

## Development, Testing and Implementation of SAMP-Based Stencil Nano Coatings

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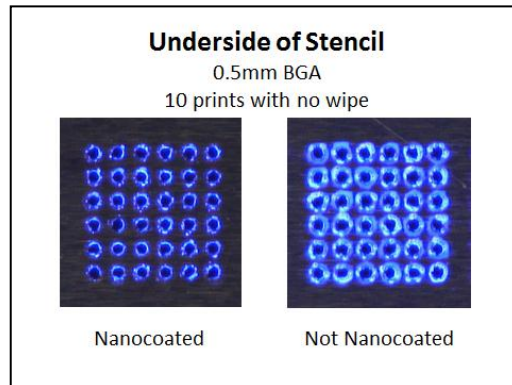
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### Abstract

Stencil nanocoatings have demonstrated significant improvements in numerous aspects of solder paste printing, including print yield, transfer efficiency, print definition and under wipe requirements. By lowering the surface energy of SMT stencils, they reduce flux bleed out around the perimeters of apertures and enable cleaner paste release during stencil-PCB separation.

With several years of commercial success behind the original nanocoating materials, a new generation has been developed that improves upon many of the characteristics of the original formulations. Advancements in durability, detectability and cost boost the overall performance of these flux-repellent stencil treatments. Numerous tests have been performed to characterize stencil nanocoating materials throughout their development cycles and quantify their actual performance in SMT production environments. Laboratory tests have used liquid contact angles as response variables to characterize chemical and abrasion resistance and overall repellency. Production environment print tests have used automated solder paste inspection (SPI) to quantify volume repeatability, transfer efficiency, wipe frequency and overall print yields. These studies have focused on the end results of coating durability and print quality improvements, but have not explored the relationship between flux flow and surface energy modifications on the underside of the stencil. The novel test approach reported in this paper used solder paste treated with UV tracer dye to help image the flow of the flux on the bottom of the stencil (fig 1).

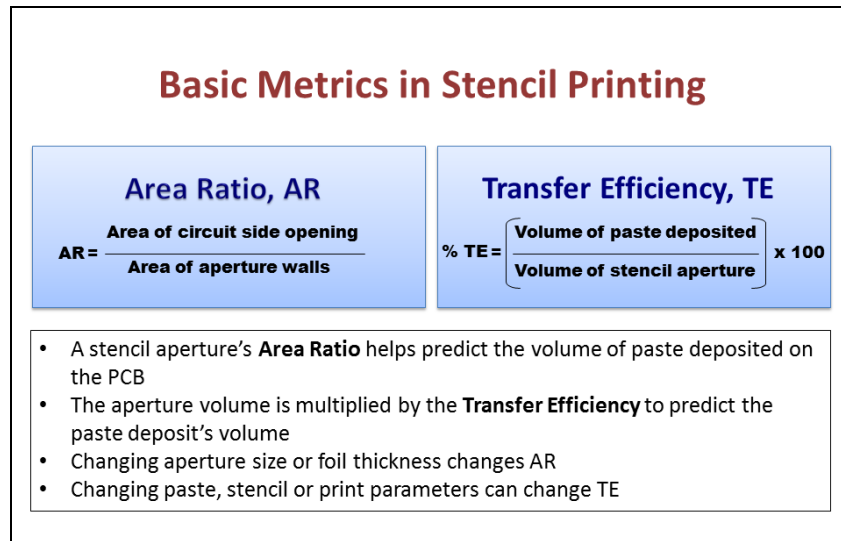


**Figure 1.** Tracer dye in the solder paste flux fluoresces under UV light

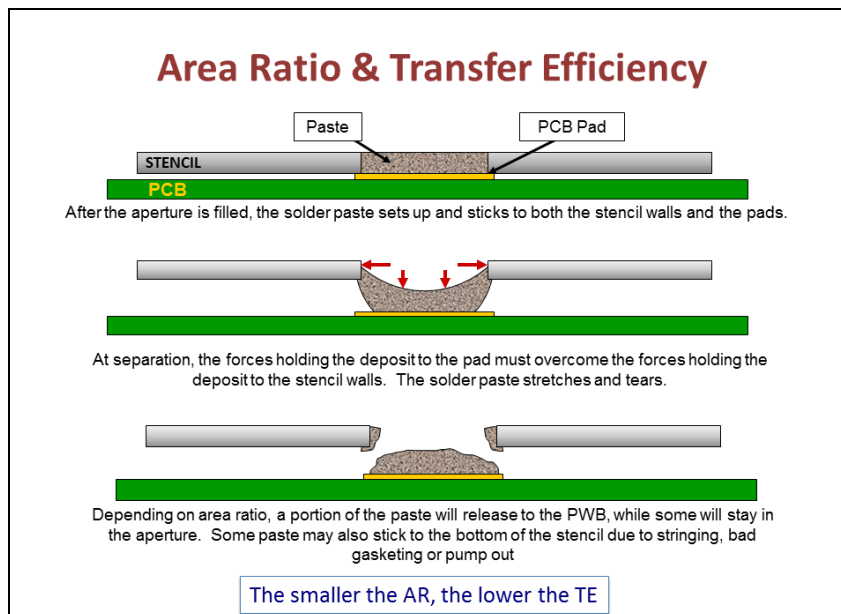
This paper reviews the test methods and results, and describes the chemical structure of Self Assembling Monolayer Phosphonate (SAMP) nanocoating materials and their influence on the solder paste printing process. The discussion concludes with an overview of related applications of SAMP treatments in the SMT assembly, including printer tooling and accessories, area array/BTC rework stencils and jigs, and placement nozzles.

### Introduction to Solder Paste Print Analysis

Nanocoatings are referred to as hydrophobic – repelling water, oleophobic – repelling oil, and fluxophobic – repelling solder paste flux. Their theory of operation is based on reducing the adhesion of solder paste to the SMT stencil. The adhesive properties of solder paste play a large role in print quality. Paste sticks to both the stencil and the PCB, and during the separation phase of the print process, the forces holding the paste to the PCB compete with the forces holding the paste in the stencil. The competing forces are proportional to the contact areas of both surfaces. The relationship between the contact areas is mathematically modeled by a quotient known as the Area Ratio (AR).



**Figure 2.** Area Ratio and Transfer Efficiency information



**Figure 3.** Diagram of solder paste transfer process

The AR is typically calculated as the area of the aperture on the circuit side divided by the area of the aperture walls as seen in figure 2.<sup>1</sup> Variations on the AR calculation are sometimes incorporated, including substituting actual pad area for aperture area, simplifying calculations for squares with rounded corners by using formulas for simple squares, or calculating wall areas based on straight vs. trapezoidal geometries. Regardless of the details in the calculations, all the formulas attempt to model the AR because it helps predict the proportion of solder paste that gets transferred to the PCB, referred to as the Transfer Efficiency (TE). At certain AR thresholds, the opposing adhesive forces tear the thixotropic solder paste material, depositing some on the PCB and leaving some behind in the aperture, as shown in figure 3.<sup>1</sup> The AR-TE relationship varies

from paste to paste and process to process, but typically, ARs greater than 0.80 produce nearly 100% TE, and ARs between .65 and 0.80 produce 75-100% TE.

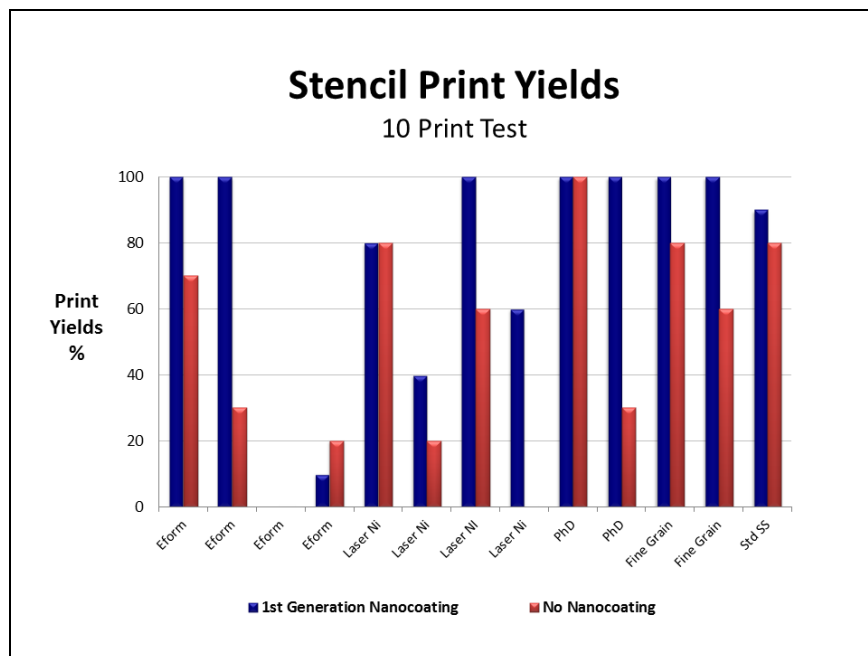
ARs less than 0.65 are not recommended with general SMT processes and materials because they result in insufficient and highly variable TE, significantly reducing print and assembly yields. TE is a commonly employed metric in stencil printing to quantify the performance of stencils, pastes or print parameters.

As important as TE – and arguably more so - is volume repeatability. Fine feature SMT devices require consistent prints. A large format BGA can have over 2000 I/O on one device. One insufficient or excessive paste deposit can cause a failure that requires all of the device's joints to be desoldered and resoldered in the rework process, jeopardizing the functionality and reliability of the entire assembly. Print volume repeatability is typically calculated based on measurements of a specific feature size. The standard deviation of the paste volume readings are divided by the average of the volume readings. It is known as the Coefficient of Variation (CV) in statistical terms, and is usually expressed as a percentage in the context of print volume repeatability, with lower values being better than higher ones. CVs of 10% or less generally indicate acceptable print repeatability. As ARs get smaller, CVs usually get larger. Deposit volumes are typically measured with laser- or white light-based automated Solder Paste Inspection (SPI) systems.

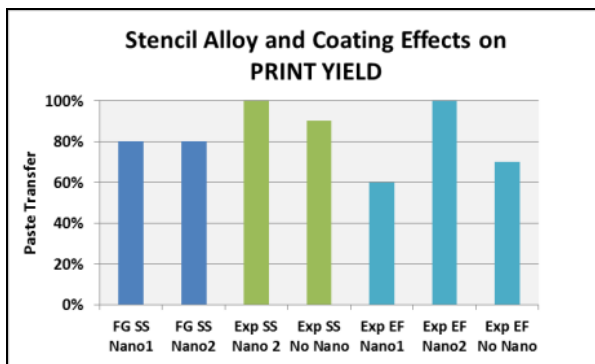
A third and less quantifiable factor in print quality is print definition. Whereas TE and CV are based on numerical measurements, print definition is based on a Likert scale that uses visual assessment. An ideal solder paste print will have a prismatic form - typically round, square or rectangular when viewed from the top down - with vertical sides and a flat top. As AR begins to decrease, the verticality of the sides diminishes and the top becomes rounded. The loss of crisp print definition is a direct result of the tearing of the solder paste upon release from the stencil. It is manifested as continued loss of prismatic form in the deposits as AR continues to decrease, and other geometric aberrations such as tall peaks on the deposits or strings of solder paste that fall over on the PCB to bridge multiple deposits often occur. Print definition is usually judged on a scale of 1-5, with 1 being unacceptable and 5 representing the ideal form. Appendix A shows an example of visual standards for rating print definition.

## Background

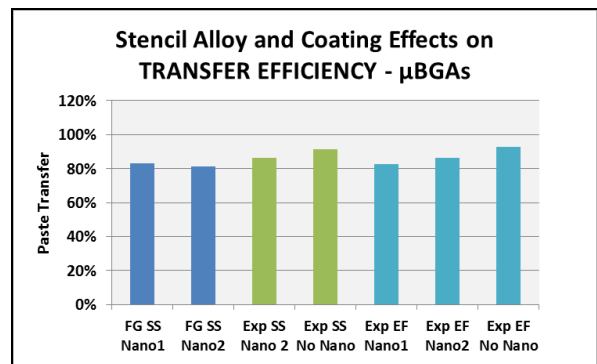
Initial testing of nanocoating in 2011<sup>2</sup> revealed vastly improved print quality when nanocoating was applied to SMT stencils. Tested on 13 pairs of stencils manufactured by electroforming, laser cutting, or both, the coating dramatically improved the yields of nearly every pair, as seen in figure 4. Based on the test results, the nanocoating was applied to all the high volume stencils in the PCB assembly operation, and overall print yields increased by approximately 5%.



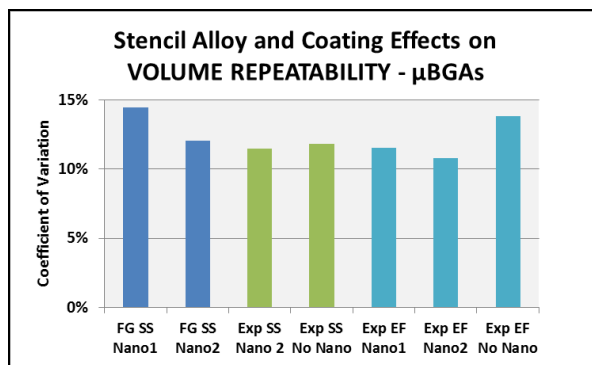
**Figure 4.** Effects of nanocoating on print yields for a variety of stencil types in initial (2011) study<sup>2</sup>



**Figure 5a:** Effects of stencil materials on overall print yields



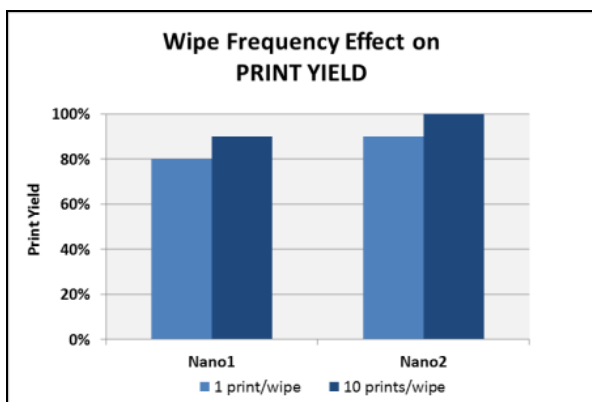
**Figure 5b:** Effects of stencil materials on  $\mu$ BGA transfer efficiencies



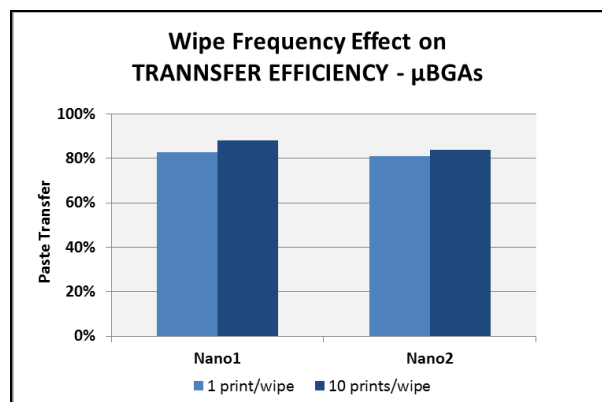
**Figure 5c:** Effects of stencil materials on print volume repeatabilities

**Figure 5.** Print test results from subsequent (2013) study<sup>3</sup>

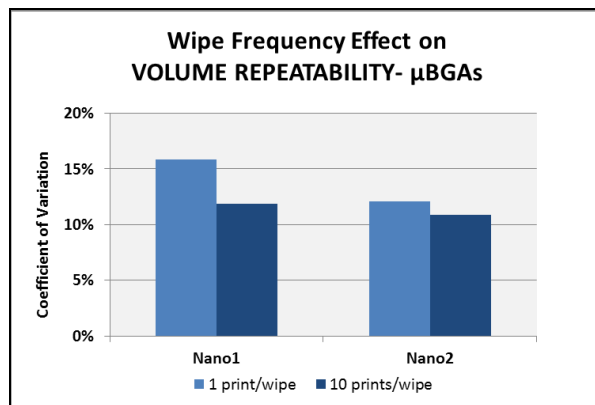
A subsequent set of formal experiments on the nanocoatings in 2013<sup>3</sup> compared the new generation of material to the 1<sup>st</sup> generation. Stencils with the new generation of nanocoating (Nano2) consistently produced higher print yields and lower CVs than stencils treated with the original nanocoating (Nano1) and untreated stencils. Stencils coated with Nano2 also produced slightly lower TEs than untreated stencils, which, as explored in these tests, may be due to improved print definition. Figures 5a through 5c summarize the test results. The  $\mu$ BGA prints reported in the results were based on 10.5mil circular apertures in a 4mil FG foil, with an AR of 0.66.



**Fig. 6a.** Effect of stencil under wipe on print yield



**Fig. 6b** Effect of stencil under wipe on transfer efficiency



**Fig. 6c.** Effect of stencil under wipe on print volume variation

**Figure 6.** Stencil under wipe frequency print test results<sup>3</sup>

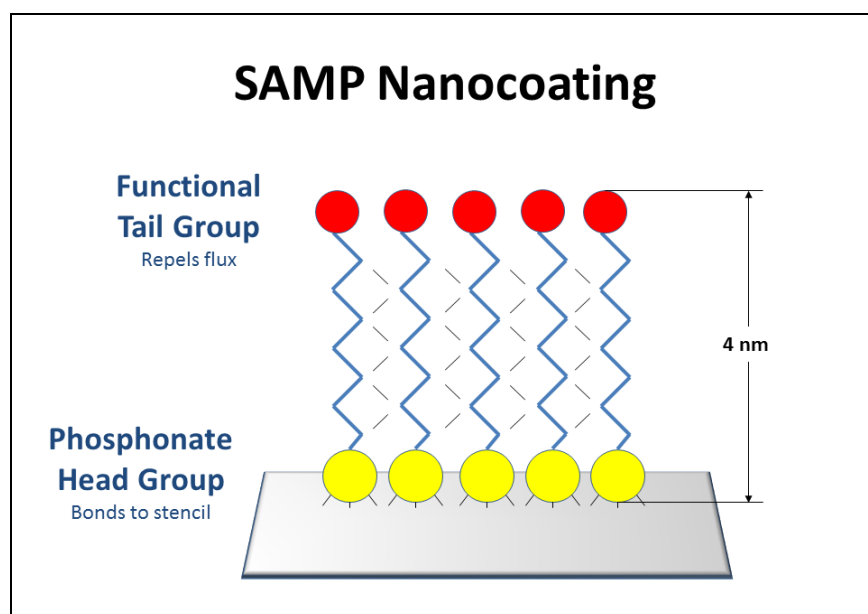
The 2013 experiments also tested wipe frequency. The production process used a vacuum/dry/vacuum wipe after every print. The two conditions tested were the production process at 1 print per wipe, and an extended process of 10 prints before the wipe. The results are shown in figures 6a through 6b.

The process with 10 prints and no wipe produced higher yields and lower CVs than the process with 1 print per wipe for both nanocoatings. In both cases the newer nanocoating performed better than the original.

The consistently higher yields and lower volume variations found in the latter set of experiments was anticipated and expected, based on the original experiments and production history. The increase in print quality at the extended wipe intervals was completely unexpected, and spurred the experiment to visualize the flux flow on the PCB side of the stencil, as reported in this paper.

### Nanocoating Stencil Treatment

The nanocoatings used in both experiments are based on a proprietary Self-Assembling Monolayer Phosphonate (SAMP) technology. The first round of tests used the original formulation, referred to as Nano1; the more recent tests and those presented in this document used a new, more concentrated formulation referred to as Nano2.



**Figure 7.** Diagram of stencil nanocoating molecule

The monolayer technology works by building a single-molecule layer of fluxophobic material on the stencil. The engineered molecule is comprised of a phosphonate head group and a functional tail group (fig 7). The phosphonate creates strong bonds with the oxides on the stencil's surfaces; the tail group repels flux, water and oil.

The coating is applied in several steps:

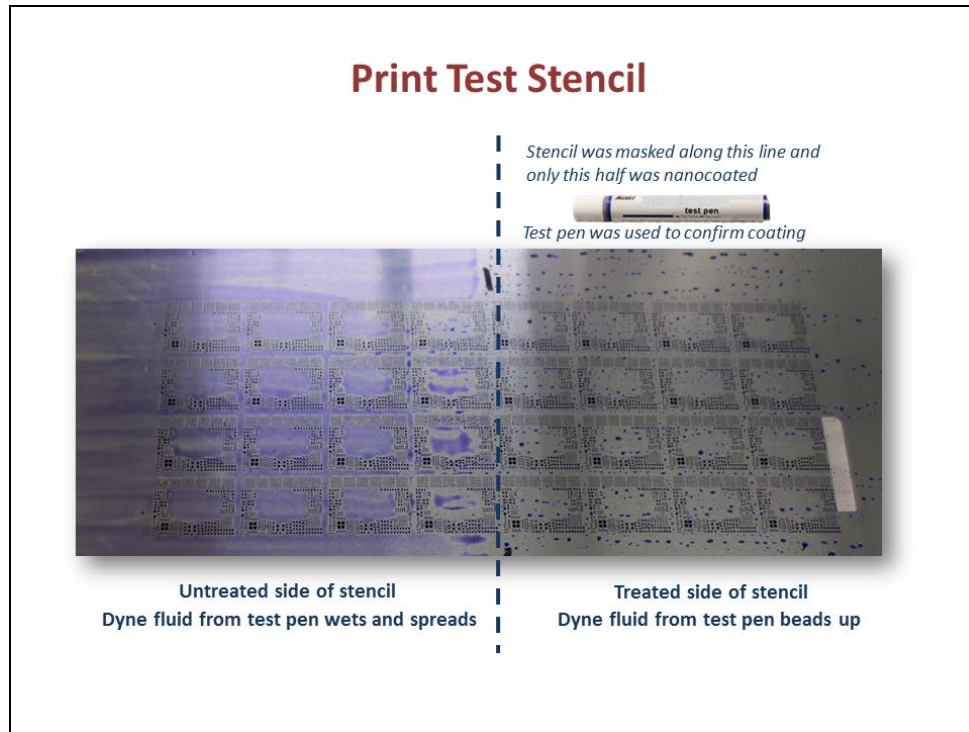
- The stencil is rinsed to remove any residual debris from the manufacturing process or previous printing processes.
- Part 1 of a two-part system is applied. This primer helps to form an oxide layer on the stencil's surface. It is applied via a wet wipe.
- The primer is rinsed from the stencil using deionized or distilled water.
- Part 2 is applied. This is the monolayer that bonds to the oxides formed in the priming step. It is also applied via wet wipe.

Each stencil treatment is delivered in a two-piece package with one primer wipe and one coating wipe. The wipes are discarded after use. The materials are safe to rinse to drain and/or dispose of in regular refuse cans.

To check for proper application, dyne fluid is applied to the surface of the stencil via a dyne pen. Presence is indicated by the beading up of the dyne fluid on the stencil.

### Experimental Design

To effectively image the flow of flux on the PCB side of the stencil, UV tracer dye was added to the lead-free, halogen-free solder paste that is used in production by its manufacturer.

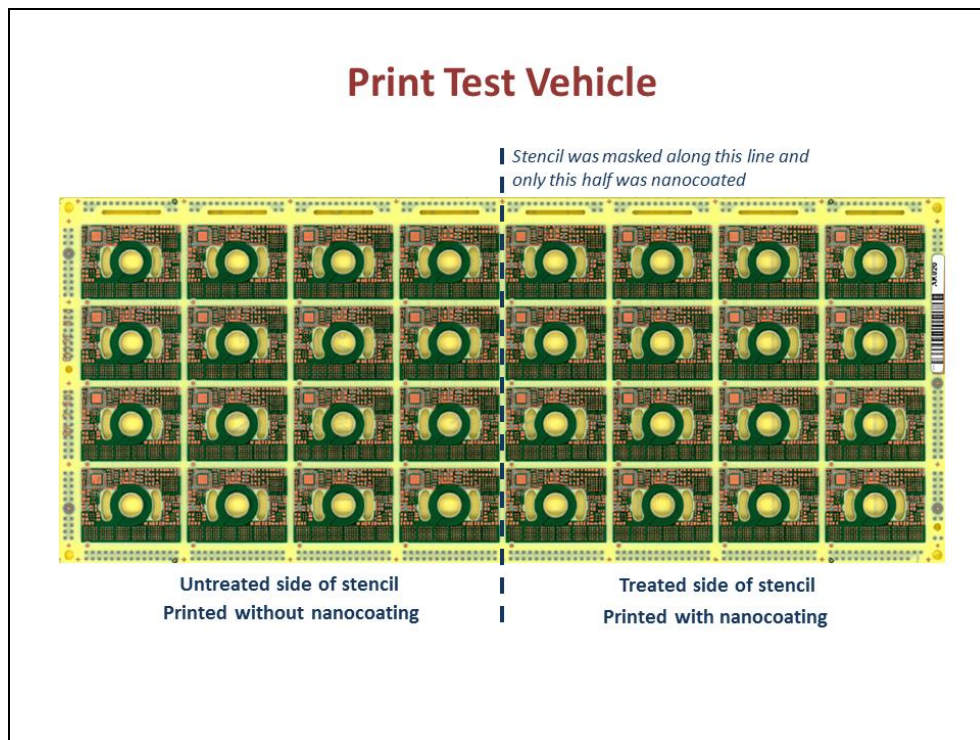


**Figure 8.** Test stencil with half of print area nanocoated and half left untreated

To compare performance of treated and untreated stencils, a single stencil was masked and half was treated. The stencil was laser-cut fine grain stainless steel (FG). A preliminary DOE determined the best masking and coating methods by testing two masking materials, two masking/priming process sequences and two application directions. The best process defined by the DOE was used to mask the experimental stencil, shown in figure 8.

Treating only half a (symmetric) stencil virtually eliminated all noise that could be induced to the experimental system by variables such as different stencils, PCBs or print strokes, and allowed direct side-by-side comparisons of print performance.





**Figure 9.** Print test vehicle

The test vehicle was a 4x8 array of individual PCBs used in power management components (fig 9). It is a highly miniaturized, densely populated design with approximately 15,000 apertures in its 3x7 area, with 8500  $\mu$ BGA and 1900 0201 apertures, and 32 QFN devices.

PCBS were printed on a well maintained and calibrated production line stencil printer using production print parameters:

- Print speed: 7 mm/sec
- Print pressure: 8 kg (250mm blades)
- Separation speed: 20mm/sec

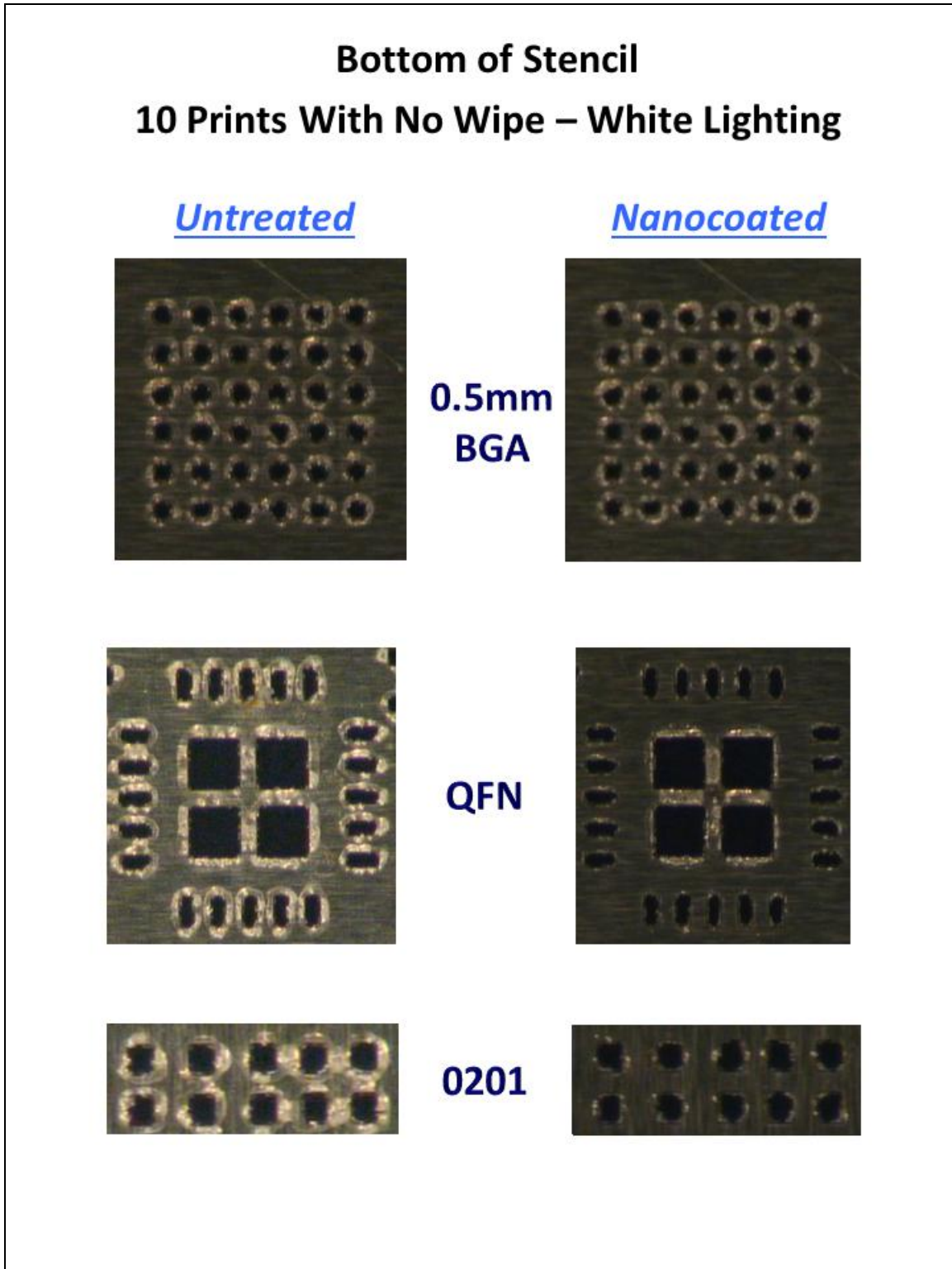
Prior to printing test boards, 2 dummy prints were printed to assure paste was at working viscosity

Several different print-wipe test sequences were tested:

- 10 prints, no wipe
- 10 prints, 1 vacuum/dry/vacuum (V/D/V) wipe after 10<sup>th</sup> print
- 10 prints, 1 V/D/V wipe after every print (typical production process)
- Solvent/vacuum/dry/vacuum wipe after 10 prints with V/D/V wipe after each print. The printer was not equipped with solvent wipe capability, so the process was mimicked by removing the stencil from the printer, manually wiping it with a commercially available presaturated stencil wipe and immediately loading the stencil back into the printer for the usual V/D/V wipe sequence.

After each test sequence, the bottom side of the stencil was photographed at 40X magnification with a digital video microscope using the apparatus' white light, and also with a UV flashlight instead of the apparatus' built-in lighting. Representative prints on the 10<sup>th</sup> boards were also photographed.

## Results & Discussion

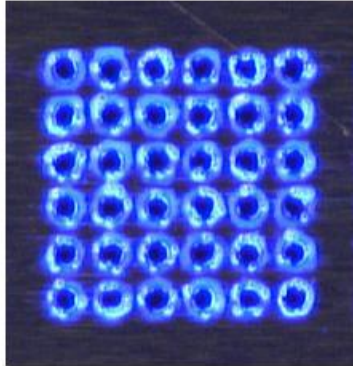


**Figure 10.** Images of bottom of stencil photographed under white light after 10 prints with no under wipe

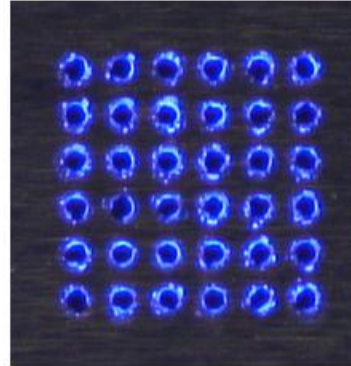


**Bottom of Stencil**  
**10 Prints With No Wipe – UV Lighting**

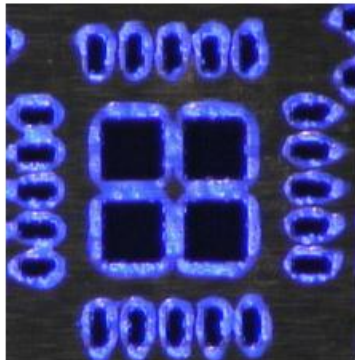
Untreated



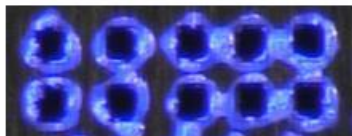
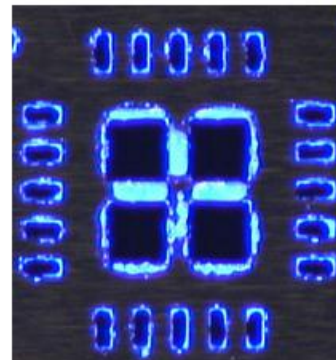
Nanocoated



**0.5mm  
BGA**



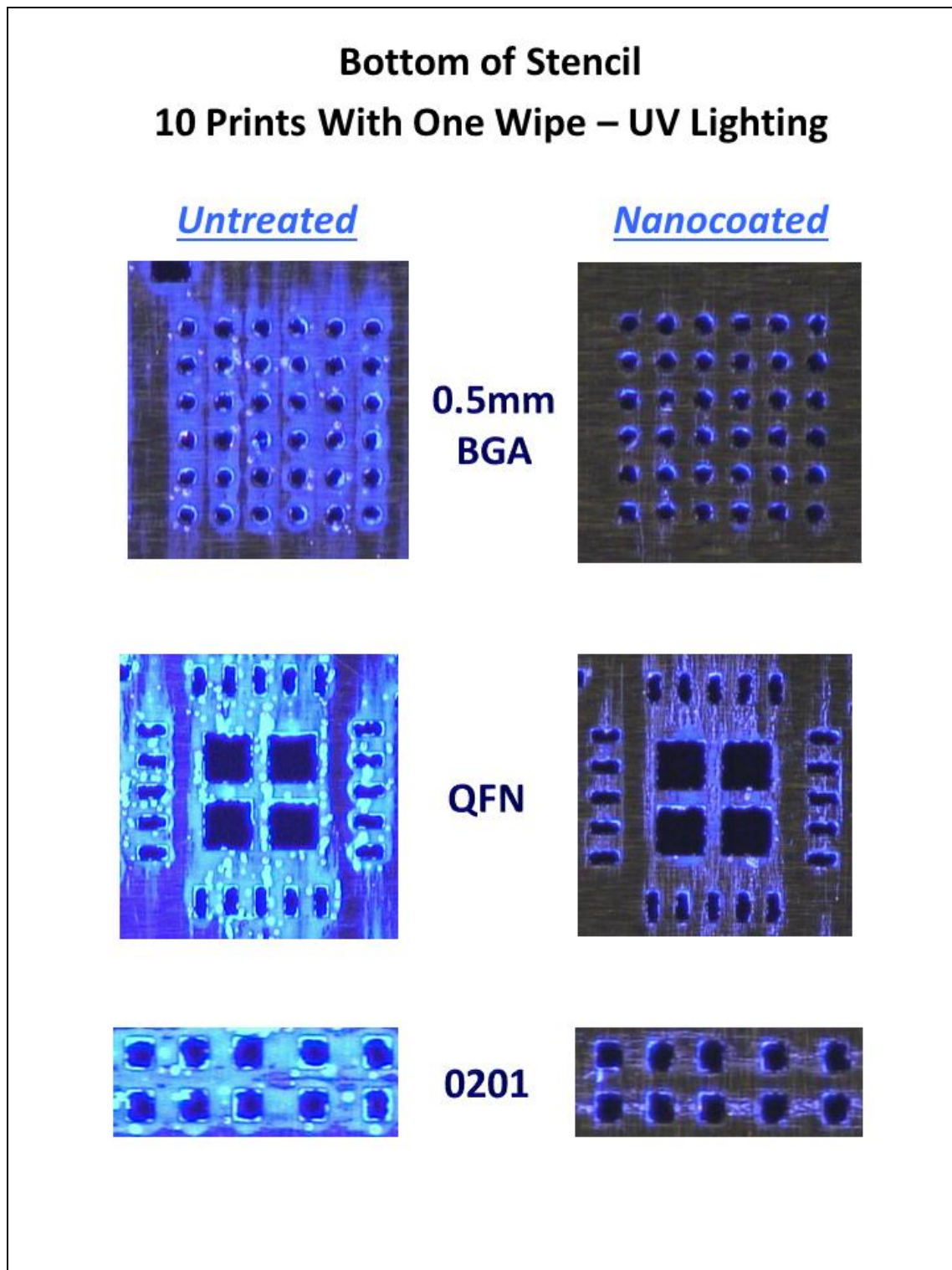
**QFN**



**0201**



**Figure 11.** Images of bottom of stencil photographed under UV light after 10 prints with no under wipe



**Figure 12.** UV images of stencil after 10 prints and 1 dry wipe

The flux flow on the underside of the stencil shown in figure 10 was visible under white light but not easy to discern, given the translucent nature of the flux. The observation of the flux was very dependent on the lighting and camera settings under which it was photographed. The visibility of the flux under the UV lighting (fig. 11) is vastly improved over the white light image. The presence of the flux on the bottom of the stencil is extremely obvious as it fluoresces brightly under the UV flashlight.

*\* Note that none of the photographs have been altered from their original form except for cropping. They have not been sharpened, color adjusted, modified in contrast or brightness, or undergone any other form of image manipulation.*

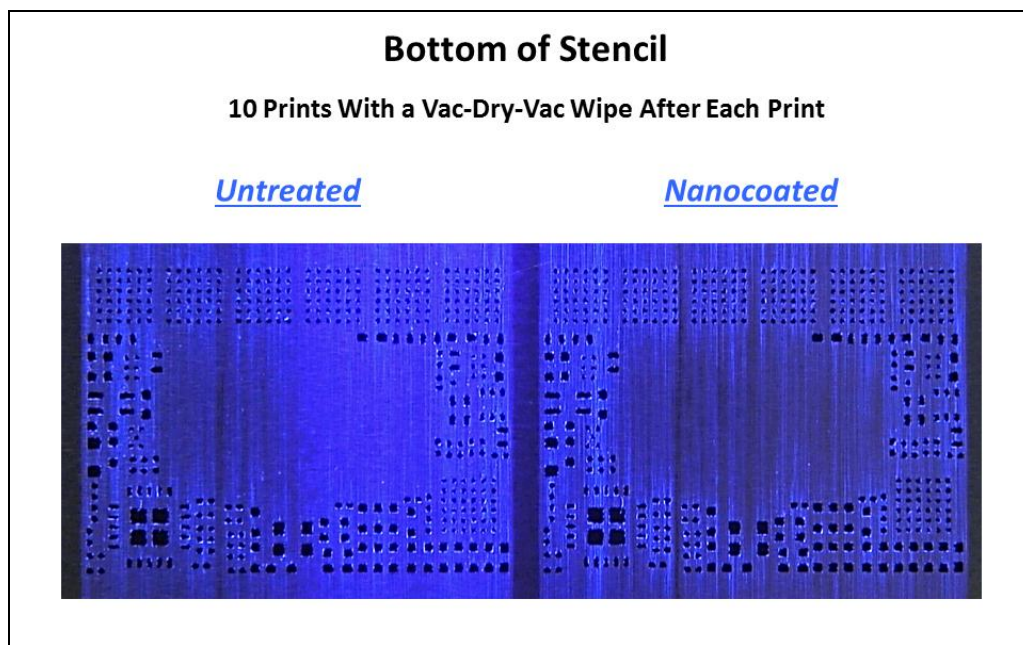
The differences in flux flow between the treated and untreated portions of the print area are plainly visible. The flux bleeds out around the apertures on the untreated side, but is much more contained on the treated side. In many cases, the outlines of the apertures are clearly discernable. Preventing solder paste flux from wicking out on the underside of the PCB offers several benefits to the stencil printing process:

- **Better gasketing:** solder paste particles will flow where the flux flows on the bottom of the stencil and impede gasketing. Preventing flux flow prevents the 1-2mil diameter particles (Type 3 solder paste) from accumulating on the bottom of the stencil and ensures better gasketing.
- **Crisper print definition:** Limiting the flux flow limits the area of the stencil to which the flux can stick during stencil-PCB separation, which can in turn result in crisper prints with fewer peaks, dog ears or strings, and a tighter perimeter at the base of the deposit.
- **Cleaner PCBs:** Flux in unintended areas of the stencil deposits flux in unintended areas of the PCB. The flux will get activated in the reflow process and pose no imminent reliability threat, but its residues can cause signal integrity problems in high-speed circuitry.

The physical effects of the nanocoating treatment on solder paste flux flow on the PCB side of the stencil are obvious under the UV lighting, and the benefits of constraining its flow include better print yields and overall print quality, and less flux residue on the PCB.

After the 10<sup>th</sup> print and a V/D/V dry wipe, the effects of the nanocoating treatment were more pronounced, as shown in Fig 12. The dry wipe smeared the flux across the bottom of the stencil. It removed stray solder particles that may have deposited on the bottom side of the stencil, but it did not remove the flux. The untreated side showed much heavier flux smearing than the treated side. Two factors may be responsible for the cleaner appearance:

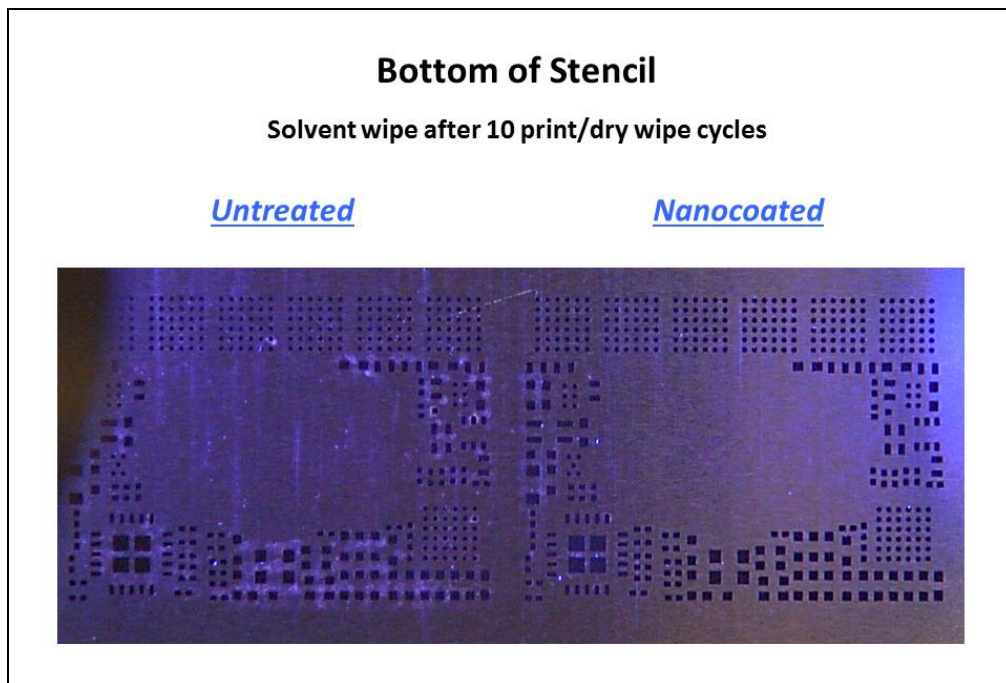
- Less flux was on the underside of the stencil prior to the wipe (fig. 11)
- The repellent action of the nanocoating enabled easier flux removal



**Figure 13.** UV image of stencil after 10 prints with a wipe after each print

The results of the test using 10 prints with a V/D/V after each print also favored the nanocoated side, although the results are not as obvious. Figure 13 shows two circuit images on the stencil, one on the treated side and one on the untreated side. The photograph shows more flux smearing after the 10 wipe cycles, but the flux film is heavier on the untreated side, as evidenced by the more saturated blue appearance. Upon closer examination in comparing similar apertures on both sides, those on the treated side appear larger, indicating less flux/paste accumulation in them.

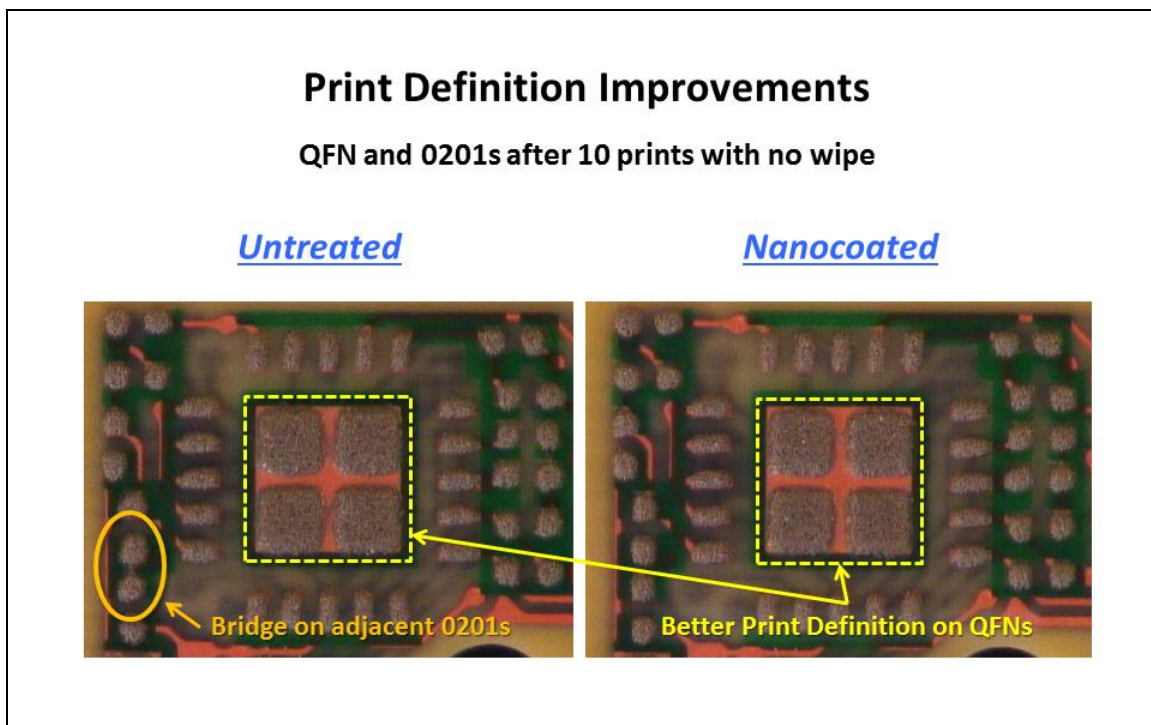




**Figure 14.** UV image of stencil after solvent wipe

The results of the solvent wipe test also favored the nanocoated side of the stencil. The solvent wipe cleaned the nanocoated side more effectively than the untreated side, as shown in figure 14. While both sides are relatively clean, the untreated side demonstrates more tell-tale fluorescence surrounding the apertures and streaking in the direction of the wipe. The flux removal effect of the wet wipe is uncanny, however, considering the images in figure 13 represent the “before” condition of the wet wipe and those in figure 14 represent the “after” condition.

The differences in the conditions of the undersides of the stencils were obvious using the UV tracer dye and light source. Differences in print quality were also investigated by photographing the paste deposits under white and UV light.



**Figure 15.** Improved print definition of nanocoated stencil

At the 40X optical magnification level of the microscope, differences in print definition on the  $\mu$ BGAs were not discernable from the top-down view. Oblique angle photographs were attempted, but the autofocus function on the camera kept continually adjusting due to the angled focal plane of the tilted PCB. Photographs of slightly larger features on the BTCs and 0201s did show obvious differences in print definition, as seen in figure 15. After 10 prints with no wipe, solder paste deposits from adjacent 0201s are bridged, and comparison of the window-paned ground pads of the BTCs reveals significant differences in print definition.

It has been theorized that the slightly lower TE demonstrated by nanocoated stencils is due to crisper print definition, but not proven. The images captured in figure 15 provide data in support of the theory, and while not convincing due to the small sample size, are sufficient evidence to warrant continued study of the relationship between lower TE and improved print deposit quality.

### **Summary and Conclusions**

This experiment focused on visualizing the flow of solder paste flux around stencil apertures on the PCB side of an SMT stencil. UV tracer dye added to solder paste made the difficult-to-see flux highly visible under UV lighting. Using a stencil with one half of a symmetric print area nanocoated and the other half uncoated enabled studying the differences within an experimental system that eliminated most of the external noise associated with comparing different prints on different PCBs or with different stencils.

Flux flow was difficult to see under white light, but immensely obvious under the UV lighting. The nanocoated area of the stencils constrained the flux flow and kept it in or near the apertures; whereas the flux wicked out on the bottom of the stencil on the uncoated area, often bridging two or more apertures with flux. The nanocoated areas also appeared to show less flux smearing after dry wipes, and cleaned more easily with solvent wipes. Overall, the nanocoated area of the stencil stayed cleaner than the uncoated side and cleaned more easily with both wet and dry wipes.

Print definition was improved on the nanocoated side. The microscopy equipment was unable to capture the smallest features in sufficient detail to provide accurate comparisons; however, the crisper print definition was evident on the 0201s and QFNs.

The primary purpose of the nanocoating is to reduce the adhesion of solder paste to the SMT stencil, which it has been proven to do successfully for several years, on all types of stencil materials. Additional applications in circuit assembly operations include:

- Rework mini-stencils, to ease the operator dependence of the manual paste deposition process and improve print quality
- Paste-on-ball rework jigs, to facilitate cleaning and handling
- Printer support tooling, which must be kept clean and free of solder paste to be effective
- Printer conveyor rails, which must also be kept clean
- Hand tools used in printers and printing areas that are prone to contamination with solder paste
- Placement nozzles that pick up solder paste after dropping components

Application of the nanocoating to squeegee blades has been discussed, but can pose some risk because friction between the paste and the blades helps to create the rolling motion needed for proper paste flow.

### **Recommendations for Future Work**

Plans for the next study on the behavior of flux on the underside of the stencil and the effects of nanocoating and underwiping are underway at the time of paper submission. They include:

- Printing more boards for larger sample size and better simulation of a production environment
- Using an automatic SPI system to capture print volumes, transfer efficiencies and 3-D images of print deposits
- Introducing a new test vehicle that is 3-up panel to test untreated, original and new formulations of nanocoating
- Testing with both no-clean and water-washable solder pastes
- Upgrading the microscopy equipment to capture higher magnification and higher resolution photographs

Additional areas of future study may include:

- Further investigation of abrasion resistance and durability (see Appendix B for current data)
- Optimization of under wipe processes for nanocoated stencils
- Effects of nanocoating metal squeegees
- Development or derivation of a metric that combines transfer efficiency, volume repeatability and print definition into a single, comprehensive indicator of print performance

As stencil nanocoatings continue to grow in popularity, more characteristics will be studied, documented and published.

#### **References**

1. "Enabling Technologies for Broadband Printing," C. Shea, Proceedings of IPC International Conference on Soldering and Reliability, November, 2013
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
4. "Low Surface Energy Coatings Rewrite the Area Ratio Rules," R. Bennett and E. Hanson, Proceedings of IPC APEX/EXPO, February, 2013



## APPENDIX A

# Visual Standard

for print definition inspection: 0201 / 0.5 mm CSP

1	No paste or almost no paste $D < 1/2A$ , $H < 1/3T$		
2	>1/2 pad area covered but insufficient height $D > 1/2A$ , $H < 2/3T$		
3	>2/3 pad area covered, reaches the same height as the stencil $D > 2/3A$ , $H = T$ for $< 1/3A$		
4	>2/3 pad area covered and diameter of top is >1/3 of aperture $D > 2/3A$ , $H = T$ for $< 1/2A$		
5	Perfect deposit, same shape and size as stencil aperture $D = A$ , $H = T$ for $> 2/3A$		

T = Stencil Thickness    A = Aperture Diameter    D = Paste Diameter    H = Paste Height

White lines on paste drawings are contours at 50 micron intervals

Source: Philips, circa 2000

## APPENDIX B

### Durability and Abrasion Resistance Data

Tests performed by the manufacturer during the development of the nanocoating indicated excellent abrasion resistance.

Repellency is measured by contact angle, as seen in Figure B-1. Abrasion resistance is tested by cyclically abrading the treated surfaces with an abrasion tester in accordance with methods prescribed by ASTM test standards, and measuring oil or water contact angles at set intervals. The abrasion media in these tests was paper.

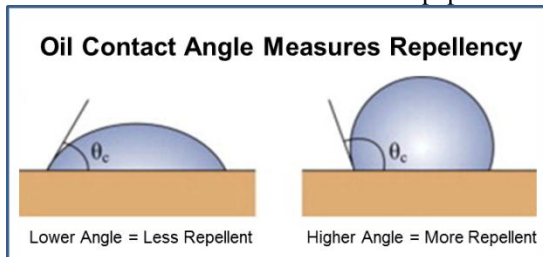


Figure B-1. Diagram of relationship between fluid contact angle and repellency

Contact angles remained steady through 25,000 cycles, showing some decline at 50,000 and 100,000 cycles, as shown in Figure B-2. The measured contact angle of oil on an untreated stencil is 10°; therefore, even after 100,000 abrasion cycles, the nanocoating is present to some extent.

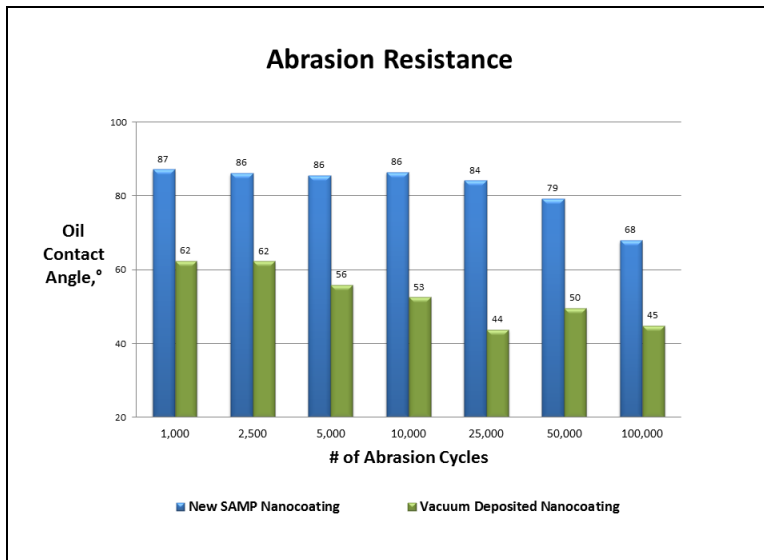


Figure B-2. Results of abrasion resistance tests

In the context of a PCB assembly environment, stencil wipe frequency may vary from 1 print per wipe to 10, 20 or 25 print per wipe. No direct correlations between laboratory abrasion and actual production abrasion have been studied, but assuming a simple 1:1 relationship, at 1 print per wipe, performance compromises may be anticipated in 25,000 to 50,000 print range. At 10 prints per wipe, the compromises may be noted in the 250,000 to 500,000 print range. These ranges extend beyond the typical life of an SMT stencil or PCB revision.