Quantitative Evaluation of New SMT Stencil Materials

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Abstract
High yields in the stencil printing process are essential to a profitable SMT assembly operation. But as circuit complexity continues to increase, so do the challenges of maintaining a successful solder paste deposition process. To help assemblers address the challenges presented by evolving technologies, stencil suppliers have provided a variety of options in stencil technology, including new foil materials, manufacturing processes and coatings.

A study was undertaken to quantify the effects of stencil material on paste deposition in high volume production processes. The experiment focused only on laser cut stencils, and compared the typical stainless steel, non-electro polished foils with electro polished stainless steel, fine grain stainless steel, and electroformed nickel. The DOE strived to maintain consistency of all other variables involved in the process, changing only the stencil material. The test vehicle design varied theoretical area ratios from 0.50 to 0.75 in 0.05 increments (actual area ratios varied between 0.48 and 0.77). Output variables were paste deposit volumes, which were expressed as transfer efficiencies based on measured (actual) aperture volumes.

The transfer efficiencies of the four materials are compared and performance differences are discussed. High magnification photographs of the aperture walls provide visual images of the wall topographies. The effect of electro polishing is shown and discussed.

Key Words: Stencil Printing, Stencils, Laser Cut, Electro polish

Introduction
Given the number of factors that influence the stencil printing process, the main challenge of this experiment was to isolate the effect of stencil material alone. To stabilize all other variables in the process, great care was taken to maintain consistent experimental conditions, including tuning and calibration of the laser cutters, controlling the environment during the cutting and printing operations, maintaining the same paste lot and print parameters throughout the test, and measuring the deposit volumes as accurately as possible.

Experimental Setup
The first part of the experimental setup involved the material selection and machine preparation. Four materials were chosen based on availability and economic feasibility, and coded as follows:
- "**A**": 301SS that has been modified such that it's grain size is in the 1-2 micron range, as compared to typical stainless steel with grain sizes in the 20 - 30 micron range.
- "**B**": Nickel - the foil was electroplated on a mandrel as a solid sheet without apertures and then laser cut.
- "**C**": 304SS that has been developed to provide better cutting properties than standard stainless steel and increase the stencil's print life in production - *without electro polishing after laser cutting*.
- "**D**": the same material as stencil C - *with electro polishing after cutting*.

The foils were all pre-stretched on 29 x 29 x 1.5 inch frames, and cut on a LPKF G6080, a state-of-the-art fiber optic laser cutting system that uses oxygen as its gas medium. Prior to cutting, the machines were subjected to a setup routine that

included cleaning of the optics, focusing of the 1mil (25 micron) laser beam, and test coupon validation per a company-defined procedure. Each stencil was cut overnight on sequential nights, following the same setup routine each night. The ambient temperature during the cutting operation was held at 70-72°F.

The electro polishing performed on stencil D was a process developed in-house by the stencil supplier. It varied from many traditional electro polishing processes in that it was optimized specifically for SMT stencils, as opposed to general electro polishing that is often performed on a variety of machined parts by a third party.   The specialized process utilizes modified hardware to ensure uniform current density and continuous agitation of the electrolyte, and offers better control of dimensional stability than traditional electro polishing processes.
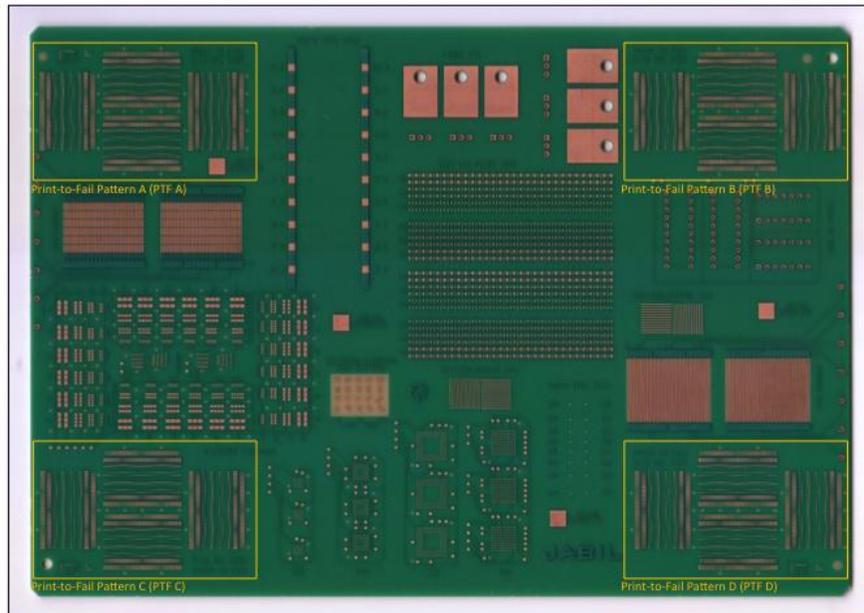

Figure 1. Jabil Print Test Vehicle, 10.0" x 7.0", 0.062" thick (Top Side)
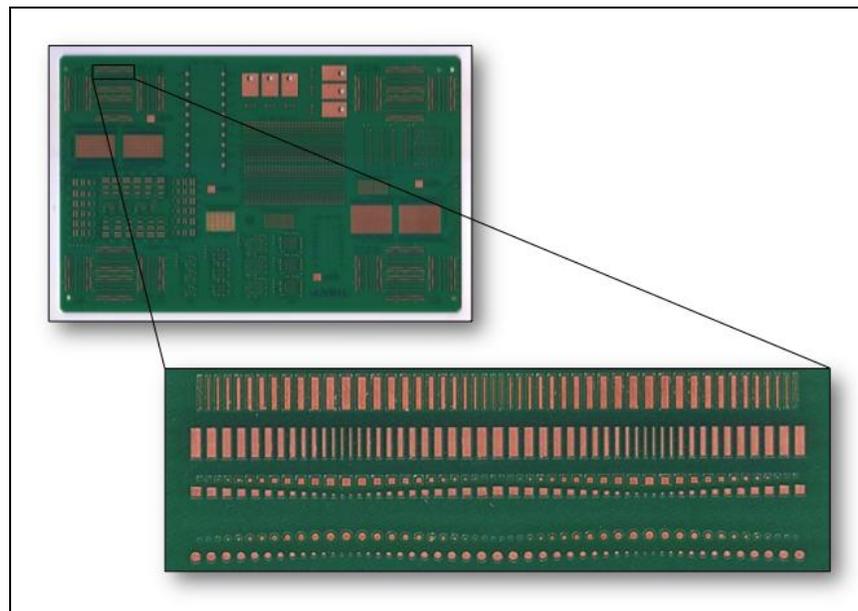

Figure 2. "Print-to-Fail" pattern on print test vehicle

Print tests were performed in Jabil's Global Operations Support and Manufacturing Engineering laboratory in San Jose, California. Jabil's standard print test vehicle, shown in figure 1 was used for this series of tests. The pads in areas labeled "print to fail" (enlarged in figure 2) were used for measurement. The "Print to Fail" test pad design incorporates pads of decreasing size in circular, square and rectangular shapes; solder mask defined (SMD) and non-solder mask defined (NSMD). They provide a wide range of area ratios for printing experiments. They are referred to as the "Print to Fail"

pattern because they act as a meter for quick visual assessment of the finest feature to print acceptably. It should be noted that visual assessment was not employed in this series of tests; the only data collected and reported was generated with automated measurement equipment.

The print test coupons contain copper features of different:
- Size: from 3 to 15 mil; 10 to 15 reported in this test
- Shape: Circular (C), Square (S) or Rectangular (R); C and S reported in this test
- Pad Definition: Solder Mask Defined (SMD) or Non-Solder Mask Defined (NSMD); both reported in this test

Each test board contained 64 features of each combination of shape, size and pad definition. Ten prints were measured for each stencil in the test, providing a sample size of 640 data points for each configuration.

The boards were printed with a popular no-clean, Type 3, lead-free solder paste. The laboratory temperature was held at 77°F ±5°F. A recently calibrated and well-maintained MPM Accela stencil printer was used to print all the test boards at the same parameters throughout the tests. A calibrated and maintained Koh Young 3030VAL automatic solder paste inspection system was used to measure solder paste volumes. The machine uses white light phase shift interferometry technology, and consistently provides a %GR&R of less than 10, indicating excellent repeatability and reproducibility.

Personnel from the stencil manufacturer were present in the test laboratory for the print trials. While the test lab used automated inspection to capture paste volumes, the stencil manufacturer used manual optical inspection to measure paste coverage areas to informally corroborate the readings.

After the tests were completed, the stencils were dismantled for analysis. Aperture walls were examined with a Scanning Electron Microscope (SEM) at 400x and 800X magnification, and the apertures that were used in the print test were measured using an OGP Avant Supra 400.

The pads on the test vehicles were also measured for analytical and reference purposes. They were not used in any calculations; however their size tolerance is a consideration in the analysis.

Results, Observations and Discussion
Aperture sizes
The tolerance specification for laser cut apertures is ±0.5 mil. All of the measured apertures were well within specification. Most of the apertures were slightly smaller (by an average of approximately 0.3mils) than their specified size; the electro polished apertures were slightly larger (by an average of approximately 0.3mils) than their spec. Table 1 shows the average deviation from their nominal size.

Table 1. Measured aperture sizes (PCB side)

Material	Shape	Dev. From Nom. (mils)
A	S	-0.225
A	C	-0.338
B	S	-0.375
B	C	-0.363
C	S	-0.225
C	C	-0.165
D	S	+0.313
D	C	+0.375

Again, the actual aperture measurements were used to calculate the actual area ratios of each aperture and the actual volumes of each aperture. All four stencil foils were measured as 5.00 mils thick.

Print Performance
Transfer efficiency (TE) is a measure of how much solder paste has been released from the apertures. It is calculated by dividing the volume of solder paste in a deposit by the volume of its aperture, and expressing the quotient as a percent. The Area Ratio (AR) of a stencil aperture is calculated by dividing the area of the PCB-side aperture opening by the surface area of the aperture walls. TE is often plotted as a function of AR as a means of characterizing a stencil printing process, and is commonly used to evaluate pastes, stencils, aperture designs and other items associated with solder paste printing.

It is generally recommended that, for most SMT processes using Type 3 solder pastes, ARs should be 0.66 or greater. At ARs greater than 0.66, TEs should be 80% or more.[1] At ARs between 0.5 and 0.66, print behavior is generally less predictable but good quality can be achieved using advanced print technologies. ARs below 0.5 are not recommended for Type 3 solder pastes.

Note that for both aperture volume and AR calculations, the dimensions of the apertures can either be measured or estimated (as the specified dimension). Sometimes the use of estimates – often called *theoretical* volumes or ARs – is acceptable, as in cases where the same stencil is used for all prints. For purposes of the current study however, where the stencil themselves are being compared and the sizes vary from nominal, the actual volumes and ARs were required.
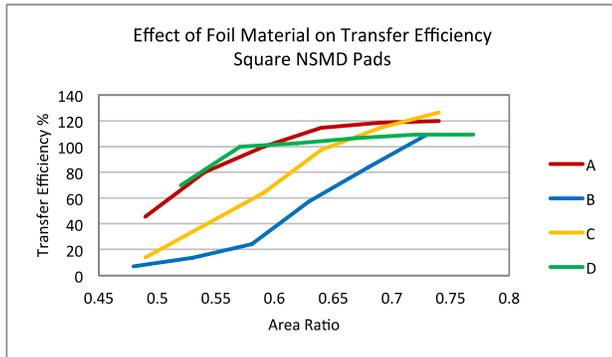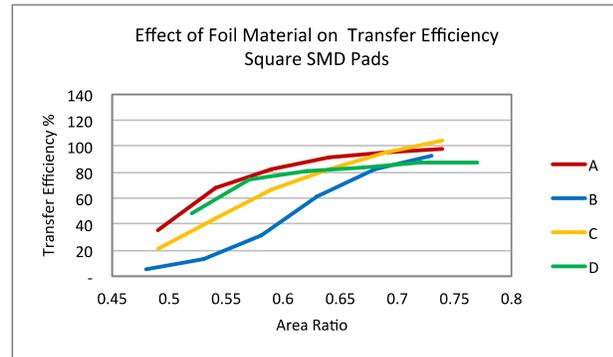

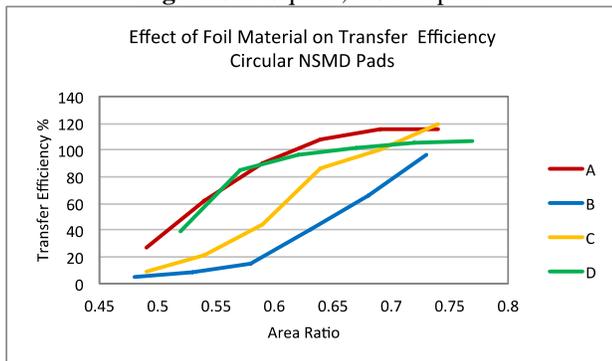**Figure 3a.** Square, NSMD pads

Figure 3b. Square, SMD pads

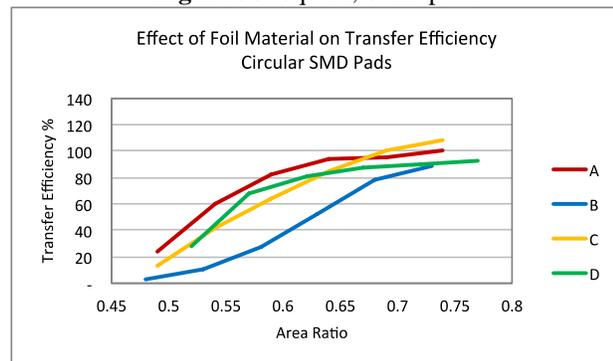**Figure 3c.** Circular, NSMD pads
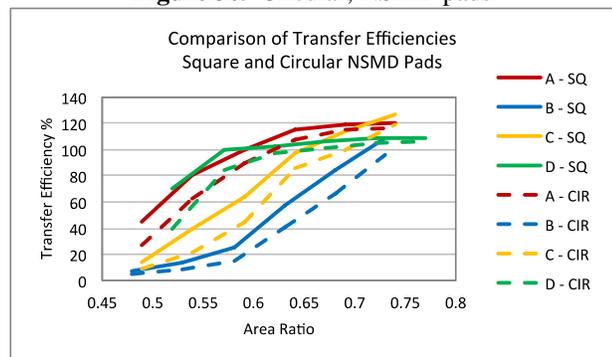

Figure 3d. Circular, SMD pads

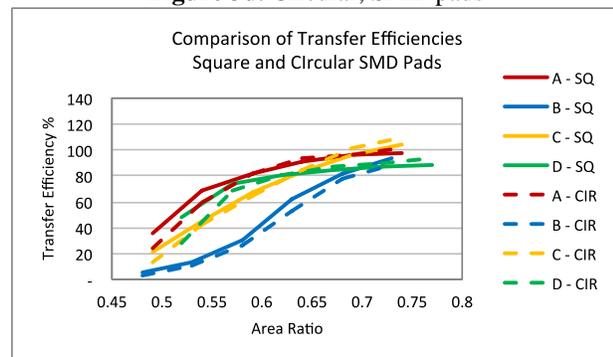**Figure 3e.** Square and Circular, NSMD pads

Figure 3f. Square and Circular, SMD pads

Figures 3a – f. Actual transfer efficiencies of different foil materials of print features of varying size, shape and pad definition.

Transfer efficiency is plotted against area ratios in figures 3a – f. The trends were clear and repeatable for all experimental configurations. Materials A and D consistently provided the highest material transfer rates at lower area ratios, and the most stable transfer rates in the acceptable printing range above 0.66. Material C performed well at area ratios above 0.66, releasing more than 80% of its aperture volume, but its performance fell off sharply below 0.66. Material B was the worst performer in nearly every case.

As expected, square apertures released better than circular ones. Comparison of SMD vs NSMD pads was not performed due to their relative size differences. The SMD pads averaged approximately 0.5mil undersized, while the NSMD pads averaged almost 2mils undersized. Comparison of transfer efficiencies would not be appropriate under this circumstance, and could lead to erroneous conclusions regarding pad design.

The slopes of the trend lines indicate the robustness of the process. Flatter slopes are desired over steeper ones, because they indicate less effect of natural variation of the input variables (AR) on the output (TE). Again, materials A and D demonstrated the best response. Material A shows good stability above the 0.66 benchmark; material D shows good stability at 0.57 and above. Material D also showed 80% or more transfer efficiency down to a 0.57 AR in most cases.

The distribution of the data can be observed in the boxplots in Appendix A.
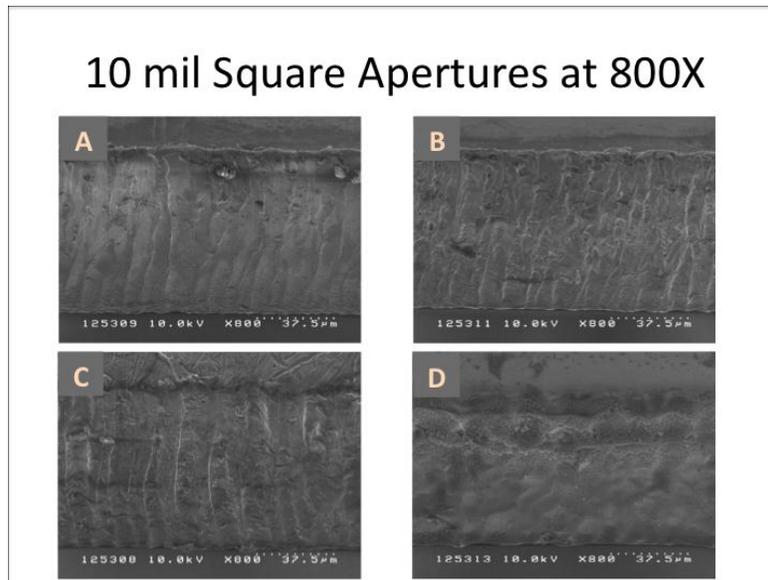
Aperture Wall Finish

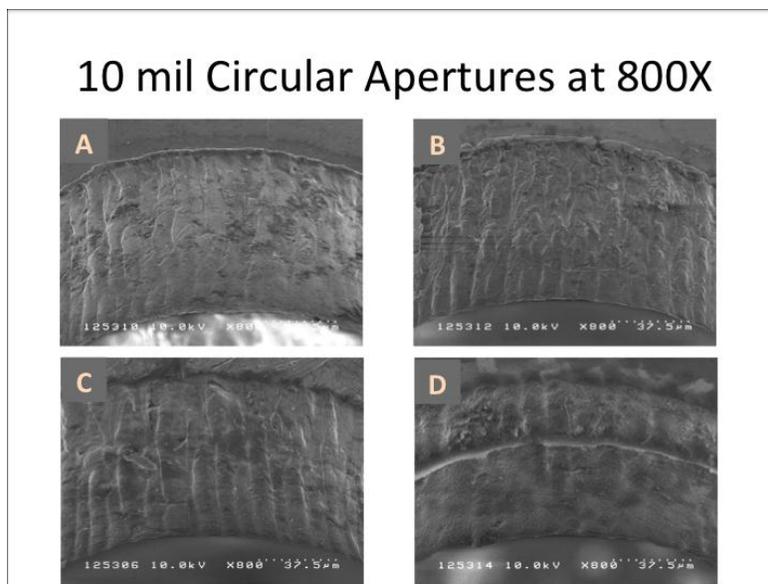**Figure 4.** SEM micrograph of the square aperture walls

Figure 5. SEM micrograph of the circular aperture walls

Aperture walls were examined with a Scanning Electron Microscope (SEM) at 400x and 800X magnification. The 800X images of the square apertures can be seen in figure 4, and the circular ones in figure 5.

Materials A and D appear to have smoother surfaces than materials B and C. Material C and D are the same, except D was electro polished after laser cutting.
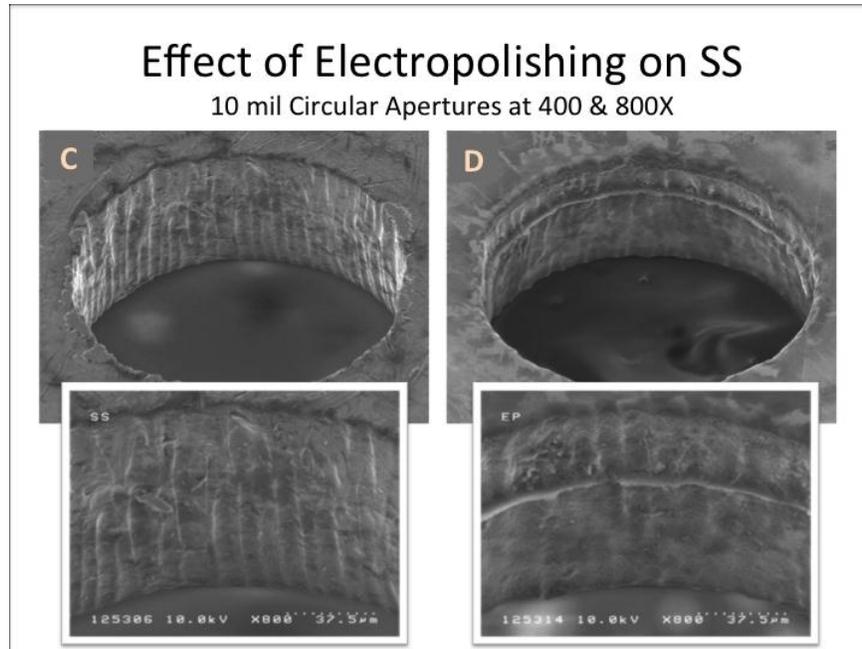

Figure 6. Effect of electro polishing on aperture walls. Both stencils were cut from the same material.
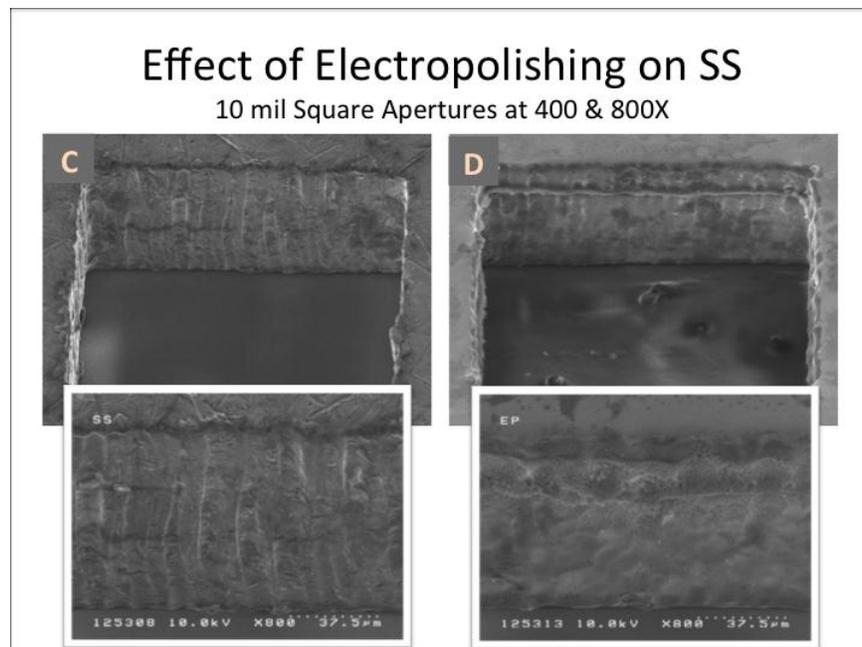

Figure 7. Effect of electro polishing on aperture walls. Both stencils were cut from the same material.

The effect of electro polishing material C is shown in figures 6 and 7. In both cases, the topography of the walls of the electro polished aperture appears much smoother than the unpolished aperture. Additionally, a small ridge is visible on the polished aperture. It is unknown if this ridge influences material release.

Cross sections of the apertures of materials C and D were prepared and examined with optical microscopy.
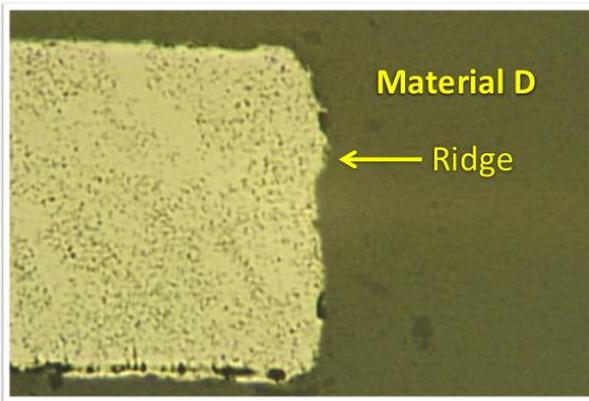
Figure 8a. Cross section of laser cut, electro polished stainless steel foil
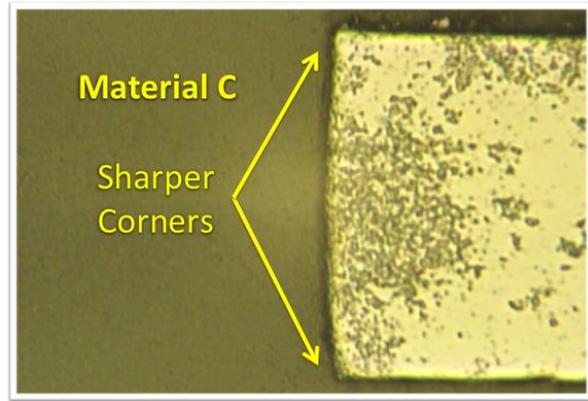

Figure 8b. Cross section of laser cut, non-electro polished stainless steel foil

Figure 8a shows the electro polished wall and 8b shows the non-electro polished wall. The ridge that appears so prominently on the SEM is visible, but does not appear to be as pronounced as it was in the SEM micrographs. Additionally, the corners of the electro polished wall appear more rounded than those on the non-electro polished wall.

The slight rounding of the corners is a well-known attribute of the electro polishing process, but the ridge formation was not expected. A separate study is underway to evaluate and understand the effects of electro polishing on different materials.

Conclusions
The apertures in materials A, B and C were all slightly undersized, by up to 0.3mils. The apertures in material D were slightly oversized by a similar amount. All foils were cut on the same laser cutter; foil D was electro polished after cutting.

The two materials that provided the best transfer efficiency were materials A and D. Material D showed the most predictable response across the area ratio range of 0.57 to 0.73.

Materials A and D also showed the smoothest walls when observed at high magnification. A relationship between the surface roughness of the walls and the release performance of the stencil is noted, but not quantified. The aperture walls that appear smoother provided better solder paste release, especially at area ratios at or below 0.66.

A ridge was observed in the walls of the electro polished apertures; a separate study to optimize the electro polishing process will address the ridge formation and aperture size variance.

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References
1. Shea, C, et al, "Characterizing Transfer Efficiencies and the Fine Feature Stencil Printing Process," *Proceedings of SMTA International*, September, 2005.
2. IPC, "IPC-7525A Stencil Design Guidelines," February, 2007.

APPENDIX A

Boxplots of Results

NSMD Pad / Circular Aperture C10-C15 / 0.005" Foil Thickness

NSMD Pad / Square Aperture S10-S15 / 0.005" Foil Thickness

SMD Pad / Circular Aperture C10-C15 / 0.005" Foil Thickness

SMD Pad / Square Aperture S10-S15 / 0.005" Foil Thickness