

Broadband Printing: The New SMT Challenge

Rita Mohanty & Vatsal Shah, Speedline Technologies, Franklin, MA
Gary Nicholls, Ron Tripp, Cookson Electronic Assembly Materials – Engineered Products,
Johnson City, NY

Abstract

The Surface Mount Technology (SMT) industry has overcome many challenges in the last 30 years, since its introduction in the 1980's. One recent challenge has been the lead-free assembly. People have been working for more than ten years to address this challenge. While the industry is finally getting a good handle on the lead-free assembly process, another significant challenge has begun to surface. The most current challenge is the adoption of miniature components assembly process. Miniature components used today includes 01005, 0201 passives to 0.3mm-0.4mm CSP and BGA.

By itself, miniature components have their own challenges, but when combined with larger components on the same board, the challenges multiply by several fold. To make matters worse, the design and functionality demanded by consumers require the placement of miniature passives next to larger, castle-like components. This creates a fundamental challenge in satisfying the solder paste need for both small and large components. Even though this is an industry-wide issue, no significant studies can be found in the literature. There are many different approaches that can be taken to address this issue. These include step stencil, augmented stencil printing process, multiple printing passes, etc.

In a recent publication, Speedline reported work done at a very basic level to understand the printing challenges associated with "Broadband Printing". Broadband Printing is defined here as the printing process that satisfies the solder paste volume required for a PCB with both miniature and larger components existing side by side.

This paper will investigate the capability of a single thickness stencil to satisfy the paste requirement for mixed components board by creative stencil design. Some of the stencil design factors that will be explored will include over printing of larger components, using different stencil technology, and stencil thickness. In addition to the printing study, components will be placed and reflowed to access the solder joint character. The post assembly boards will be inspected by using IPC-A-610 standard for fillet characterization. In addition, X-ray inspection and mechanical strength test will be conducted to characterize the solder joint integrity.

Key words: Broadband printing, dynamic printing, over printing, mixed size component assembly, pad finish, stencil technologies.

Introduction

A typical surface mount process consists of three major process steps: Printing, Pick & Place and Reflow. Each of these steps are affected by many known and unknown (noise) factors and have been studied by many researchers. What is new here is the introduction of miniature components (01005, 0201, 0.4mm pitch CSP etc.) along with much larger components (larger BGA, QFN, QFP and passives), otherwise known as Broadband printing or Dynamic printing. Most board assemblers believe that 50%-80% of the assembly defect can be attributed to printing defects. Adding miniature components to the board, increases the print defects opportunities by several fold. In order for us to optimize the entire surface mount process with mixed size components; we first need to understand the challenges involved with broadband printing. Among the most common factors affecting printing are, process equipment, stencil technology, pad finish, paste type, level of operator training etc....

Printer

The solder paste printing process is a highly complex process that involves a series of interdependent factors. These are: print speed, print pressure, separation method, squeegee type (blade or enclosed print head), board support and printer alignment. While print speed, pressure and separation method can be optimized through a series of process development steps, printer alignment is inherent to a printer. In fine-pitch printing, positioning capability is the most critical factor in a printer. The printer must align the stencil to the substrate with high accuracy and repeatability. A printer alignment capability can be defined as its ability to meet the design specifications and is expressed as CpK (Process Capability Index). CpK, which is known as the "actual" process capability, incorporates centering and spread of the alignment as compared to the specification limits. In more common terms, CpK reflects the accuracy and repeatability of a printer. In the early days of electronics assembly processes, demand on accuracy and repeatability was not as high as it is today due to the larger form factors of that time. As the technology in component packaging continues to advance with components and their spacing rapidly decreasing in size, accuracy and repeatability is becoming highly critical to the assembly process.

For example, for a 12mil pitch device, the typical designed pad size is 7mil to 8mil wide. Typical stencil opening is 1mil to 2mil less than the pad width to ensure good gasketing during the paste deposition process. These dimensions allow only 1mil to 2mil between either side of the opening and the edge of the pad. If the printer alignment system is incapable of maintaining this relationship and paste is deposited beyond the edge of the pad, there is a possibility of bridging to an adjacent pad and producing an unacceptable board.

Stencil

It is well known that the stencil is a major factor in the overall SMT assembly process yield. The function of a stencil is to deliver a controlled volume of solder paste to PCB pads. The printing process involves two-steps: (1) the aperture fill process, where solder paste fills the stencil aperture, and (2) the paste transfer process, where solder paste is transferred from the stencil aperture to the PCB pads. The fill process largely depends on solder paste type, squeegee blade type and print parameters. On the other hand, paste transfer depends on the stencil technology, area ratio (area of the aperture opening divided by the area of the inside aperture wall), and its wall smoothness. The paste transfer process can be viewed as a competing process where the pad on the PCB below the stencil aperture is pulling the solder paste out of the aperture while the aperture sidewalls are holding the solder paste inside the aperture. When thinking of the paste transfer process in this manner, it is easy to understand why the area ratio and aperture sidewall smoothness have such a significant effect on paste transfer.

There are many different types of stencil technologies available to a board assembler. Common types are laser cut stainless steel & nickel, chemical etched, and electroformed. Laser cut electroformed nickel and laser cut stainless steel stencils are very similar with respect to aperture size accuracy, aperture taper and the variability around both the size and the taper. In addition, both of these stencils have very similar aperture wall smoothness. The Electroformed stencil on the other hand has similar size accuracy but narrower size distribution around the average. The Electroformed stencil, because of the manner in which it is made has a significantly smoother wall surface than the laser cut stencils and also has a slightly smaller taper, (which makes the actual aperture size slightly larger) and these two things together produce somewhat larger paste deposition than is generally obtained with laser cut stencils. One of the objectives of this study is to understand the effect of various stencil factors in the paste transfer efficiency while dealing with broadband printing.

Paste

Solder paste is not only the material that acts as the glue to hold the components on the board, but also provides the critical electrical connection between the board and the component. Hence, the criticality of paste character is without a doubt one of the most important factors in the SMT process. A typical solder paste system consists of solder alloy powder, flux, viscosity modifier, and a solvent system. Solder paste rheology and printing performance can be controlled by manipulating these factors. As we migrate to ultrafine pitch components, most paste suppliers have migrated to smaller powder size and new rheology modifier formulations. With smaller powder size comes the challenge of complete reflow of solder paste under air environment. One of the objectives of this study is to understand the effect of reflow environment on the overall quality of board assembly.

Board finish

There are varieties of surface finish available in the industry for lead-free assembly. Among the most common are HASL (Hot Air Solder Level), OSP (Organic Surface Preservative), Immersion Tin, Immersion Silver and ENIG (Electro-less Nickel Immersion Gold). Each type of surface finish has its own advantages and disadvantages. In most cases, the choice is specific to the application.

For many years, HASL was the choice of pad finish due to its cost effectiveness and high solderability throughout the soldering process. One of the biggest disadvantages of HASL was its poor coplanarity. As we migrate to fine pitch and high I/O count devices, pad surface flatness becomes very critical. For this reason, the current study will focus on OSP and ENIG pad finishes only.

OSP is simply an organic coating applied over clean copper pad to prevent it from oxidizing. It burns off during the reflow process allowing the copper pad to be soldered to the component lead. For fine pitch components, it provides superior coplanarity, solderability and no "black pad" issue. In addition, it is quite comparable to HASL in regards to cost per unit.

ENIG, which is the most expensive pad finish of the three, provides a very flat surface with excellent solderability. Regardless of its high cost, this pad finish has been used by many board assemblers with great success. One of the biggest drawbacks of this finish is its susceptibility to "black pad" issue. "Black pad" is a term used in the industry to describe the cracking of the electroless-nickel layer underneath the gold finish. The hypothesis here is that with different pad finish, hence different surface characteristics, printing and reflow process may be greatly influenced.

Experimental Approach

The following section describes the experimental methodology used in this study. A two-step approach was used to understand the effect of various print and reflow factors. Step one focused on the printing process that included the following printing factors: stencil technology, stencil thickness and board finish. Step two focused on effect of reflow environment, stencil technologies and pad finish on solder joint integrity.

Test vehicle

Figure 1 shows the test vehicle used for this study. The test vehicle was a 10" x 8" x 0.062", four layer FR-4 board with ENIG and OSP surface finish. The test vehicle was divided into four quadrants with the same pad layout in each quadrant. The top half of the board was a "step and repeat", while the bottom half was the "mirror image" of the top half. This board layout was created to understand the interaction between pad orientations, pad location, board and stencil stretch. Each quadrants incorporated wide range of commercially available components and packages that included both miniature components (01005, 0201 passives) and larger components (256BGA, 180QFP, etc.).

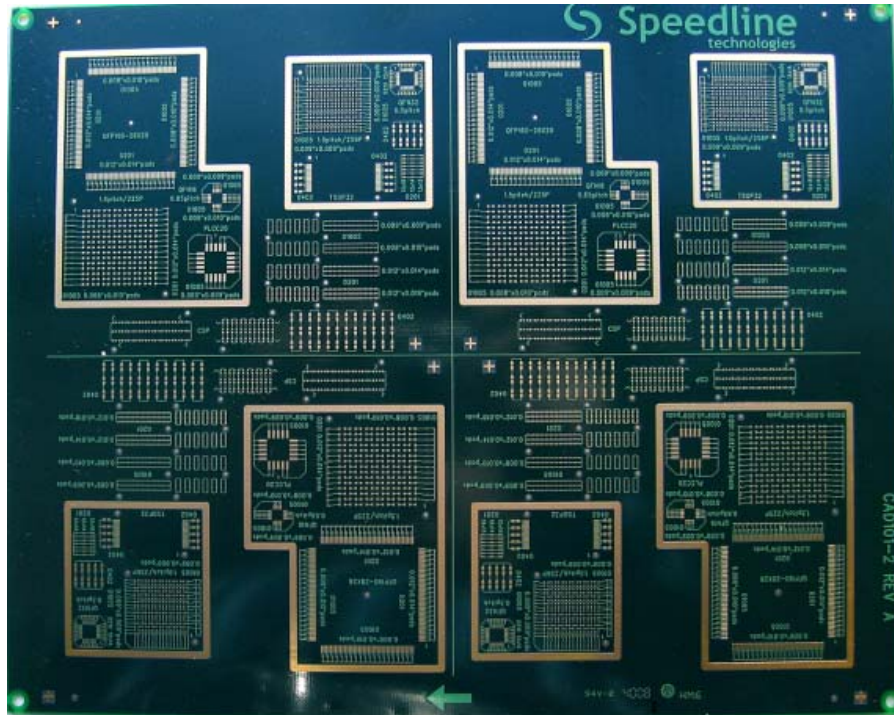


Figure 1. Test vehicle

Stencil design

As the objective of this experiment was to overprint the larger components to provide higher volume of paste, the larger components aperture size was systematically increased from 100% to 160% , (based on the component type) of the pad size. Table 1 shows the aperture layout for these components and figure 2 shows typical schematic of a QFP160 and a TSOP 32 aperture size distribution.

Table 1: Overprint strategy

Components	Aperture size
QFP 160	100%, 110%, 120%, 130%
QFN 32	100%, 110%, 120%, 130%
QFN 16	100%, 110%, 120%, 130%
BGA 256	100%, 120%, 140%, 160%
BGA 225	100%, 120%, 140%, 160%
PLCC 20	100%, 110%, 120%, 130%
TSOP32	100%, 110%, 120%, 130%
0402 (around TSOP 32)	100%, 110%, 120%, 130%
0402	100%, 120%, 140%

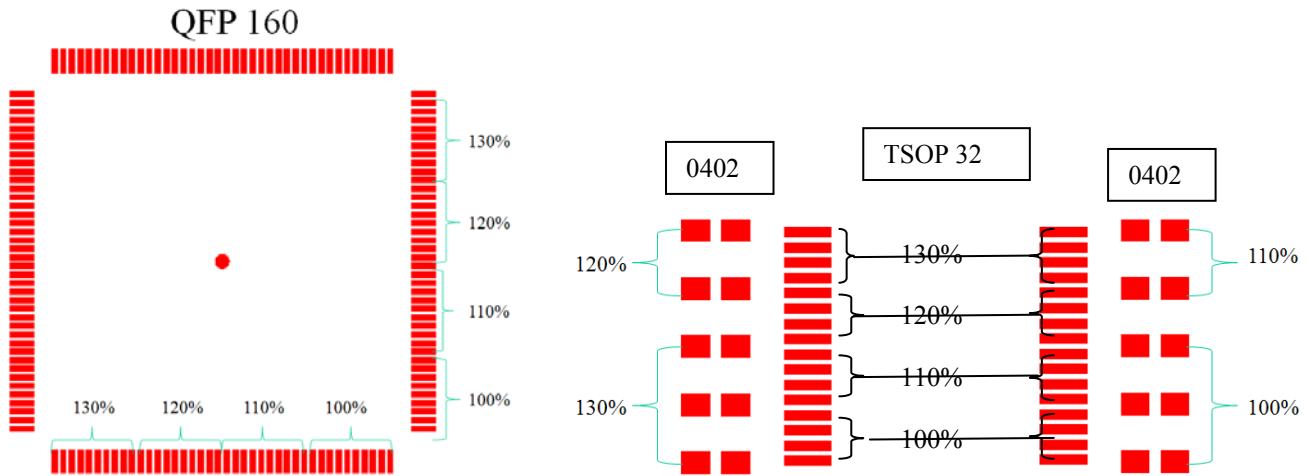


Figure 2. Aperture layout for two typical larger components

Printing DOE

A full factorial design with 2 factors, at 2 levels, was performed to optimized paste transfer efficiency. This DOE was blocked over two different stencil technologies to assess the effect of stencil technologies on both large and small pad size. Table 2 shows the actual measured thickness and taper of each stencil. Factors used for this experiment are as follows:

Variable factors:

- Stencil thickness, 3mil and 4mil
- Board finish, OSP and ENIG

Fixed factors:

- Paste type, Type 4 Alpha OM - 350
- Print speed, fixed for each stencil type
- Print pressure, fixed for each stencil type
- Separation method, fixed for each stencil type

Blocked factor:

- Stencil technology, Electroformed, and stainless steel laser cut,

Table 2. Actual dimension of the stencils

Stencil Technologies	Nominal Thickness in mil	Actual thickness in mil	Taper in mil
Electroformed	4	3.4-3.6	
	3	2.4-2.6	
Laser cut SS	4	3.9	0.8-0.7
	3	3.0-3.1	0.8-1.0

The standard order design table is shown in Table 3. Before each block of DOE was started, print parameters were optimized to provide the most optimum print quality. The print optimization started with initially printing a board with the paste manufacture recommended settings then visually inspecting it to verify the alignment of the board to the stencil. The offsets were then inputted in to the printer and the same board was cleaned and printed again. This process was repeated until the paste was completely deposited on the pads. The initial set up for print speed, print pressure and the separation speed were then modified to obtain optimum print quality. The criteria for the optimum print quality were aperture fill of the deposit, shape of the deposit and clean sweep of the stencil after every stroke. Figure 3 shows a typical acceptable print setup.

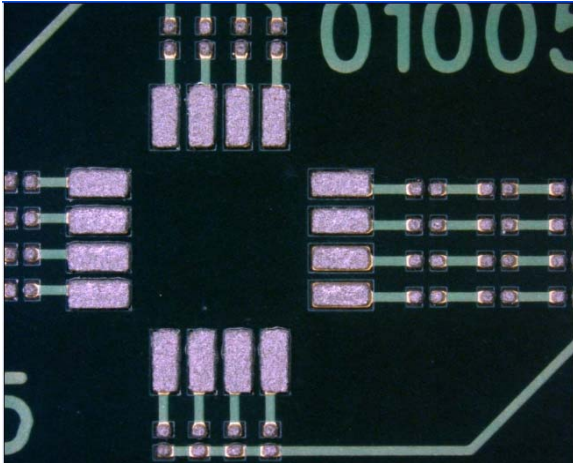


Figure 3. Print optimization results

Table 3. Standard order DOE table.

Full factorial DOE, blocked over stencil technologies					
Factor	Parameter	LEVELS		Transfer Efficiency	Stddiv
		(-)	(+)		
X1	Stencil Tkn	3	4		
X2	Pad finish	OSP	ENIG		
Qty	RO	Stencl Tkn X1	Pad finish X2		
3	1	1	-1		
3	2	1	1		
3	3	-1	-1		
3	4	-1	1		

The responses considered for this study was the transfer efficiency (TE), paste height, absolute paste volume and bridging. Transfer efficiency is defined as:

$$TE \text{ (Transfer Efficiency)} = \text{Measured Paste Volume} / \text{Theoretical Volume of the Aperture} * 100$$

A “repeat” noise strategy was adopted for this study to learn run-to-run variations. Three boards per treatment combination were printed with “rear to front” squeegee direction only. This strategy was adopted to minimize noise effects due to squeegee stroke direction on the print quality. All data analysis was conducted using JMP statistical software.

Results and Discussion

Presenting the detail results and analysis for the current study is beyond the scope of the paper. Hence, results from selected areas, representing the board design are presented here. Figure 4 identifies components included in this discussion. As it can be seen, these locations contain miniature components such as 01005, 0201, and larger components with varied aperture size such as 0402, QFP 160 and TSOP32. Since the goal of the printing experiment was primarily to understand the relationship between board finish, stencil technologies and stencil thickness, only pad to aperture ratio of 1:1 is presented here.

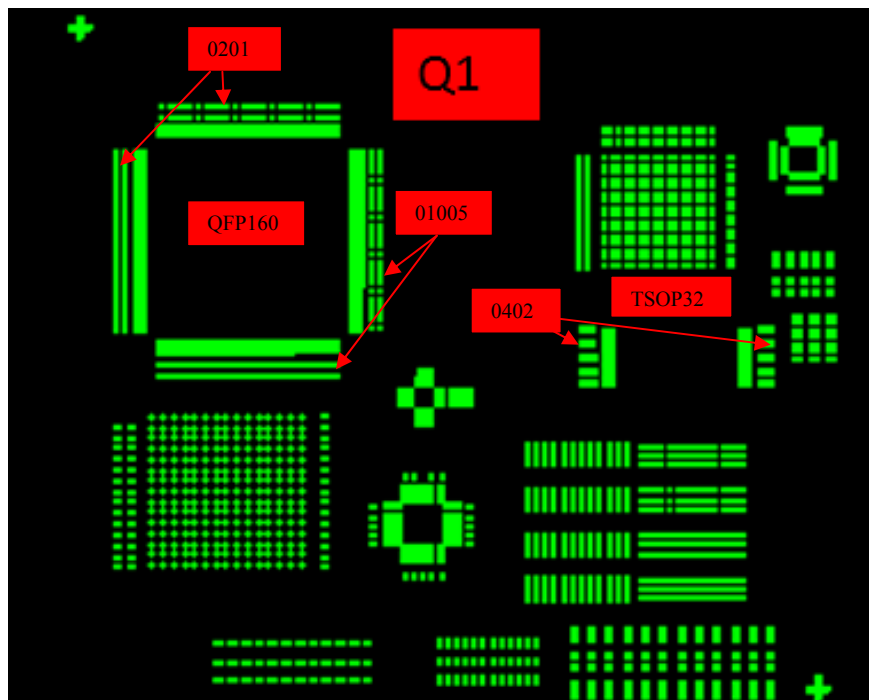


Figure 4. Representative location of large and miniature components

Data analysis

Figure 5 shows the variability plot for QFP160 for laser cut stencil DOE and figure 6 shows a similar plot for 0201. In Figure 5 the “Y” coordinate represents the absolute volume deposit in cubic mils and “X” coordinate represent aperture size (APT), within sample number (SN), within run order (RO). As a reminder, aperture 1 though 4 represent aperture ratio of 1:1-1:1.3. As you would expect, with the larger aperture size, absolute volume deposited increases steadily. We also see here the sample to sample measurement is quite consistent. This is a good indication that repeatability within each run order is consistent. Variability plots are particularly useful in determining different sources of variations affecting the DOE. It is also useful in determining qualitative results for the DOE. For example, Figure 5 clearly shows that there is a shift between run order 1, 2 and 3, 4. Run order 1, 2 contained 4mil thick stencil and run order 3, 4 contained 3mil stencil. As the DOE analysis will show in subsequent figures, this is primarily due to stencil thickness. Results for the Electroform nickel was very similar to the laser cut stainless steel. Figure 6, which represents 0201 component shows similar trend as QFP160 with respect to stencil thickness.

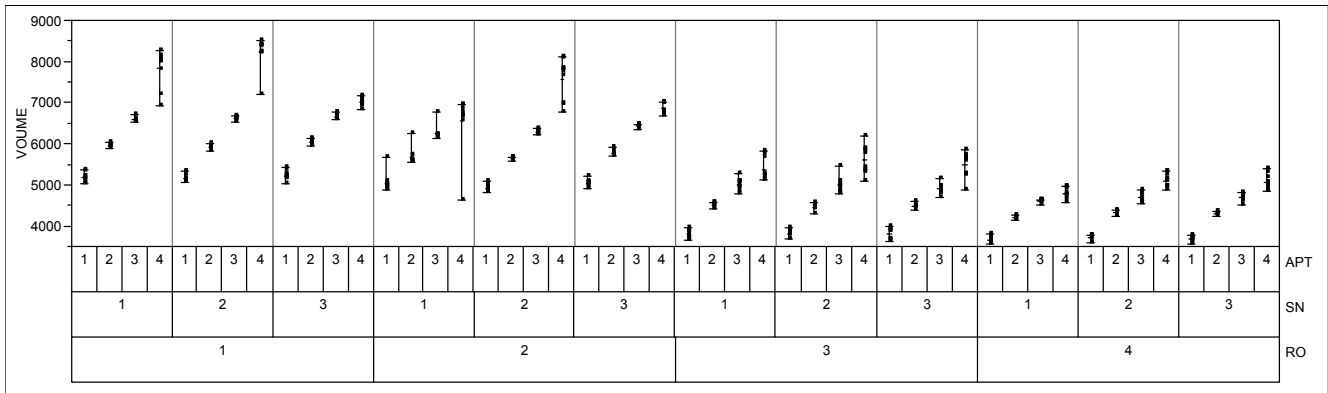


Figure 5. Variability plot for QFP160 that includes all four run order.

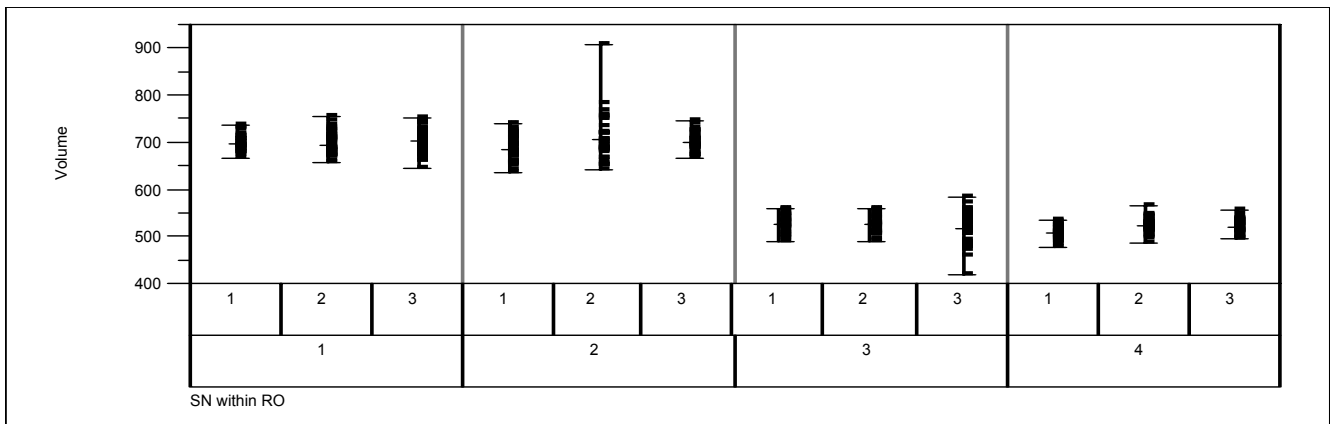


Figure 6. Variability plot for 0201 that includes all four run order.

Print DOE analysis

A series of main effect and interaction plots, covering both miniature and large components, is presented below for stainless steel laser cut stencil. Electroform stencil displayed similar behavior. As it can be seen from the plots below, pad finish has the strongest effect on the paste transfer efficiency. Next to pad finish, interaction between pad finish and stencil thickness appears to be significant. Effect of stencil thickness is not as important for QFP160 and TSOP32 as it is for 0402, 0201 and 01005. For miniature components, the thinner stencil appears to have better transfer efficiency than thicker stencil due to higher area ratio. As one would expect, absolute paste volume as the response shows stencil thickness has stronger effect. Thicker stencil delivers higher volume of paste regardless of the component type. Both SPI and visual inspection showed no significant bridging for the components reported here. This was true for both stencil technologies.

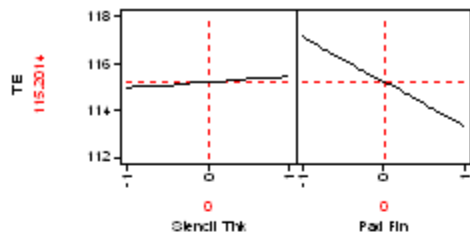


Figure 7a. Main effect plot for QFP160 Laser cut stencil

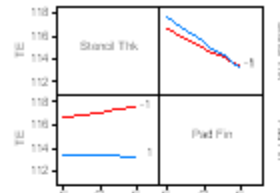


Figure 7b. Interaction plot for QFP160 Laser cut stencil

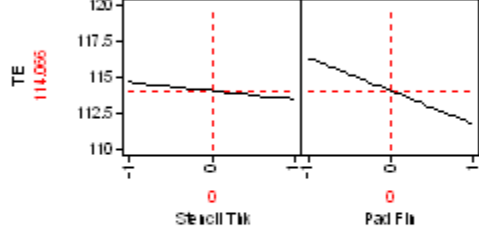


Figure 8a. Main effect plot for TSOP32 Laser cut stencil

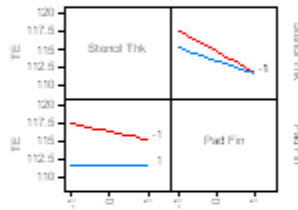


Figure 8b. Interaction plot for TSOP32 Laser cut stencil

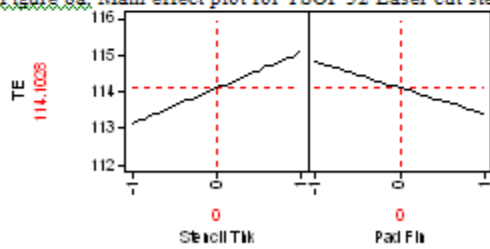


Figure 9a. Main effect plot for 0402 Laser cut Stencil

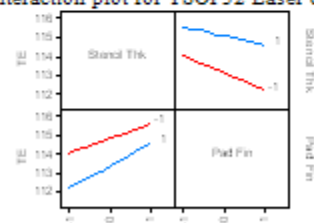


Figure 9b. Interaction plot for 0402 Laser cut stencil

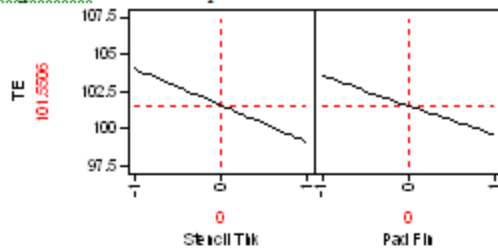


Figure 10a. Main effect plot for 0201 Laser cut Stencil

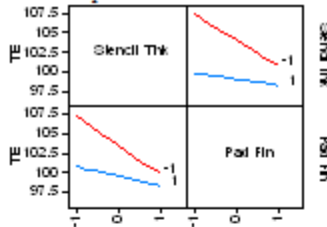


Figure 10b. Interaction plot for 0201 Laser cut stencil

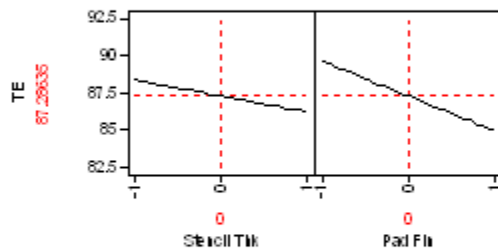


Figure 11a. Main effect plot for 01005 Laser cut Stencil

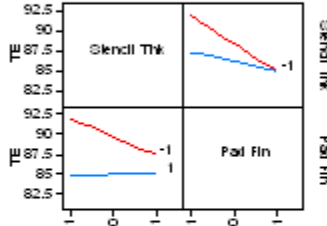


Figure 11b. Interaction plot for 01005 Laser cut stencil

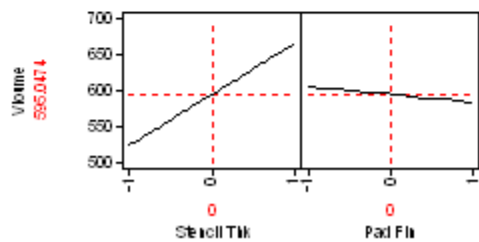


Figure 12a. Main effect plot for absolute volume for 0201

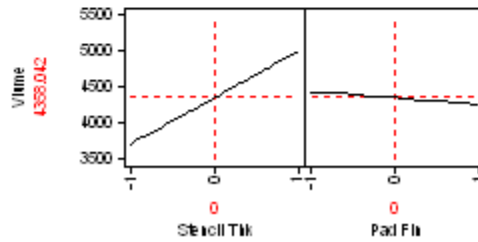


Figure 12b. Main effect plot for absolute volume for QFP160

Print DOE Summary

It can be summarized from the above results, in regards to stencil thickness, the thinner stencil (3mil) provided better transfer efficiency while thicker stencil (4mil) delivered higher volume of paste. This is significant for miniature components, since

3mil stencil can provide adequate volume of paste with better transfer efficiency. Larger volumes of paste may not be desirable due to higher opportunity for assembly defects such as tombstoning and paste squeezeout (bridging).

DOE analysis showed that regardless of the component type and stencil technologies, OSP finish provided higher transfer efficiency than ENIG. Further investigation is underway to understand the effect of pad finish on transfer efficiency.

In summary, the current study showed that all factors considered in this study (stencil thickness, stencil technologies, and pad finish) show significant effect on printing process. In addition, there exist complex interactions between these factors which need to be further studied.

Board Assembly Study

Based on the results from the printing DOE, the board assembly study was designed as follow:

Variable factors:

- Stencil technology (laser cut stainless steel and Electroform)
- Pad finish (OSP and ENIG)
- Reflow environment (Nitrogen and air)

Fixed factors:

- Stencil thickness (3mil)
- Paste, Type 4 Alpha OM-350
- Optimum printing parameters (based on stencil technologies)

Response factors

- Visual inspection based on IPC 610D
- X-ray inspection
- Assembly defects (tombstoning, solderballing, missing components and bridging)

A Fractional Factorial DOE was conducted for this phase of the study to understand the effect of various land patterns and aperture shapes on component assembly. Three boards were printed per run order using the optimum print parameters with one squeegee stroke direction (Rear to Front) only. Components were placed on the boards and reflowed according to treatment combination. The reflowed boards were visually inspected to meet the IPC 610D standards for solder paste characterization and then X- ray inspection was performed on these boards. The standard order design table is shown in table 4.

Table 4. DOE table for reflow experiment

Fractional factorial DOE						
		LEVELS				
Factor	Parameter	(-)	(+)			
X1	Pad finish	ENIG	OSP			
X2	Reflow Atm	N2	Air			
X3	Stencil Tech	Laser	Efab			

Qty	RO	Pad finish X1	Reflow Atm X2	Stencil Tech X3	Visual	X-ray
3	1	1	-1	-1		
3	2	-1	1	-1		
3	3	-1	-1	1		
3	4	1	1	1		

Board Assembly Results

Limited analysis from the assembly study is presented below. Details of this study will be presented at a later time. The reflowed boards were inspected to ensure that it met IPC 610D standard. Typical images showing acceptable fillet formation and cooling line are presented in figure 12. Visual inspection of the assembled boards clearly showed that the overprinted pads (pads with more than 100% pad to aperture ratio) did not cause bridging after reflow. In other words, the larger pads with excess paste showed good “pull back” characteristics. Figures 13 and 14 show typical images of QFP160/01005 and TSOP/0402.

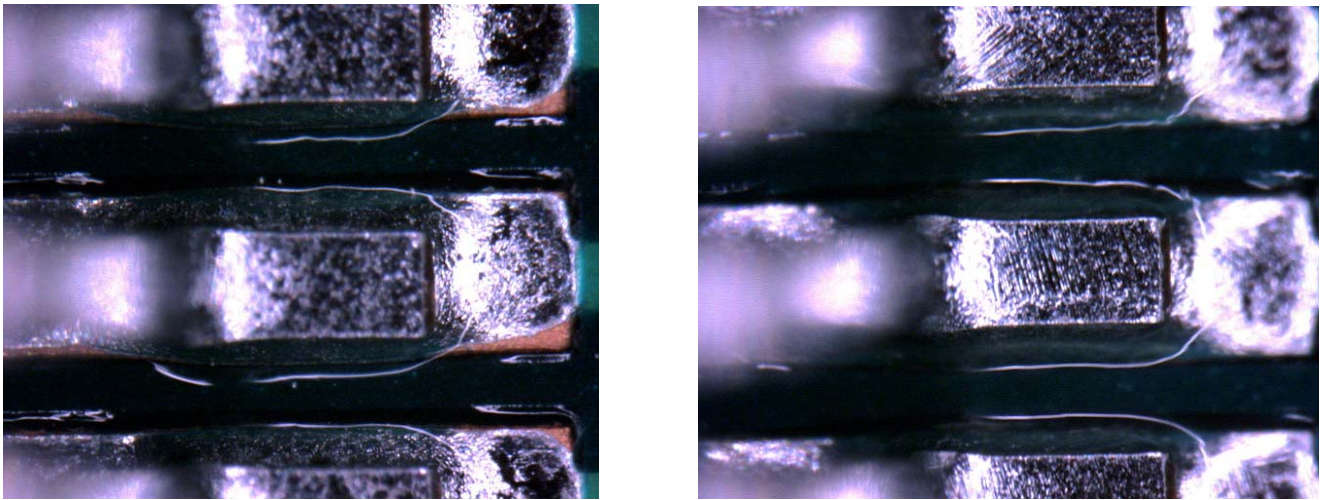


Figure 12. QFP 160 showing fillet and cooling line. Left: 1:1 aperture ratio. Right: 1:1.3 aperture ratio

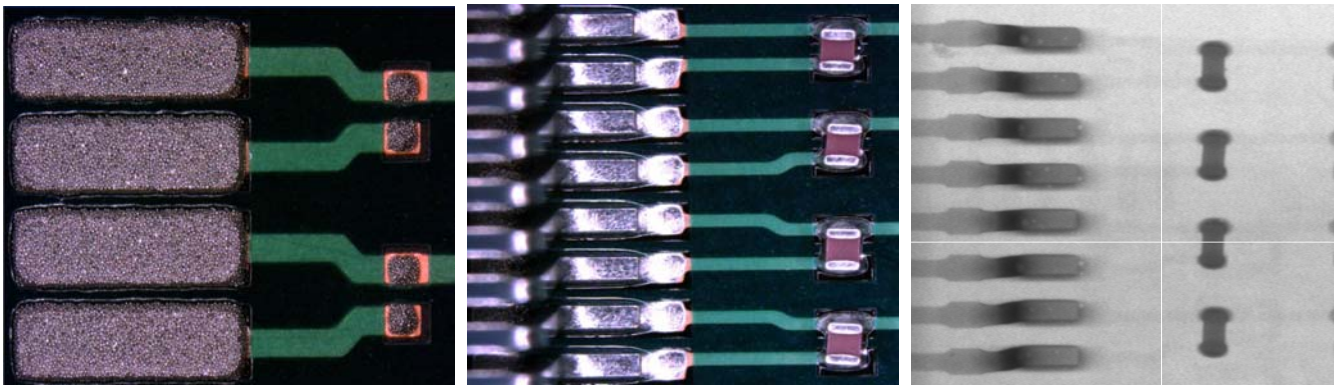


Figure 13. QFP160. From left to right, green paste, reflow board and X-ray image of the same area.

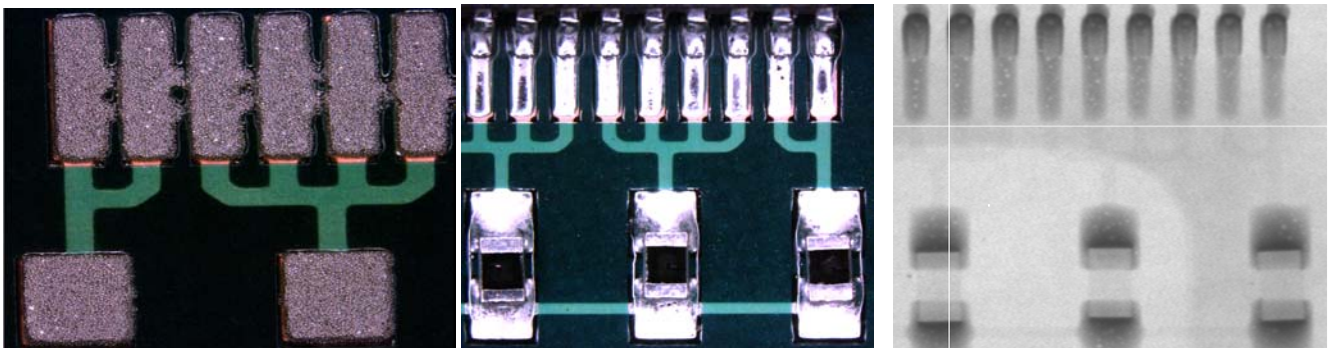


Figure 14. TSOP32. From left to right, green paste, reflow board and X-ray image of the same area.

Visual and X-ray analysis showed that only passive components displayed defects such as solderballing and tombstoning. Other packages such as QFP and TSOP showed no visual defects. In addition to the above mentioned defects, all components showed voiding after reflow. Further investigation is necessary to fully understand the implication of voiding.

DOE analysis showed reflow atmosphere had the strongest effect on assembly defect. Board finish, which was a significant factor for paste transfer efficiency (from the above print experiment), did not appear to be significant for board assembly. Figure 15 shows the DOE analysis for the board assembly experiment.

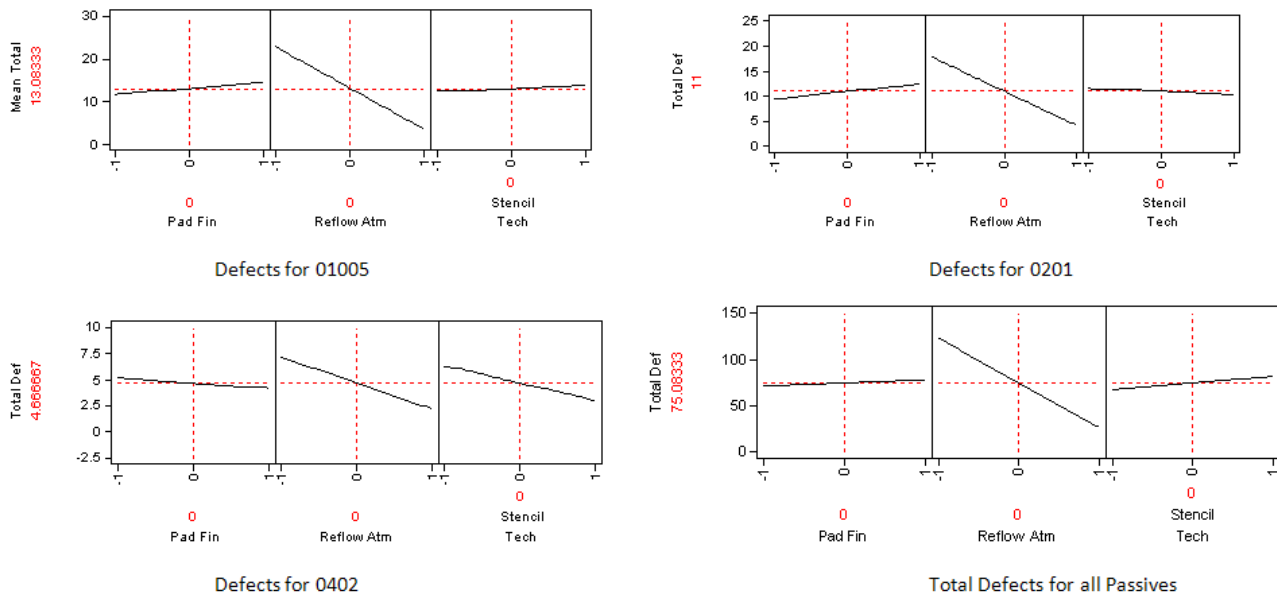


Figure 15. DOE analysis for Q1; passive components only

Summary and Conclusion

Multiple DOEs were performed to understand the effect of various design and process factors on the overall assembly of boards with mixed-size components. Various statistical analyses were performed to determine the effect of stencil technologies, stencil thickness and pad finish on paste transfer efficiency. Results showed that the 3mil stencil provided better paste transfer for miniature components while the larger components were not greatly affected by stencil thickness. In regards to the stencil technologies, both laser cut stainless steel and Electroformed stencil performed comparably. Stronger than the stencil thickness effect was the pad finish. OSP pad finish showed higher paste transfer regardless of component size and stencil technologies. One of the explanations for this phenomenon could be the interaction between pad surface finish and paste chemistry. ANOVA analysis also showed there exists a complex interaction between stencil and pad finish.

Based on the printing study, only 3mil thick stencil was included in the reflow DOE. Since the aperture design incorporated overprinting of larger components, 3 mil stencil was believed to be better suited to study the effect of overprinting. The results suggest that nitrogen definitely improves reflow characteristics of the solder paste with miniature components. Larger components had minimum to no effect in regards to reflow environment. Unlike the printing results, pad finish had no significant effect on the assembly yield. In regards to the effect of overprinting, results showed there was good pull back of the paste causing no bridging. This is clearly encouraging. Visual inspection showed that the fillet formation around the larger components appears to be adequate.

It is encouraging to see that 3 mil stencil with creative stencil design (overprinting the larger components) meet the IPC 610D visual inspection criteria. This is a step in the right direction when dealing with mixed size components. Additional work is under way to determine if the solder joints truly meet mechanical and long-term reliability requirement.

Future Work

The results and analyses in this paper focused only on one quadrant and selected components. Analyses of the remaining components and quadrants will provide better understanding of the process. These analyses will provide better understanding of factors interaction that was evident in the initial results. Visual inspection of the assembled boards showed that the solder joints met IPC 610D standard. X-ray inspection showed clear evidence of voids in the solder joint. Additional destructive testing, such as shear test, will be necessary to understand the true mechanical integrity of the solder joint.