumes to indicate crisper print definition. However, the improvements in volume data do not fully account for the overall improvements noted elsewhere in both research and in production.

This paper and presentation outlines a series of tests performed at three different sites to understand the SPI measurement processes and algorithms, and suggests inspection parameters to better capture and quantify the correlation between nano-coatings and solvent under wipes with overall print quality and process performance.

**Introduction**
With smaller electronic component features, it is imperative that solder paste deposits and volume transfer be repeatable and reproducible from board to board. Numerous factors can adversely affect the reproducibility and repeatability of print process. For smaller pad features, solder paste transfer efficiency is critical to prevent poor solder joints. Solder paste build up onto the aperture walls and bottom side of the stencil lead to insufficient transfer of solder paste onto small pads. The criticalities of high solder paste release from apertures and under stencil cleanliness increases when printing small feature deposits.

During the solder paste transfer process, the goal is for the solder paste to have a stronger attraction to the printed circuit board pads than to the walls of the stencil apertures. The process is affected by the stencil design; solder paste properties, print pressure and board separation speed. The adhesive forces of the solder paste to the aperture opening must be reduced when stencil printing to small feature pads. As the area ratio decreases, the force applied to the paste by the aperture walls increases, causing a decrease in solder paste transfer efficiency. A smooth wall and clean surface exerts less adhesion for the solder paste to stick. Additionally, modifying the stencil surface with a hydrophobic coating allows the solder paste to repel against the stencil aperture, rending a crisper print.

**Research Hypothesis**
The purpose of the research is gain knowledge as to the effects of hydrophobic coatings and understencil cleaning on print quality, yield and process performance.

$H_1$~ Hydrophobic Coated Stencils improve transfer effectiveness on small feature prints
$H_2$ ~ Engineered Wipe Solvents improve transfer print yields on small feature prints

**Hydrophobic Surface Coatings**
Hydrophobic surface coatings modify the stencil surface using a coating that adheres to the metal surface. The self-assembled phosphonate monolayer imparts hydrophobicity by adhering to the metal complex. The thickness of the coating is 3-5 nanometers. The coating contains a reactive head group and tail groups connected through a stable phosphorous carbon bond (figure 1). The head group reacts with the surface while forming strong and stable metal phosphorous bonds.[1] The tail group

sticks out from the surface rendering a non-stick surface property. The strength of the covalent chemical bond renders a coating that can withstand numerous print and cleaning cycles.

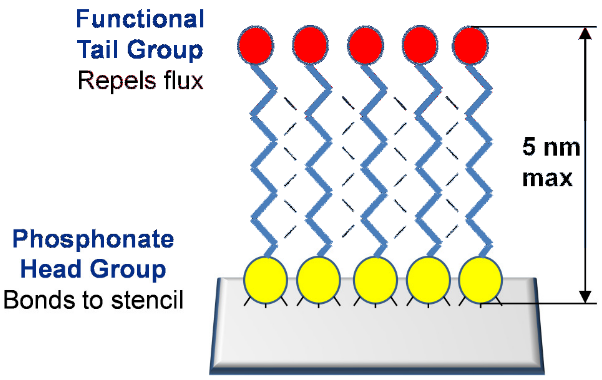



Figure 1: Reactive Head and Tail Groups

Treating the stencil with hydrophobic surface treatments provides the potential to improve solder paste release, reduce flux build-up away from the aperture and increase the number of prints before wiping the bottom side of the stencil. Nano-coated stencils work in two complementary ways to reduce the adhesive force between the solder paste and aperture wall. First, by adding the extremely thin coating, the roughness of the aperture is reduced. Additionally, the coating fills in some of the valleys in the surface topology. This coating on the aperture wall decreases the adhesion forces. The coating chemically modifies the surface of the aperture while decreasing the chemical attraction that the paste has to the metal surface.

The theory behind nano-coating has to do with surface energy, terms that denote how liquids interact with surfaces. Unmodified metal surfaces are typically high in surface energy. Surfaces with high surface energy are held together by strong or high energy chemical bonds (ionic, covalent or metallic). High energy surfaces are typically able to be wetted (a liquid can readily spread over the surface of the material) by most liquids due to the interaction of the surface and the liquid being stronger than the interaction between liquid molecules. Low energy solids, on the other hand, are held together primarily through physical interactions, such as hydrogen bonds (Van der Waals attractive forces). Since these surfaces interact with liquids via weaker methods, the surface tension of the liquid is too great for the surface to overcome, and the liquid does not spread.

Nano-coatings impart low surface energy, which is specifically important within the sidewalls of the aperture. Small levels of solder paste buildup along the aperture sidewall can result in transferring insufficient solder paste. The nano-coating repulsive force leaves less solder paste buildup and improves release. By improving paste release, there is less solder paste buildup next to the apertures on the bottom side of the stencil. Transferring sufficient solder paste to small pads improves the strength of the solder joint and reduces opens.

**Understencil Wipe Process**

The understencil wipe process is designed with a roll of fibrous wiping material for wiping across the underside of the stencil. The stencil printing machine software provides the operator a recipe of options for programming the wipe sequence. A common wipe sequence is a dry wipe, followed by a wet wipe with solvent, followed by a vacuum wipe to attract stray solder balls and to remove trace levels of the wipe solvent into the wiper roll. . Each wiper sequence traverses back across the stencil in the opposite direction of the previous wiper sequence.

Isopropyl alcohol (IPA) is the common solvent used when a wet wipe is programmed into the wiping recipe. IPA has been the go-to solvent for cleaning unreflowed solder paste. Historically, the choice of IPA made sense, as most solder flux packages dissolved in IPA. The vapor pressure of IPA allowed for a solvent that evaporated and absorbed into the wipe paper. This beneficial property left a clean and dry surface. The problems with IPA are flammability and poor solubility match for many lead-free no-clean solder pastes (Figure 2).

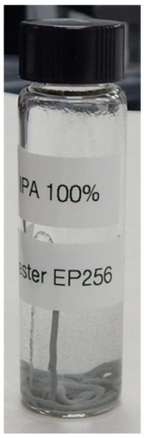



Figure 2: IPA is a Poor Match on many No-Clean Solder Pastes

A critical requirement in cleaning the bottom side of the stencil is the ability to rapidly dissolve the flux component within the solder paste. By doing so, the solder spheres release and can be picked up with the wiping paper. Secondly, the flux stickiness and spread on the bottom side of the stencil is effectively cleaned. If flux builds up on the bottom side of the stencil, the flux bleed-out will transfer to the next board printed. It can create immediate stencil-PCB separation issues, and can also create longer-term electrochemical reliability issues. The flux bleed will eventually bridge solder pads, which can increase leakage risks when running no-clean processes (Figure 3). On fine feature parts, removal of flux bleed is critical in preventing the flux from spreading away from and bridging across solder pads.

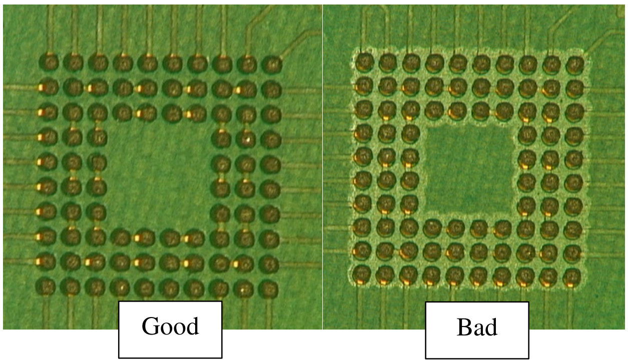



Figure 3: Preventing Flux Bleed

An ideal wipe solvent is non-toxic, compatible with the stencil printer, rapidly dissolves a wide range of flux compositions and dries similar to IPA. The drying feature is a critical design factor. Slow drying wipe solvents leave the bottom side of the stencil wet (Figure 4). Low evaporating wipe solvents can cross contaminate the solder paste as well as transfer the wipe solvent up the apertures and onto the board being printed.

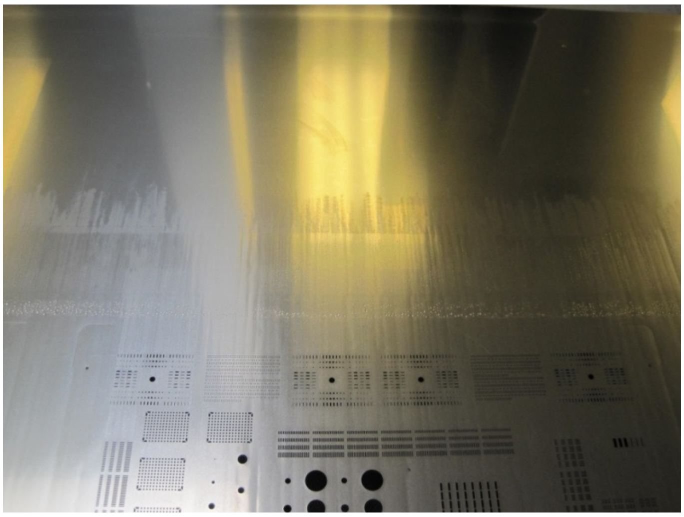


Figure 4: Slow evaporating wipe solvent

The engineered wipe solvent used in this study is a solvent-based stencil cleaning fluid specifically designed to clean lead-free wet solder paste. The wipe solvent dissolves the flux vehicle, which allows solder spheres to release from the stencil during the stencil cleaning process.

**Methodology**

A factorial experiment was designed to study the effect of nano-coating and wet wiping using an engineered solvent. The response variable relates to transfer effectiveness on fine aperture prints. It was executed in Indium Corporation's test laboratory.

Test Vehicle:

The test vehicle used in the study is a popular industry standard board that is commonly referred to as the "Jabil Solder Paste Test Board," available through Practical Components. It is a 3-up panel that measures approximately 5 x 8in. Each of the 3 boards on the panel contains numerous test patterns, including square, circular and rectangular pads that are both solder mask defined (SMD) and non-solder mask defined (NSMD) in sizes ranging from 3-15mils; bridging/slump patterns from 0.1 to 0.25mm; and area array patterns for 0.4 and 0.5mm pitch BGA devices. The area array patterns were used in the majority of the data analysis.

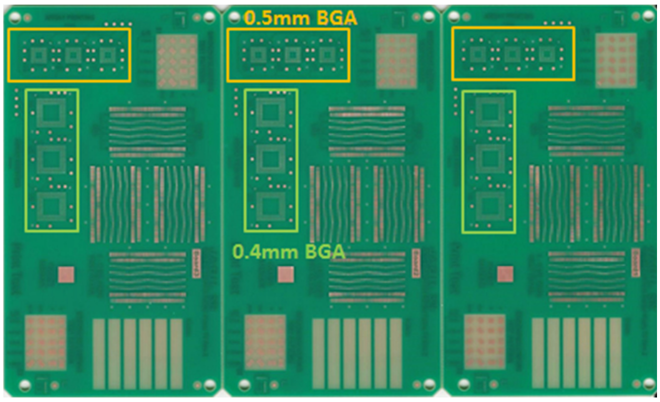



Figure 5: Jabil Three up Test Board

Factors:

Surface Treatment: The stencil for the 3-up test panel contained the following treatments in each print area:

1. Board 1: Nano-Coating #1
2. Board 2: No Treatment
3. Board 3: Nano-Coating #2

Wipe Solvents:

1. No-wipe solvent (Dry Wiping)
2. IPA
3. Engineered Wipe Solvent

Solder Paste:

1. Lead-free no-clean solder paste with ultra-violet (UV) tracer added

Number of Prints before Wiping:

1. Wipe after every print
   a. Dry Wipe
2. Wipe after six prints
   a. Vacuum Wipe
   b. Wet or Dry Wipe
   c. Vacuum Wipe

Wipe Possibilities:

1. D: Dry Wipe
2. DV: Dry Wipe /Vacuum
3. Wet / Vacuum
4. Vacuum / Wet / Vacuum
5. Dry / Wet / Vacuum

Responses:

1. Solder Paste Inspection using a Koh Young 3020 Moire-based SPI system
2. Visual assessment of under wipe efficacy using digital camera and UV light source

**Solder Paste Inspection Data Findings**

The results of the initial review of the volume and variation data generated in the DOE were inconclusive.

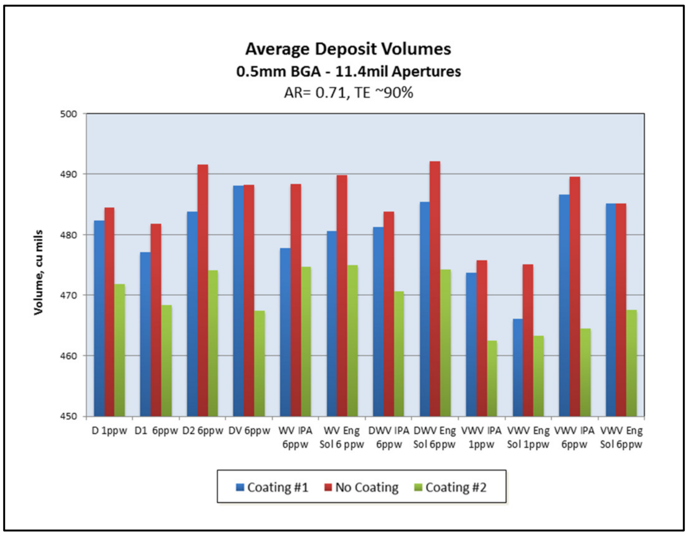



Figure 5. Average Deposit volumes for 0.5mm BGAs measured on Indium's Moire SPI

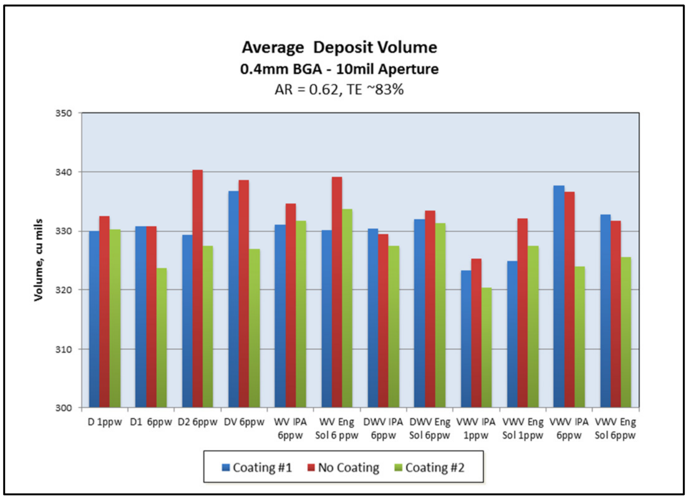



Figure 6. Average deposit volumes for 0.4mm BGAs measured on Indium's Moire SPI

The average volumes did not vary substantially among the different wipe cycles or coatings, as seen in Figures 5 and 6. Over the course of the tests, the volume range average for the 0.5mm BGA deposits was 470-490 cu mils and the range on the 0.4mm BGA deposits ran from 320-340 cu mils. Within each dataset, the standard deviations were approximately 6% or less.

One trend appeared to emerge; nano-coating #2 consistently deposited slightly lower volumes than the untreated print area or the one treated with nano-coating #1. While the differences are small - on the order of approximately 3% - they are consistent not only within this set of experiments, but with many previous tests as well.[2-3] The continued findings of slightly lower transfer efficiencies led to Hypothesis #1, that the hydrophobic coated stencils improve transfer effectiveness.

Transfer effectiveness refers not only to the amount of solder paste deposited, but also to the desired shape of the deposit. Ideally, solder paste deposits have vertical walls and flat tops, but as apertures get smaller and area ratios get tighter, that crisp print definition gives way to domed-shaped deposits with angled walls and rounded tops. Hypothesis #1 asserts that the coating on the stencil enables crisper print definition by limiting flux and paste spread on the bottom of the stencil, allowing cleaner release during PCB-stencil separation.

Empirical data has supported Hypothesis #1 with numerous visual observations. To attempt to characterize print definition quantitatively, a test was devised to use SPI equipment to numerically capture the shape of the deposit.

The SPI system used in the first trials was a popular 2-camera benchtop system based on Moire interferometry. Like most SPI systems, it sets a measurement threshold at a known distance above the PCB surface, precisely measuring everything above the threshold, and estimating volumes below the threshold. The volume estimate is calculated by multiplying the area at the threshold by the height of the threshold. Typical default thresholds are 40µm, or roughly 1.5mils, above the PCB surface. This distance is sufficient to stay above the topographical features of the PCB that could introduce noise into the solder paste measurement, such as copper traces, solder mask, or ink. This distance may, however, be too high to capture the subtle shape differences at the base of the deposits that are related to the cleanliness of the stencil's bottom.

To characterize the deposits' shapes, successive measurements of the same deposits were taken using thresholds at 60, 50, 40, 30, 20 and 10µm above the PCB surface. The area measurements at each level were used to calculate the edge length of the square deposits, which were then divided by 2 and plotted in bar chart format to represent deposit profiles. The measurements for the 0.5mm and 0.4mm BGAs are shown in Figures 7 and 8.

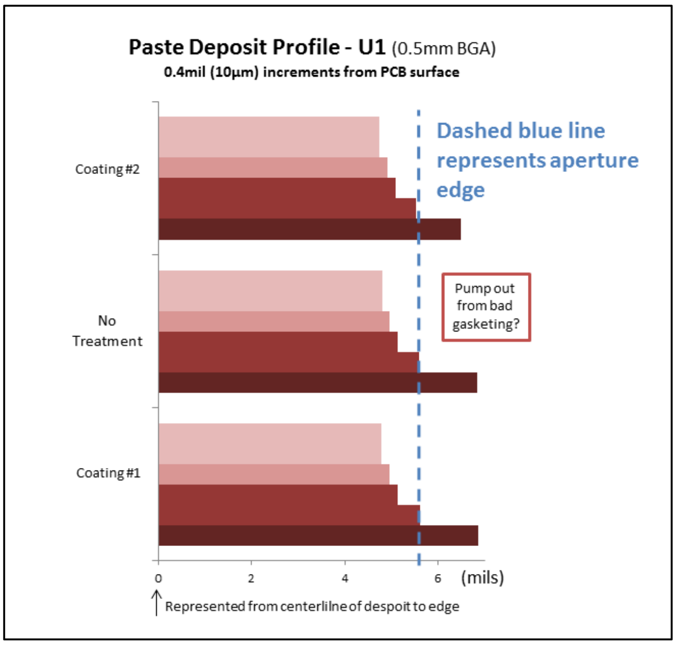



Figure 7. Paste deposit profiles for 0.5mm BGA constructed from area reading at decreasing measurement thresholds on Indium's Moire SPI

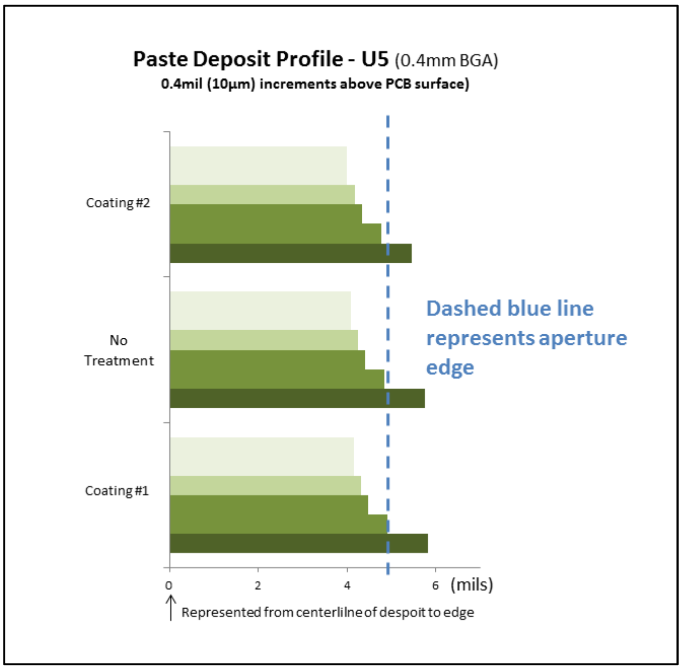



Figure 8. Paste deposit profiles for 0.5mm BGA constructed from area reading at decreasing measurement thresholds on Indium's Moire SPI

The results showed that differences in readings among the different stencil treatments are only apparent at the 10 and 20µm threshold levels. Above these levels, the areas all "look the same," indicating they would produce similar estimates for the volumes under the thresholds.

To explore the effect of SPI parameters on area and volume readings, a similar experiment was run on Vicor's NPI line using a similar Moire interferometry SPI (KY 3020) machine (Figures 9 and 10). Additionally, SPI experts from Parmi, a leading manufacturer of laser-based SPI machines were consulted and similar tests were run on the Parmi Sigma X in the Parmi laboratory.

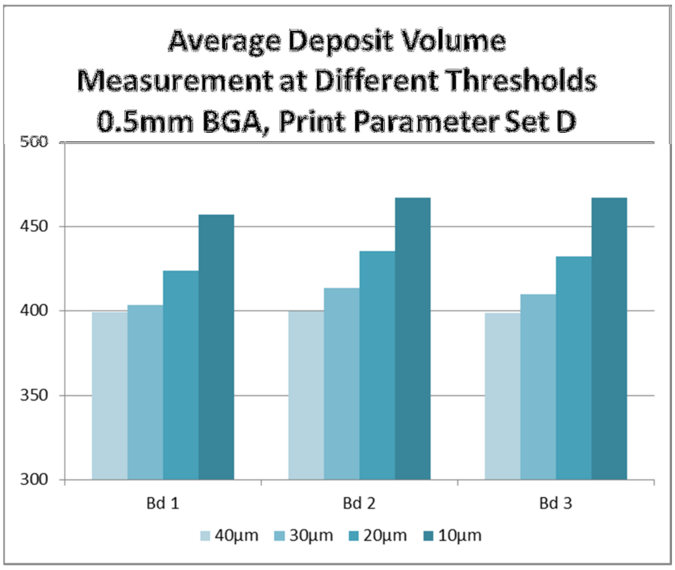



Figure 9. Increasing volume reading with decreasing measurement thresholds (no coating on stencil) on Vicor's Moire SPI

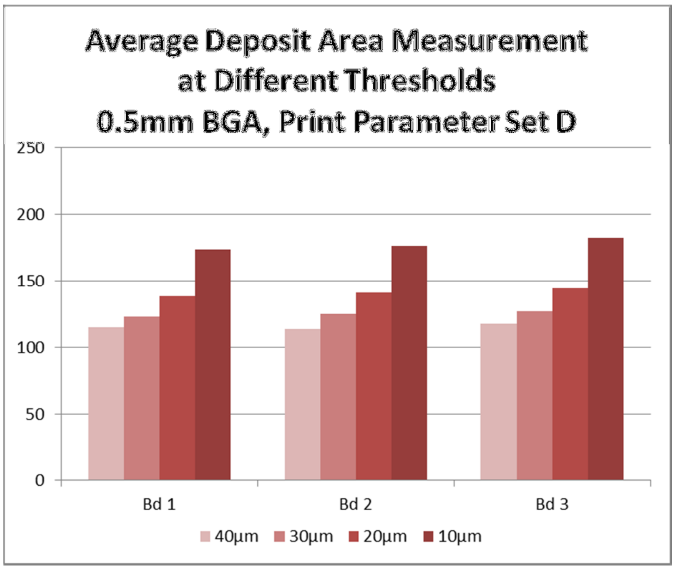



Figure 10. Increasing area readings with decreasing measurement thresholds (no coating on stencil) on Vicor's Moire SPI

Similar tests repeated in the Parmi laboratory demonstrated similar results, shown in Figures 11 and 12.

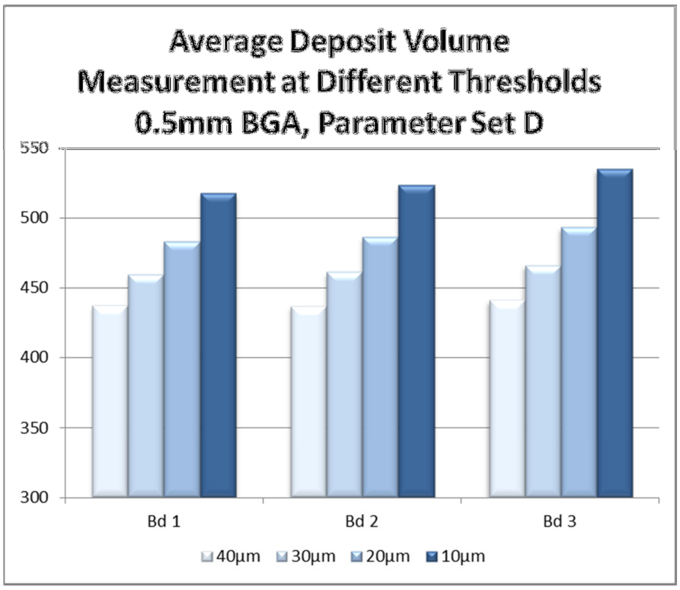



Figure 11. Increasing volume reading with decreasing measurement threshold (no coating on stencil) on Parmi's laser-based SPI

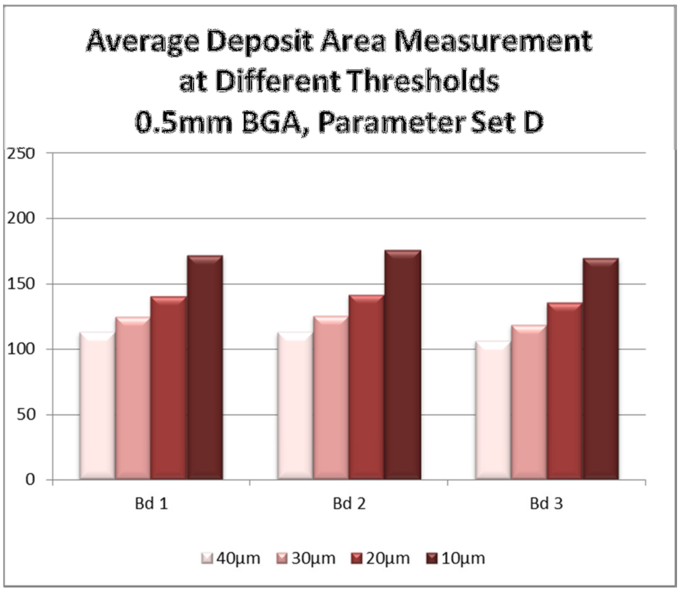



Figure 12. Increasing area reading with decreasing measurement threshold (no coating on stencil) on Parmi's laser-based SPI.

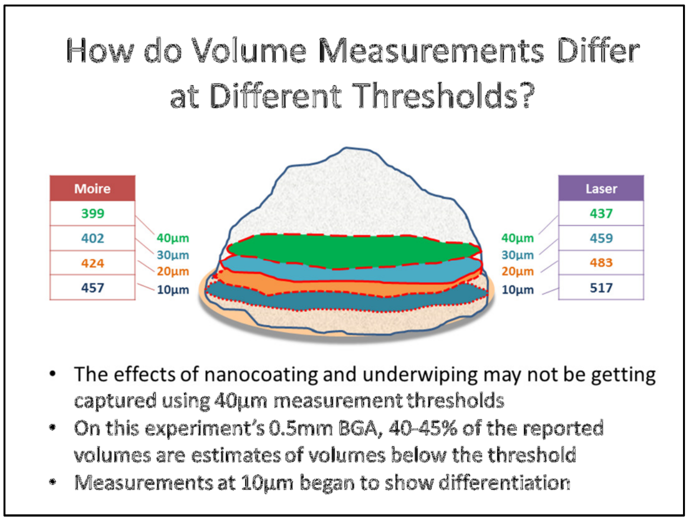



Figure 13. Different volume readings at different measurement thresholds

In all three sets of tests, area and volume readings increased as measurement thresholds decreased. Figure 13 shows the comparison of the Moire and laser SPI volume readings at descending thresholds. Note that different prints were measured in the different laboratories so volume readings should not be compared between machines, and accuracy assessments should not be made based on this data.

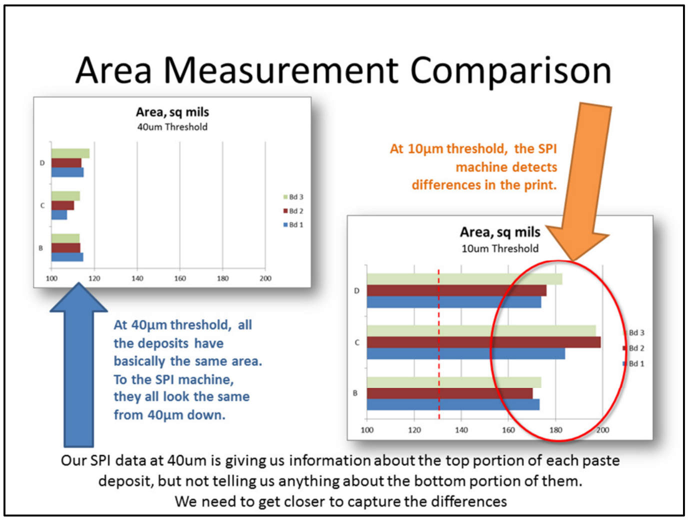



Figure 14. Differentiation in area data more obvious at low measurement threshold

At the typical default 40µm threshold, differences between prints are not obvious; at the 10µm threshold, they are. Figure 14 shows area data generated with three different sets of print parameters (labeled B, C and D) at Vicor. Print parameter set C was the same as B, except for 1.5mil offsets in X and Y to purposely create gasketing issues. The effects of the compromised gasketing are noticeable at the 10µm level, but not at the 40µm level.

Calculations based on the readings taken at all three test sites indicate that for the 0.5mm BGA's deposit (11.4mil square) at the 40µm threshold, the SPI machines measure the top 55-60% of the deposit, and estimate the bottom 40-45% of it based on its cross-sectional area 40µm above the PCB pad. At the 10µm level, the machines measure the top 85-88% of the deposit and estimate the bottom 12-15% based on the cross-sectional area 10µm above the PCB pad.

Note that the Type 4 solder paste used in this test, and in many fine feature applications, has a typical particle size in the range of 20-38µm. Theoretically, it is possible for an entire layer of solder paste pump out to go undetected at the 40µm threshold, particularly with pastes comprised of smaller, more uniformly sized and shaped particles.

It should be stressed that a 10µm SPI measurement threshold is not advisable for production monitoring because the noise that nearby topographical features can introduce into the measurement system can affect measurement accuracy. However, for laboratory exploration of the quantifiable effects of a clean stencil contact surface, the lower measurement thresholds may be required. In Moire-based SPI machines used in this experiment, the threshold setting is global only, applying to all measurements taken off a PCB. In the Parmi laser-based machine used in this test, the threshold is adjustable locally for individual devices or pads, offering more flexibility for both laboratory and production-based studies.

**Visual Assessment of Under Wipe Efficacy**

An understencil wipe was performed after six stencil prints. The three-up board allowed for comparing and contrasting both the nano-coating and wipe solvents. The stencil was set up where the stencil's print area for first board was coated with nano-coating #1, the second board with no-coating and the third board with nano-coating #2.

The solder paste used for this research was a lead-free no-clean solder paste. An ultraviolet tracer was blended into the solder paste. After the six boards were printed, an understencil wipe was completed. Following the wipe, the stencil was removed from the stencil printer, turned over to the back side and imaged using a black light flash. The black light captured the flux left on the bottom side of the stencil.

The understencil wipe data findings that are reported used a programmed sequence into the stencil printer menu:

1. Vacuum wipe
2. Wet or dry wipe
3. Vacuum wipe

The data findings in Table 1 show the influence of the wipe recipes, nano-coating influence and wipe solvent influences.

- Dry Wipe /Vacuum Wipe: The dry wipe followed by a vacuum wipe recipe found that the nano-coatings reduced the level of flux stains on the underside of the stencil. On the non-coated stencil, a more pronounced level of visible flux stains was present across the bottom side of the stencil.
- Vacuum Wipe / IPA Wipe / Vacuum Wipe: The levels of flux next to and within the apertures were more pronounced for both the nano-coated and non-coated stencil areas. The data indicates that IPA was not very compatible with the flux vehicle. IPA's poor match for the flux composition resulted in significantly higher levels of flux remaining on the bottom side of the stencil.
- Vacuum Wipe / Engineered Solvent Wipe / Vacuum Wipe: The levels of flux on both nano-coated and non-coated stencil areas were very low. The data indicates that an engineered solvent matched to the flux composition removes flux build-up on the bottom side of the stencil and renders more consistency from the understencil wipe process.

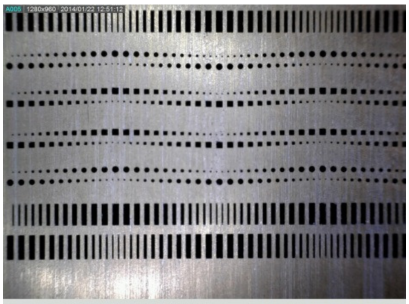
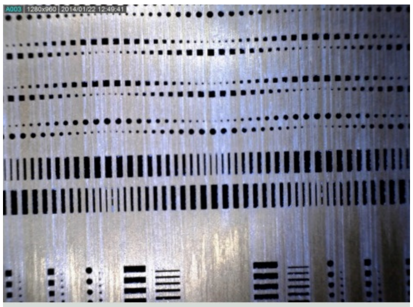
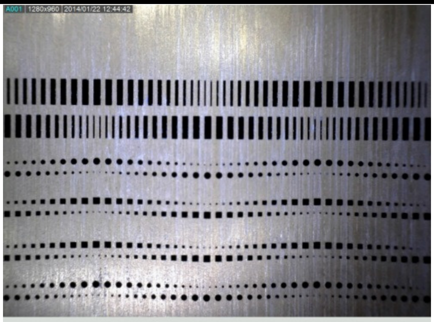
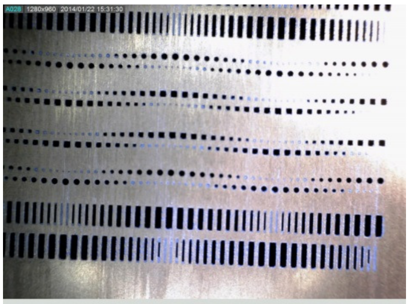
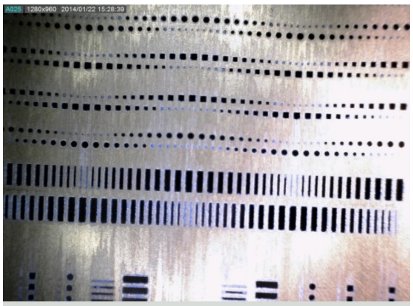
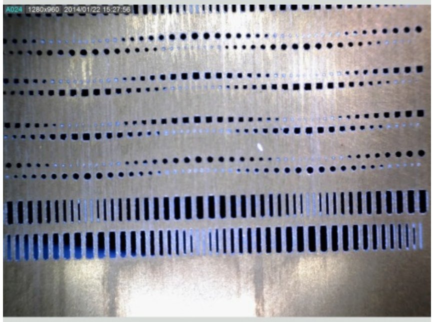
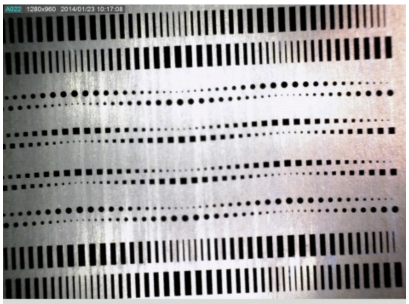
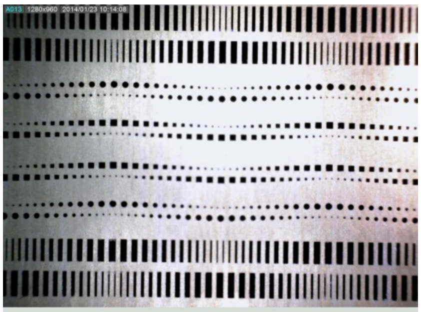
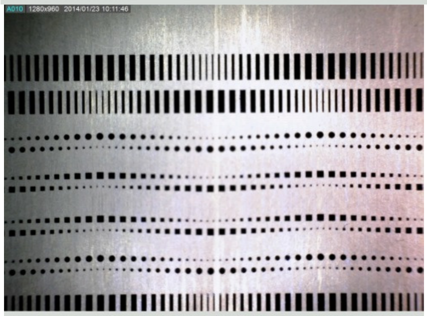
| Wipe Type | Nano-Coating #1 | No Coating | Nano-Coating #2 |
|---|---|---|---|
| **VDV** |  |  |  |
| VWV IPA |  |  |  |
| VWV Eng Solv |  |  |  |

Table 1: Visual results of the understencil wipe recipes on the PCB contact surface of the stencil

**Inferences from the SPI Data Findings**

Initial findings indicated no significant, measureable difference in recorded transfer efficiencies among the different test parameters, with the exception of the continuing trend of nano-coating #2 consistently showing slightly lower paste transfer than nano-coating #1 or the untreated stencil areas. The investigation into deposit shape quantification, however, revealed definite differences in shape geometries as measurement thresholds were set closer to the PCB surface. Subsequent investigations and calculations confirmed the inability to adequately capture shape differences at the base of the deposits using standard production measurement parameters.

**Inferences from Visual Assessment of Under Wipe Efficacy**

The visual findings show a reduced level of flux buildup by coating the stencils with a nano-coating. If a wipe solvent is not used, the nano-coatings are effective at reducing the level of flux buildup on the bottom side of the stencil. The nano-coating provided two benefits:

(1) Better paste release, and

(2) Lower levels of flux buildup next to the aperture on the bottom side of the stencil.

The visual findings also indicate the effects of a poorly matched solvent to the flux composition. When a solvent does not dissolve the flux composition, the flux tends to agglomerate as sticky goo. As such, the flux spreads across the bottom side of the stencil. The data leads the researchers to think that this condition could get worse over the course of a print run.

The visual findings indicate the effects of a properly engineered solvent to the flux composition. When the solvent dissolves the flux composition, the level of flux on the bottom side of the stencil is significantly reduced. A properly engineered solvent worked well for both coated and non-coated stencils. A critical consideration when selecting an engineered solvent is the solvent's vapor pressure to assure that the solvent is evaporated quickly once a wipe cycle is complete.

**Conclusions**

Measuring the effects of solvent under wipes and stencil nano-coatings on individual solder paste deposits is challenging. On a large scale, data from production lines clearly indicate better SMT yields when either engineered solvent wipes or nano-coatings (or both) are employed in the printing process. Visually, the difference in stencil cleanliness when solvent under wipes or nano-coatings are used is easy to see; intuitively, it is obvious that a cleaner stencil contact surface enables better gasketing to produce better print quality, and clearer apertures release more consistent paste volumes. Quantitatively, however, automated SPI measurements have historically given only slight indications of print quality differences.

Visual results indicate that, when dry wiping, nanocoated stencils clean up more readily than non-coated stencils. They also indicate that the wet wipe with engineered solvent effectively cleans solder paste from all stencil areas, regardless of coating type.

SPI results that consistently show slightly lower TEs for nanocoated areas continue to support the hypothesis that nanocoatings improve print definition and therefore transfer effectiveness. Initial attempts at quantitatively profiling paste deposits also support the hypothesis; however, the small amount of data is not sufficient to draw a firm conclusion, and more testing is needed.

Research relies heavily on quantitative analysis to characterize the levers that influence a process. Performance differences that can be measured can be compared to understand the relationships among a system's inputs and its outputs. Quantifying the effects of solvent under wipes and stencil nano-coatings on typical solder paste deposits requires measurements that capture the differences in deposit volumes and shapes. SPI measurements taken using typical production parameters do not fully capture the differences in critical areas of paste deposits – their bases, where pump out, slump and the effects of poor alignment, gasketing or release close the gaps between the PCB pads. To effectively study the influence of solvent under wipes and stencil nanocoatings in these critical areas – *which may be the key to higher yields and future process improvements* - laboratory test vehicles and inspection parameters should be developed that enable lowering the measurement threshold while maintaining accuracy.

**Continuing Research**

Research on the effects of solvent under wiping and stencil nano-coating continues with both SPI data collection and visual assessments. More SPI work is being performed with lower measurement thresholds, and paste release videos are being recorded and analyzed. The results of these studies will be published as they become available.

**REFERENCES**


1. Aculon (2013). NanoClear Features and Benefits. Aculon Incorporated.
2. "Evaluation of Stencil Materials, Suppliers and Coatings," C. Shea and R. Whittier, Proceedings of SMTA International, October, 2011
3. "Fine Tuning the Stencil Manufacturing Process and Other Stencil Printing Experiments," C. Shea and R. Whittier, Proceedings of SMTA International, October, 2013