As originally published in the SMTA Proceedings.

Impact of Stencil Manufacturing Technology and Supplier's Capability on Performance of Multi-level/ Step Stencils

Supriya Agrawal, Mohammad S Alam, Sih Fei Lim, Li Cheng Khaw
Intel Corporation
OR, USA
supriya.agrawal@intel.com

ABSTRACT

Optimization of stencil aperture and thickness for each component on a Printed Circuit Board (PCB) is critical to ensure high product quality and maximize yield. As per IPC, one of the key considerations while designing stencils is to maintain an area ratio (AR) above 0.66 for acceptable paste release [3]. A step stencil is required when a single stencil thickness is not able to meet the AR requirements for certain fine pitch or smaller components while still having to accommodate high paste volume requirements for larger components like headers and connectors.

As PCBA complexity increases, using multiple thicknesses or levels within a stencil is common. Densely designed PCBs and multi-level stencils could lead to an increased risk of solder paste variation on components that are close to the step edge leading to solder joint defects. Traditional methods (such as the chemical etch process) of manufacturing step stencils do not address these challenges. Recent advances in manufacturing technology have necessitated the exploration and adoption of improved step stencil technology.

In this paper, we evaluate and compare the print performance of four different step technologies: a) Chemically etched (CE), b) Laser weld (LW), c) Milled (ML), and d) Electroform (EF). We also study the capability and limitations of four suppliers to manufacture each step technology.

The results indicate that the Milled stencil performs better than other step technologies against a weighted criterion. However, when choosing a step technology, it becomes important to assess suppliers' capability to manufacture that technology. We find that suppliers tend to be uniquely capable of manufacturing one technology and may not be versatile in manufacturing multiple technologies.

Key words: Area Ratio, Step Technology, Stencil Print, Transfer Efficiency, Yield

INTRODUCTION

The miniaturization of electronic devices for densely populated integrated systems leads to the incorporation of mixed technology parts in the SMT process. Complex PCB designs of today could include very small components, such as 01005's and 0.3mm pitch devices, as well as large components, such as headers, connectors, pin-in-paste parts, and RF shields on the same assembly [1, 2].

Area ratio (AR) and solder paste volume are the two most critical factors that ensure acceptable printing during the assembly process. Area ratio is defined as the ratio of the area of the aperture opening to the area of the aperture wall. A high area ratio ensures proper paste release through the aperture openings whereas, a low area ratio results in inconsistent and reduced paste volume. IPC recommends an area ratio above 0.66 for a defect-free print process [3].

Maintaining the recommended area ratio and solder paste volume in complex board assembly requires the use of step stencils. For fine-pitch components or smaller passives, a high area ratio can be achieved by using a thinner stencil or stepping down from the base stencil height. For larger components on boards, a high volume and height of paste are obtained by increasing stencil thickness or stepping up locally in that area to get a healthy solder joint. Step stencils help in depositing a precise amount of solder paste for all types of components and ensure high yield and solder joint quality.

The keep-out zone around a step transition plays a crucial role in transferring the right amount of solder paste. Inconsistency in paste deposit is evident on the apertures around the step edge. IPC SPEC – 7525 [3] demonstrates the KOZ (K1 + K2) requirement (Figure 1). Here, K1 is the distance between the step edge and nearest aperture in the step-down area and K2 is the distance between the step edge and nearest aperture in the step-up area

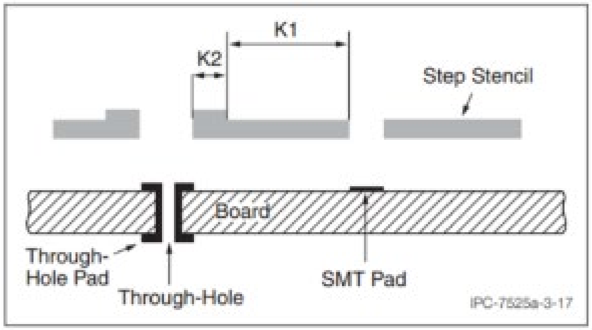

Figure 1. Step Stencil KOZ Illustration (IPC-7525a-3-17) [3].

The recommended KOZ for each 1 mil step is listed in Table 1. IPC recommends at least 61 mils spacing between apertures on different steps for each 1 mil step.

Table 1. KOZ Requirement for Step Stencil as per IPC

Step	K1	K2	Spacing (K1+K2)
1 mil	35.4 mil	25.6 mil	61 mil
2 mil	70.8 mil	51.2 mil	122 mil
3 mil	106.2 mil	76.8 mil	183 mil

The miniaturization of electronic devices and the density of components in PCBs do not allow us to maintain a KOZ of 61 mils in most cases. The technologies to manufacture step stencils can play an important role to ensure consistent paste deposit with a low KOZ distance. Previously, the photochemical etching process was considered the key technology to manufacturing multi-level stencils. However, newer technologies, such as laser weld, electroform, and micro-mill are replacing chem-etch in recent years [4 – 7].

The commonly used step stencil manufacturing technologies are described below.

Photochemical Etch Process

Photochemical Etching is a subtractive process. It starts with a thicker stencil foil and reduces the selected area thickness using a wet chem-etch process. A photoresist is developed at the beginning of the process to protect the areas where thickness reduction is not needed. The remaining area where the material is exposed gets dissolved using a chemical etchant. This process can make the stencil surface rough, and an additional polishing step is required to smooth the surface. Finally, the apertures are laser cut rather than etched to improve aperture size tolerance. Many industries have migrated away from chemically etched step stencils in recent years due to poor accuracy of step thickness.

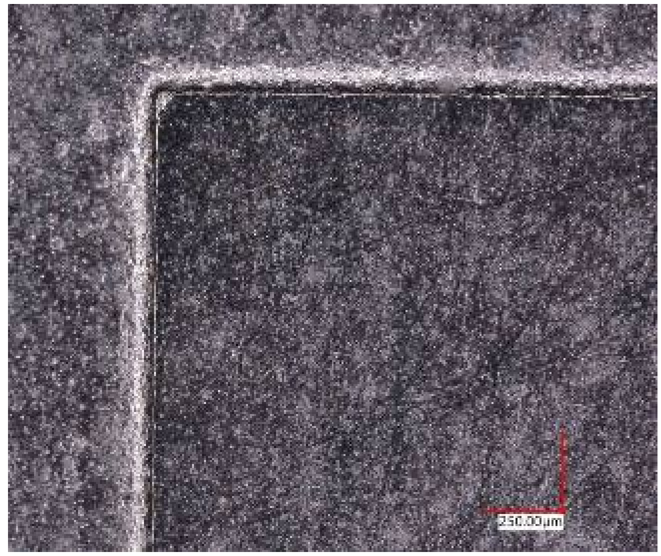

Figure 2. Steps Manufactured by Chemical Etch Process.

Laser Weld Process

In the *Laser Weld* process, stencil foils with desired thickness and size are precut and bonded to the base foil. After bonding, the apertures are formed by a laser cutting process. This technology enables flexibility, short delivery time, and excellent precision and accuracy of step thickness. The steps added using laser weld are replaceable, thus saving the additional cost of a new stencil. Some of the limitations with this step technology are the high keep-out requirements near the step edge due to inconsistency in printing and local foil warpage around the welded area when a thinner foil is used. Warped foils can lead to improper alignment and create a gap between the stencil and board during the print process.

Figure 3: Steps Manufactured by Laser Weld Process.

Electroform Process

In the *Electroform* (e-form) process, a negative photoresist image based on the stencil aperture locations is applied on a copper mandrel and nickel is built up around the apertures/ resist locations. Nickel is added based on the required thickness of the step area. The durability of the electroform stencil is much higher as nickel is harder than stainless steel. Additionally, apertures manufactured by electroform process have smoother aperture walls compared to the laser cut process. Manufacturing a 3D electroform step stencil with the use of a custom copper mandrel could be five to ten times more expensive (USD 4000-6000) than other step technologies. To reduce the cost, suppliers can manufacture electroform step stencils by one of the following methods: a) create apertures by electroform process, but create steps using the chem-etch process, b) create steps using the electroform process, and then create apertures by the laser cut process. Since nickel is a hard material, laser cutting on nickel could lead to the formation of a rough aperture surface, which takes away the key benefit of the electroform process. In the latter method, it is difficult to maintain the accuracy of step thickness owing to the additive nature of the electroform process. Furthermore, the electroform process imposes a limitation on maximum step height when a custom mandrel is not used.

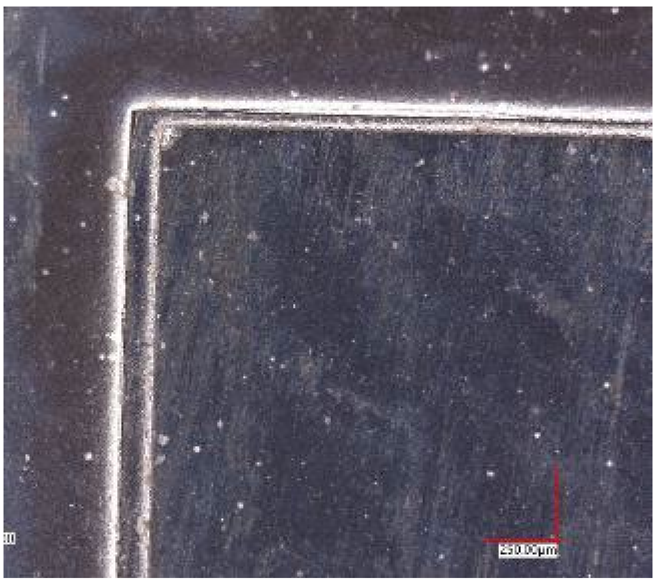

Figure 3. Steps Manufactured by E-Form Process.

Micro-mill Process

Micro-milled technology has become very popular in recent years for manufacturing multi-level stencils. The micro-milled process is a subtractive process and starts with a thicker foil as the base and the material is milled out in selected areas to reduce the thickness. Aperture openings are then created using a laser cutting process. This technology has been reported to provide excellent accuracy in step height and step transition with z-axis dimensional accuracy within 5um. Also, complete edge control ensures a consistent angle and radius allowing apertures to be designed closer to steps and pockets. A more gradual transition in stepped areas can extend the life of the squeegee and stop paste build-up within the transition areas Overall better print deposit, as well as consistent volume transfer around the step edge with a small keep-out zone (<0.4 mm), is also observed in other studies [7].

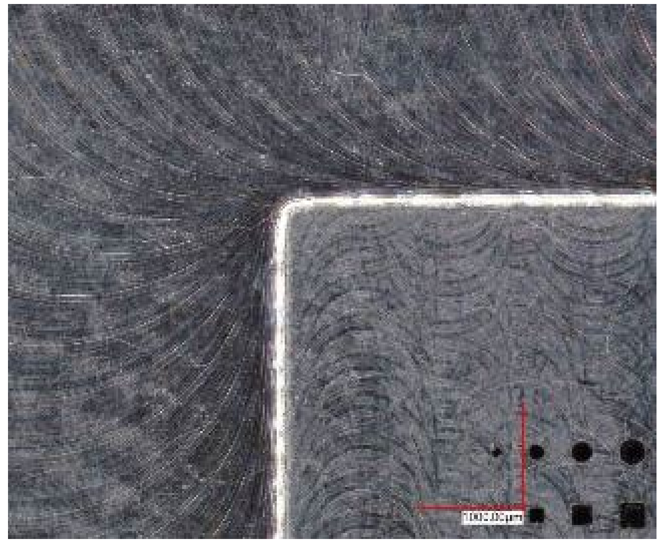

Figure 4. Steps Manufactured by Micro Mill Process.

This study focused on a comprehensive evaluation of the step stencil technologies. Overall print performance of step stencils was evaluated and compared to identify the best technology to adopt and enable defect-free printing. Multiple suppliers were also evaluated in their ability to manufacture different step stencil technologies.

EXPERIMENTAL

Stencil Acceptance Criteria

To understand the capability of potential stencil suppliers a stencil acceptance criteria matrix with a list of critical to function (CTF) parameters was generated. This information provided insight into their key capabilities as well as some of their limitations. Few suppliers had manufacturing specifications on max step height or max step area, and they were excluded from further evaluation. All the suppliers who met a minimum acceptance criterion listed in Table 2 were selected for further evaluation.

Table 2. Stencil Acceptance Criteria for Laser-Cut Step Stencils.

Critical to Function (CTF)	Requirements
Aperture Size Variation	+/- 0.5 mil
Aperture X & Y Position deviation (Measure two farthest apertures located diagonally)	+-0.2 mil
Min Stencil Foil Thickness	1.0 mil
Step Height Variation	Laser weld: +/-2%, Chem Etch: +/-5%
Max Step Height change from base foil	Welding process: 4 mil (Example: 4 to 8 mil)
	Etching process: any desired thickness
	Milling process: 8 mils (Example: 12 to 4 mil)
Max step area size	No limitation for any process
Stencil Frame size thickness	0.5" (Space Saver Frame)
Stencil Inspection and Metrology	Aperture dimension check (Peak Scope)
	Aperture map comparison (Scan Cad)
	XY distance measurement check (Linear gauge)
	Step thickness check (Dial gauge with granite table)
	Foil thickness check (Micrometer)
	Aperture size sampling (Keyence microscope)
	Tension check (Tension gauge)
	Online AOI
Stencil Life	50K print cycle

Test Vehicle

Test Board Description

The selected test vehicle (TV), shown in figure 5, is a production PCB on a high-density instrument card that offers significant comparative data. The test vehicle board size is 16.5 inches x 8.3 inches, 125 mils thick with a total build-up of 26 layers. The board has more than 3000 surface mount components, ranging from the small 0201 passives, 0.4mm fine pitch 84-lead lead frame chip scale package (LFCSP) to a large right-angle connector (RAC) at 27 mm height. The board is complex and densely populated. Multiple steppings on single stencil are required to maintain min area ratio on fine pitch locations while having to accommodate high paste volume requirements for larger connectors and headers. A single-run print test using this TV produces a total of 15458 data points.

Figure 5. Production PCB Used as Test Vehicle.

Stencil Design and Build Matrix

These experimental stencils were produced by 4 different stencil suppliers, referred to as A, B, C, and D in this publication. Stencil base thickness is designed at 4mils with multiple step-down and step-up locations to create a total of five different steppings within the print area (3mils, 4mils, 5mils, 6mils, 8mils). Four different stepping technologies are being assessed: a) Chemically etched, b) Laser weld, c) Milled, and d) Electroform. All apertures are created using a laser cut process. The Design of the experiment (DOE) is shown in Table 3. The stencil design with multiple stepping regions is illustrated in Figure 6 and is color-coded based on thickness. On each fabricated stencil, two additional test coupons are incorporated outside of the print region with various circle and square openings, ranging from 4mils to 14mils. These test coupons can be cut out and are used for incoming stencil quality checks. The test coupon design is illustrated in Figure 7.

Table 3. Step Stencil DOE Table.

Factors	Level I	Level II	Level III	Level IV
Step Height from Base	-1mils	+1 mils	+2 mils	+ 4mils
Step Technology	Chem-Etch	Laser Weld	E-Form	Milling
Supplier	Supplier A	Supplier B	Supplier C	Supplier D

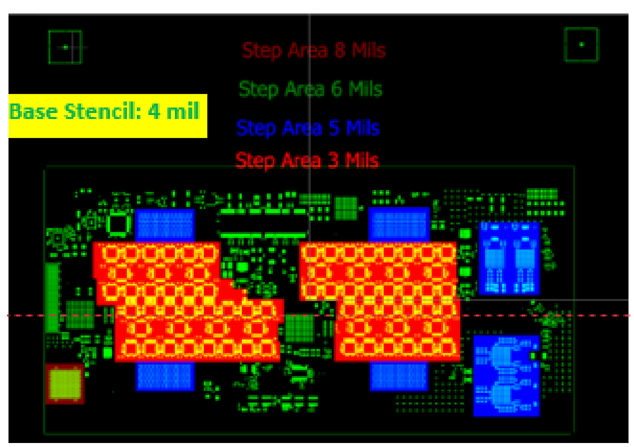

Figure 6. Stencil Design with Multiple Stepping on TV.

Experimental Plan

To evaluate the impact of step-stencil manufacturing variations from one supplier to another, and variations from one manufacturing site to another, designed experiments were performed across two sites with similar toolsets. The experimental plan was conducted in 3 phases across the two sites.

Phase 1: Proof of concept

Stencils from all the suppliers that met the stencil acceptance requirements, as mentioned in Table 2 were purchased for the Phase 1 evaluation at the US site. Four stencil suppliers were selected across two countries. Each supplier is capable of manufacturing one or more types of step technology as listed in Table 4.

Table 4. Summary of Suppliers and Step Technology Manufactured by each Supplier.

Supplier	Country	CE	EF	LW	ML
A	Malaysia	√	X	√	X
B	Malaysia	√	√	√	√
C	USA	√	√	√	√
D	Malaysia	√	X	X	X

A total of eleven stencils were brought in and an incoming stencil quality check was done to evaluate stencil machining accuracy. Further analysis was done by evaluating the print process capability of these step-stencils. Ten prints per stencil were performed and the data was analyzed using two response variables, process capability (Cp) and % out of specification (%OOS) for volume. Based on this capability assessment, stencils were down selected for Phase 2 data collection.

Phase 2: Gross Reality Check

For Phase 2, the stencils that met the Phase 1 capability assessment were subjected to further evaluation. This data collection was done to check for the repeatability of results across two sites. For this round, the print sample size was increased from 10 to 30 to accommodate for variations coming from factors like paste life on the stencil, and idle time between prints. Based on this capability assessment, one stencil was down selected for final evaluation in Phase 3.

Phase 3: High Volume Manufacturing

Phase 3 evaluation was the final step to check stencil quality and life when used over multiple days by multiple operators. Along with capability assessment, production yield was monitored and correlated with print quality. Data collection for this phase involved the print process and PCBA assembly on 200 production boards with yield as the metric. The higher number of print cycles provided an opportunity to investigate any potential stencil degradation like dents on stencil surface when subjected to multiple rounds of squeegee pressure printing, damages to step edges, and mesh to foil debonding over multiple washes in the stencil cleaner.

Solder Printing and Inspection

The solder Print process was done sequentially using an automated printer on the manufacturing line with a forward and reverse printing stroke. The underside of the stencil was cleaned with an automatic wet-dry-vacuum-dry clean mode after each print. A metal squeegee length of 440 mm was used. Print Pressure was set at 10 kg, the print speed at 30 mm/sec, the separation speed at 0.2 mm/sec, and the separation distance at 2mm. Print settings were optimized at the beginning for best printing performance and remained constant for all stencil types to provide a direct comparison between stencils.

The solder paste used in the DOE was Type 4 SAC, no-clean, and lead-free. The fresh paste was kneaded on the setup board five times before printing. A single PCB supplier was used to block additional incoming noises. The PCB was supported with a flat, non-vacuum support block, with board edge clamping. No print pallet was used as the PCB had an outrigger.

The printed solder paste on each pad of the PCB was inspected using an industry standard Solder Paste Inspection (SPI) tool. The deposited solder paste volume, area, height, volume%, and offset were measured right after each printing.

Stencil opening measurements were done with a well-calibrated Optical Coordinate Measurement Machine (OCMM) tool. Stencil thickness measurements on the cut-out coupons was measured using a micrometer. Surface roughness (Sa) was collected using a 3D surface profiler over the surface of cut-out coupons. Visual observations were made on paste residue left behind after each printing stroke for all stencils.

For production yield monitoring, inspection, and test were done through automated optical inspection (AOI), manual visual inspection, automated x-ray inspection (AXI), and in-circuit parametric test.

Data analysis was done using commercial statistical software.

RESULTS AND DISCUSSION

Incoming Stencil Quality Check

1. *Stencil Opening Measurement*

Each stencil was designed to have two 25 mm x 25 mm coupons located roughly 100 mm away from the top edge of the foil that could be easily cut out with a knife without damaging the rest of the stencil. The cutout coupon apertures were measured by an OCMM tool. Each coupon had circular and square apertures with target opening sizes ranging from 4 mils to 14 mils with an increment of 2 mils. A delta diameter was calculated as the difference between target size and measured size, and then plotted with a deviation of +/-0.5 mils as acceptance guidelines. Results are shown in Figure 8. Aperture sizes below 8 mil show increased deviation from target size and most of the suppliers struggle to meet the specified tolerances. Supplier D provided accurate aperture size up to 6 mil opening. Also, supplier D had lower stencil opening size variation when compared to others. All other suppliers did not meet the specified tolerances.

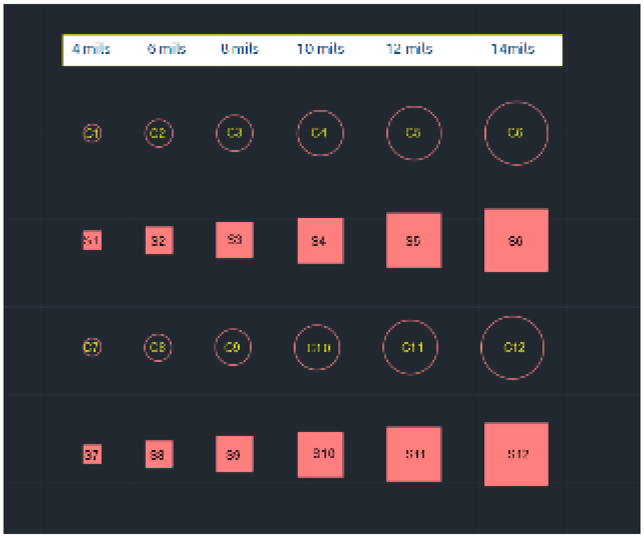

Figure 7. Stencil Coupon with Circle and Square Aperture Openings with Size Ranging from 4 to 14 mil.

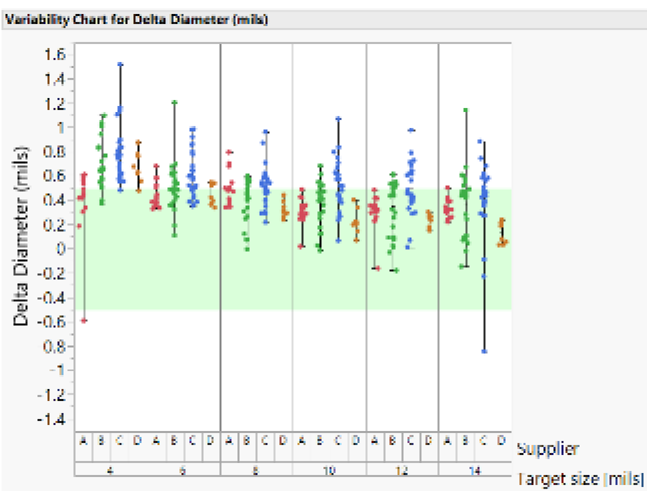

Figure 8. Stencil Opening Measurement Using OCMM Tool.

2. Stencil Thickness Measurement

Using a micrometer, the thickness of the cut-out coupon was measured. Thickness was measured at 5 locations and the average thickness measurements are shown in Table 5 below. The target thickness is 4 mils, and the acceptable thickness tolerance is ±5% from the target. All the suppliers not meeting the tolerance are highlighted in red color. The two Electro-form stencils from suppliers B and C showed poor control in stencil thickness with a deviation of more than ±10% from the target thickness of 4 mils. Supplier B manufactured the steps using the Chem-etch process and apertures by electroform process whereas supplier C manufactured the steps using the electroform process and apertures by laser cut process. This large variation in stencil thickness is attributed to additive and subtractive manufacturing processes of electroform and chem-etch stencils respectively. It is very difficult to control material deposition thickness with these two technologies, especially when there are multiple heights within one stencil. The Chem-etch from supplier A showed a very high deviation of more than +25% from the target thickness. Such a large thickness variation is not acceptable as it alters the true area ratio and the targeted paste volume.

Table 5. Stencil Thickness Measurement across Suppliers.

Step Technology	Supplier	Aperture cut	Measured Stencil Thickness (mils)
CE steps/ EF aperture	B	E-form	3.244088
CE	D	Laser Cut	3.889756
LW	A	Laser Cut	4.157472
CE	A	Laser Cut	4.929124
LW	B	Laser Cut	4.149598
ML	B	Laser Cut	3.85826
CE	B	Laser Cut	3.866134
LW	C	Laser Cut	4.157472
ML	C	Laser Cut	4.299204
CE	C	Laser Cut	3.826764
EF steps/ Laser cut apertures	C	Laser Cut	4.48818

3. Surface Roughness Measurement

Surface roughness was measured using a 3D surface profiler over the surface area enclosed in a red box on the coupon as shown in Figure 10. Stencil roughness determined the ease of paste rolling over the stencil and in turn paste residue left on the stencil after the print process. Results showed that the milled stencil had the lowest surface roughness whereas the e-form had the highest roughness (Figure 9).

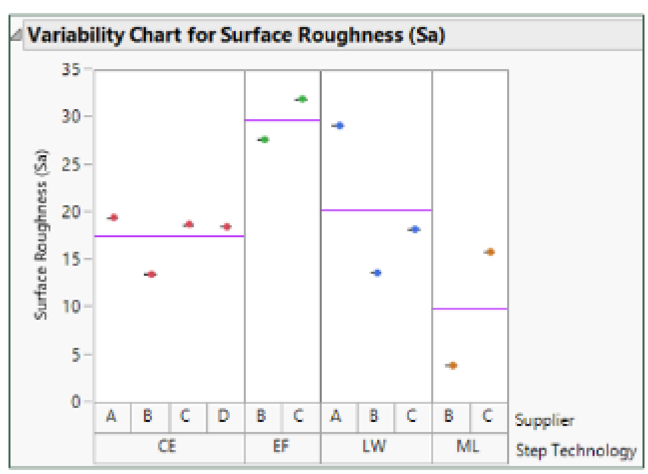

Figure 9. Surface Roughness Comparing Four Step Technology Stencils from different Suppliers.

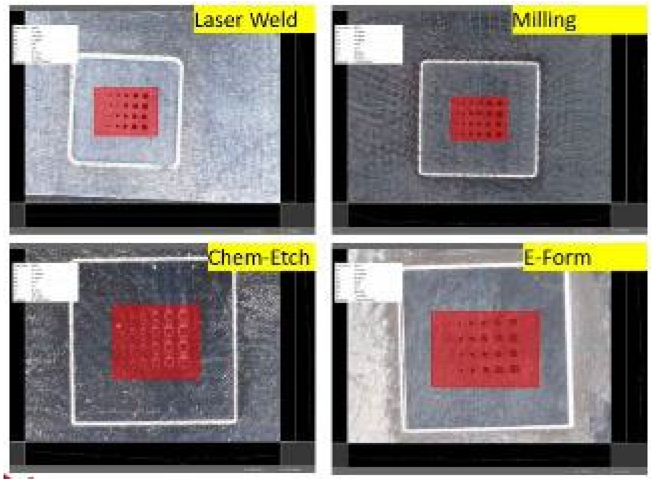

Figure 10. Surface Roughness Measured over an Area.

Paste Volume Distribution

Phase 1: Paste Volume% distribution is plotted in Figure 11 for eleven stencils. The stencil has been grouped based on step technology as seen on the horizontal axis. For each of the step technologies, data is further divided by supplier.

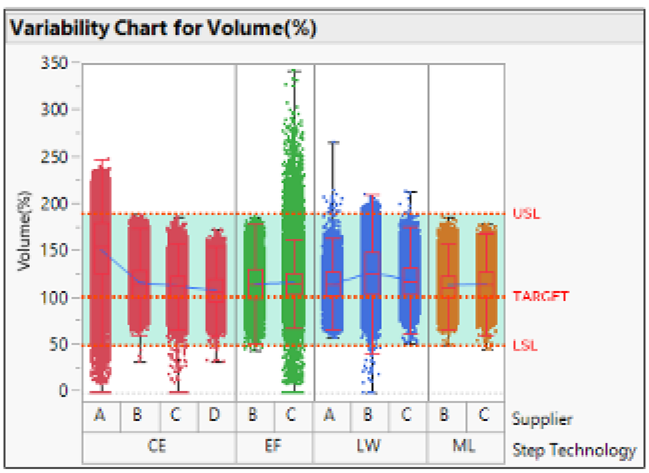

Figure 11. Volume% Distribution across Step Technology and Suppliers.

Figure 11 shows that at least two stencil technologies had a high variation in printed volume - Supplier A (Chem-etch) and Supplier C (E-Form) are way out of the specified limits

Process Capability Analysis

Phase 1

Process capability was used to evaluate the performance of the stencils using measured Volume% monitored against specifications. The lower specification limit (LSL) for volume% is 50% of the target volume and the upper specification limit (USL) is set at 190% of the target volume. These limits indicate that the desirable paste volume for all pads on the PCB should be between 50 to 190 percent of the target volume. Process Capability (Cp) is used as a first filter criteria and %OOS as a second filter criteria to select the stencils. The ideal value for Cp is >=1.33 and any stencil showing a higher deviation from this ideal value is deemed to fail our requirements. The target value for %OOS is set at 0. Any pad that is not within the specified Volume% is failing to meet the process window for acceptable volume.

The red color in the cells in Table 6 indicates that both Cp and %OOS criteria are not met, the yellow color indicates that only one of the Cp or %OOS criteria is met and the green color indicates that both Cp and %OOS criteria are met for the mentioned supplier and step technology.

Table 6. Process capability Analysis for Phase 1.

Supplier		C	A	B	D
Chem Etch	Cp	1.44	0.68	1.12	1.46
	%OOS	0	14.2	0	0
Laser Weld	Cp	1.31	1.36	0.91	NA
	%OOS	0	0	0.2	
Milled	Cp	1.37	NA	1.33	NA
	%OOS	0		0	
E-Form	Cp	1.09	NA	1.12	NA
	%OOS	1.4		0	

The results indicate that most suppliers have expertise in manufacturing one type of step technology. Supplier A provided a poor-quality Chem-etch stencil but was capable in manufacturing a good quality Laser-weld stencil with a Cp of 1.36. Similarly, Supplier B provided poor quality Chem-etch and Laser weld stencils but did a good job in manufacturing Milled stencil with a Cp of 1.33. Supplier D is only capable of manufacturing a Chem-etch stencil but provided a good quality stencil with a Cp of 1.46. Supplier C provided stencils from three technologies that met our requirement, but they sourced some of the stencils from their partner suppliers. Shipment of the stencil from distant locations affects lead-time and should be accounted for when choosing the supplier and step technology.

The results indicate that three out of eleven stencils did not meet both the criteria (red cells), two stencils did not meet one criterion (yellow cells), and the remaining six stencils met both the criteria (green cells) and some of them were further evaluated in phase 2.

Phase 2

For the next phase of study, we performed similar experiments at the Malaysia site. Out of four suppliers for chem-etch stencil, we considered only suppliers A and D.

Although Supplier A did not meet either criterion for the chem etch stencil, it was still considered for phase 2 because this stencil was already in use at the site, and since Supplier D was local to the site and they met both criteria, we chose chem etch from Supplier D. For the Laser-weld and Milled technologies, we chose only those suppliers that met both criteria. For the electroform stencil, none of the suppliers met the Cp criteria and were excluded from further evaluation. To improve the confidence from Phase 1 findings, each stencil was printed 30 times and a process capability analysis was done from the larger data set. Results show that Supplier A-Chem etch was consistently not able to meet Cp > 1.33 and specified volume limits (%OOS) across both sites. A detailed summary is listed in Table 7 below. The best performing stencil was Supplier B -Milled with the highest Cpk of 1.78.

Table 7. Process capability Analysis for Phase 2.

Supplier-Step Technology	Site US (Cp)	Site US (%OOS)	Site MY (CpK)	Site MY (%OOS)
WP Requirement	>1.33	0%	>1.33	<5%
Supplier A – Chem Etch (Old POR)	0.68	14.2%	0.58 0.50	0.9% 3.1%
Supplier D – Chem Etch	1.46	0% (10)	1.49	0% (1)
Supplier B – Milled	1.33	0% (0)	1.78	0% (0)
Supplier C – Milled	1.37	0% (2)		
Supplier C – Laser Weld	1.31	0% (9)	1.67	0% (96)
Supplier A – Laser Weld	1.36	0% (28)	1.58	0% (2)

Phase 3

After the detailed statistical analysis in Phase 1 and Phase 2, Supplier B with Milled step technology was best suited to meet the requirements and was selected for final phase data collection. The stencil was introduced in production and 200 boards were assembled to understand the impact on product yield due to the stencil. Yield analysis showed that the Milled step stencil demonstrated statistically equal and better yield performance when compared to Supplier A - Chem etch. Automated Optical Inspection (AOI) on the Milled stencil yielded 98% vs 95.16% on the old stencil. Automated X-ray Inspection (AXI) on the new stencil yielded 99.5% vs 97.92% on the old stencil. There were zero failures related to the new stencil. The in-circuit parametric test showed excellent results with >96% yield with a new stencil. Table 8 below summarizes phase 3 yield data for the old POR and the new POR step stencil technology.

Table 8. Yield comparison between Old POR and New POR Step Stencil at Phase 3.

Supplier-Step Technology	Optical Inspection Yield	Visual Inspection Yield	X-ray Inspection Yield	Parametric Test Yield
Supplier A - Chem Etch (Old POR)	95.16% (1279/1344)	98.66% (1326/1344)	97.92% (1316/1344)	93.52% (1256/1343)
Supplier B - Milled (New POR)	98% (196/200)	100% (200/200)	99.50% (199/200)	96.48% (192/199)

Visual Observation

Paste Residue after Printing

It was observed that the Supplier A, Chem-etch stencil that showed the highest variability in paste volume had a layer of paste leftover on the stencil surface after the stencil print process as shown in Figure 12. The leftover paste residue layer affected the paste release and lead to variability in the transferred paste volume [5]. Visual inspection of this stencil surface showed the surface was not as smooth or polished which led to paste sticking on it during the print process. Figure 13 shows the Chem-etch stencil manufactured by supplier D with no paste residue. The supplier D Chem-etch stencil showed good paste release with a Cp value of 1.46, demonstrating that step technology performance is also dependent on a supplier's manufacturing capability.

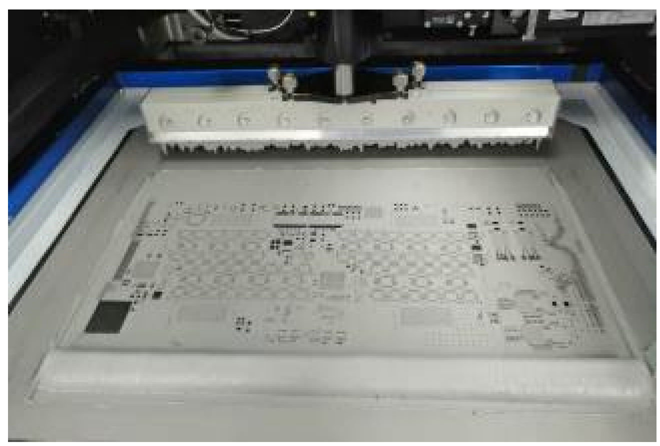

Figure 12: Supplier A Chem Etch Stencil – Rough Surface with a Layer of Paste leftover on Entire Printed Area.

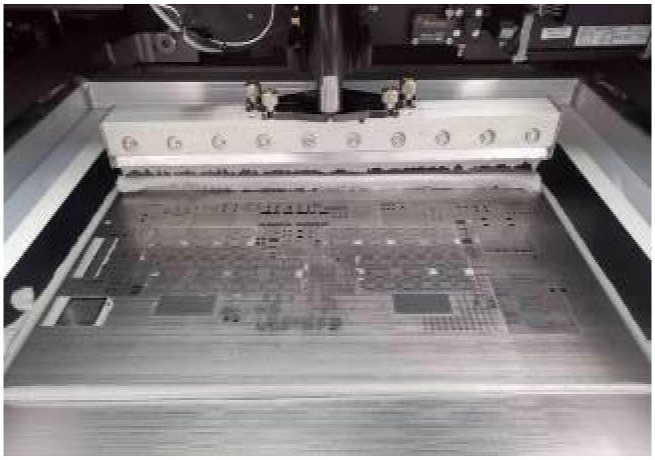
Figure 13. Supplier D Chem-etch stencil – Clean Swipe with Some Paste Residue Only Seen on Areas Close to Step Edge.

Figures 14-16 show paste residue images for other tested stencil suppliers and three types of step technology which are Milled, Laser Weld, and E-form. Visual observation showed the milled stencils had the least paste residue on the step edges. The challenging 3-mil step-down area on the milled stencil showed minimal solder residue after the print process when compared to a Laser weld or e-form stencil. Figure 16 shows an E-form stencil with large paste residue on areas close to the step edge. This can be attributed to the e-form additive process that can lead to variability in step area and height. This could prevent the squeegee blade to make even contact with the stencil surface and leaves paste residue on the step edges. This stencil did not meet Cp requirements and had high variability in paste distribution.

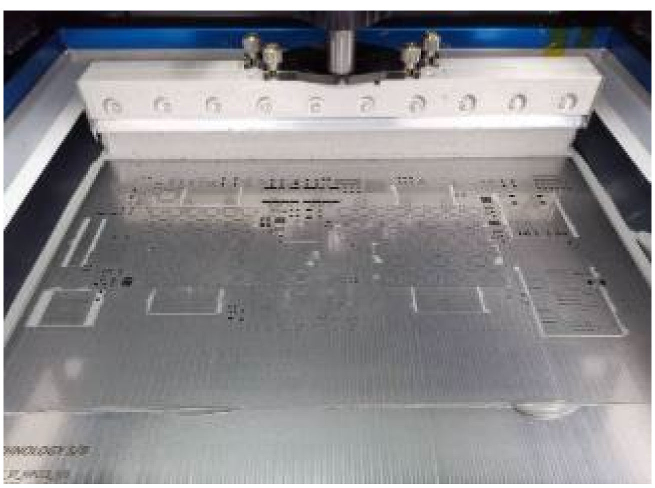
Figure 14. Supplier B Milled stencil – Clean Swipe with Paste Residue Only Seen on Areas Close to Step Edge.

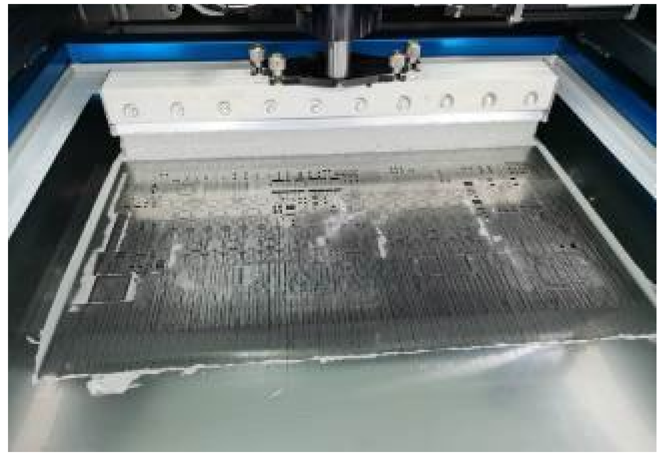
Figure 15. Supplier C Laser Weld Stencil – Clean Swipe with Paste Residue Only Seen on Areas Close to Step Edge.

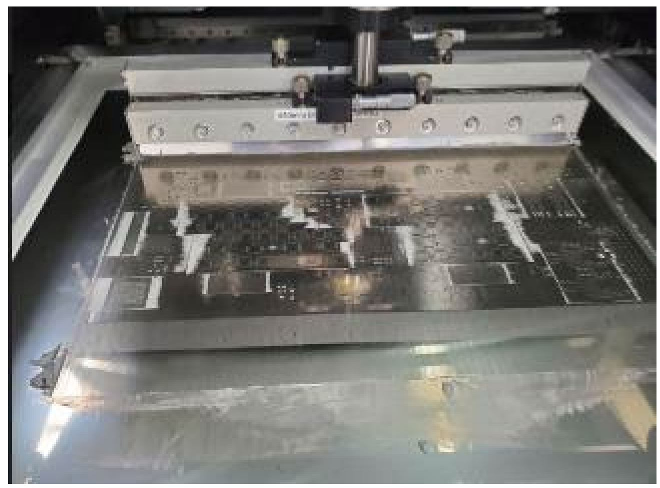
Figure 16. Supplier C E-form stencil, Huge Leftover Paste around Step Edges.

Overall Scoring System

A scoring scheme was developed to create a preference order for different step technologies. This matrix was derived based on many considerations that were initially discussed in this paper. These included process capability parameters, stencil machining quality, and visual observations like step transition and paste residue on the stencil surface and step edges. Additional emphasis was given to the future of step technology, the cost of the stencil, and the lead time to manufacture the given technology. For each parameter, a weighted scoring system was designed where scores of 1, 3, or 5 were assigned to each step technology. A high score denoted good performance whereas a lower score denoted poor performance for that parameter. Table 7 summarizes all studies done in this paper.

Table 9. Step Stencil Scorecard.

Parameter	Weighted Score	Supplier A, Chem Etch	Supplier C, Laser Weld	Supplier D, Chem Etch	Supplier B, Milled	Supplier A, Laser Weld
Cp	1: Below 1 3: 1 to 1.33 5: More than 1.33	1	3	5	5	5
%OOS	1: >5% OOS 3: Any OOS, less than 5% 5: 0% OOS	1	3	3	5	3
Clean Swipe	1: Paste Residue remain 3: Clean swipe	1	3	3	3	3
Stencil Opening Measurement	1: OOC 3: Within the control	1	1	3	1	1
Stencil Thickness Measurement	1: OOC 3: Within the control	1	3	3	3	3
Surface roughness	1: Poor (>20 Sa) 3: OK (10-20 Sa) 5: Very good (<10 Sa)	3	3	3	5	1
Step Transition	1: Poor 3: OK 5: Very good	1	3	3	5	1
Technology	1: Old technology 2: New technology 3: Future roadmap	1	2	1	3	2
Cost	1: More than USD600 2: Less than USD600	2	1	2	1	1
Lead Time	1: More than 7 days 3: Between 4 to 7 days 5: Less than 4 days	5	5	5	5	5
Total Score		**17**	**27**	**31**	**36**	**25**

CONCLUSION

Milled stencil technology showed the capability to meet the technical requirements outlined in our work. The weighted score from critical parameters indicates that Milled step technology outperforms other step technologies in many areas and has a lot of potential to meet future stencil requirements. Milled stencils provide tighter paste Volume% distribution, smooth step transition, and smoother surface finish in addition to all benefits of laser-cut stencils. The cost of milled stencils is comparable to other low-cost step technologies like laser weld and chem-etch stencils. It has the potential to maintain the lowest KOZ which continues to be a critical requirement as we move towards densely populated, mixed-part technology product boards.

Careful considerations should be given to supplier capability before selecting the stencil technology**.** Results indicated that step technology performance is highly dependent on the stencil supplier's capability. We found that each supplier excelled in manufacturing a certain step technology, but they may not be versatile enough to manufacture multiple types of step technology. Thus, when choosing a step technology, it is important to choose the best technology, but at the same time, a thorough assessment of suppliers' capability to manufacture that technology should be done.

REFERENCE

[1] H. Grumm, D. Graupner, "The Potential of Stencil Technology – Choosing the Right Stencil Options to Maximize Yield and Earnings", *International Conference on Soldering and Reliability* (ICSR), 2013.

[2] Robert F. Dervaes, Jeff Poulos, and Scott Williams, "Conquering SMT stencil printing challenges with today's miniature components", *Global SMT & Packaging*, April 2009.

[3] IPC 7525A: Stencil Design Guidelines.

[4] C. Läntzsch, G. Kleemann, "Challenges for Step Stencils with Design Guidelines for Solder Paste Printing," *IPC APEX Expo Proceedings*, 2012.

[5] C. Läntzsch, G. Kleemann, "Influence of Printer Settings on Step Stencil Design," *Proceedings of the SMTA International Conference*, 2012.

[6] G. Smith, T. Lentz, and B. Kuncle, "Step Stencil Technologies and Their Effect on the SMT Printing Process," *Proceedings of the SMTA International Conference*, 2016.

[7] G. Smith, C. Shea, and M. Butler, "Evaluating the Next Generation of Stencil Stepping Technologies," *Proceedings of the SMTA International Conference*, 2018.