Impact of Stencil Foil Type on Solder Paste Transfer Efficiency for Laser Cut SMT Stencils

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ABSTRACT
There are many different metal foil types being used by stencil manufacturers in today's SMT market. Some of these materials include standard 300 series stainless foil, fine grain foil, electroplated nickel foil along with other specialty foils optimized for the laser cut stencil industry. This paper will investigate laser cut wall quality on the different foils as well as the effectiveness of these foil types in relation to solder paste printing both with and without nano-coatings. Results will be presented along with strengths and weaknesses of different foil types to aid the end user in making proper stencil choices.

Keywords: SMT stencil, stencil printing, laser cut stencil, stencil foil material, SMT stencil quality, solder paste printing

INTRODUCTION
As innovation and demand continue to drive miniaturization in electronics, manufacturers face the constant challenge of assembling smaller and smaller components with repeatable processes and high yields. Stencil printing is the first step in the PWB assembly process and improvements to the SMT stencil can significantly improve yields, especially for more challenging miniaturized products [1]. The primary inputs in the SMT stencil manufacturing process are material, equipment and processes and by continuously improving these inputs the overall print process is improved.

The most important material in the process of manufacturing SMT stencils is the foil itself. This paper investigates foil types used with the goal of determining which foils provide the best print performance. The two foil alloys examined are stainless steel and electroformed nickel sheet and each material will be measured with and without the application of ceramic nano-coatings. There have been many claims by stencil manufacturers in the industry over the past several years that fine grain foils cut and release solder paste better than other more standard stainless steel foils. However, the term "Fine Grain" has been used loosely and has not been well defined. Some users see print improvements using fine grain materials and some do not. This paper correlates print performance to grain size of each material tested and seeks to determine if foil grain size is a primary factor in obtaining optimal print performance.

The term "print performance" is characterized by assessing transfer efficiency as well as print variation across a range of area ratios on both uncoated and ceramic, nano-coated stencils for each material. SEM photographs are also presented showing the surface topography of the sidewalls of the apertures after laser cutting. The SEM results are compared to the paste transfer efficiencies of each material to better understand how aperture wall surface smoothness compares to SMT stencil performance. This study will show that the base foil used to manufacture SMT stencils does in fact play an important role in overall stencil performance and is one of the most important inputs to provide the most consistent print process.

EXPERIMENTAL METHODOLOGY
A test vehicle was created that would show transfer efficiency over a wide array of area ratios. All seven materials are five-mils thick (125 microns) and a rounded square was used to design each aperture. Each area ratio includes 100 apertures. The test vehicle is shown below (Figure 1).

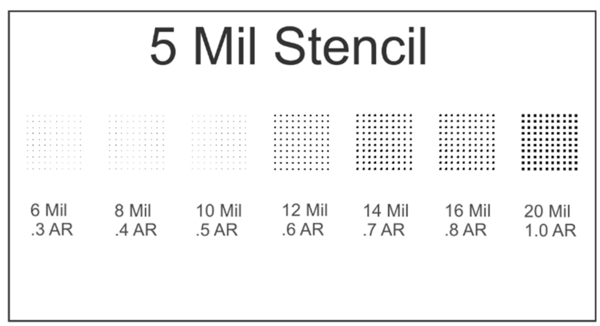

Figure 1: Test Vehicle.

Two test vehicle patterns were laser cut into each stencil. One pattern on each stencil was coated with a ceramic nano-coating and the other pattern was not coated. Two coupons were also cut into the top left and top right corners of each stencil. The coupons were outlined with a perforated pattern so they could be removed and sent for SEM processing. The overall stencil image and coupon is shown below (Figure 2).

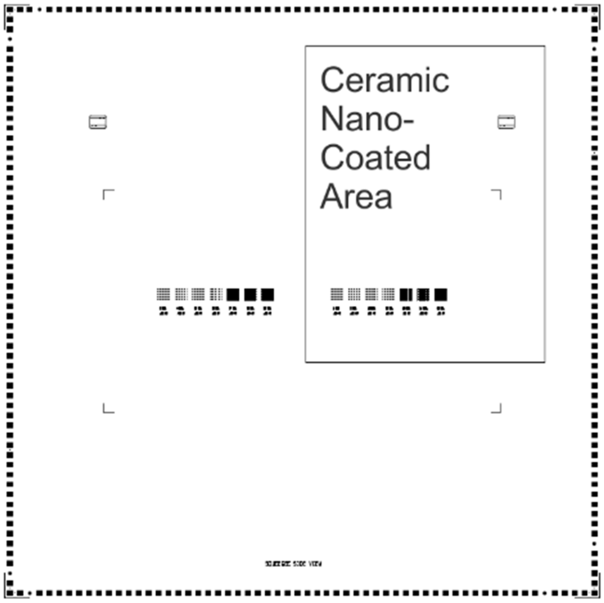

Figure 2. Test Stencil.

The coupon used for SEM photographs is also shown below (Figure 3).

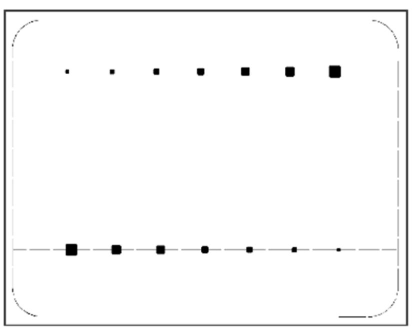

Figure 3: Test Coupon.

The test coupon consists of two rows of apertures. Each row has one aperture of each size present in the test vehicle from 0.3 to 0.8. When cutting the coupons, each aperture was initially laser cut and then a series of cuts were made across the midpoint of each aperture so that the coupon could be easily divided in half after being removed from the stencil. This allowed the SEM equipment to look directly into the sidewalls of the apertures. All stencils were cut on the same stencil on the same day with the same settings. The laser used was the most advanced stencil cutting laser currently in the market. One of the two patterns on each stencil was then coated with the same ceramic nano-coating equipment on the same day and each was cured with the exact same parameters.

A ten-print study was run for each material type using a popular no clean SAC305, Type 4 solder paste. The stencils were printed on bare copper clad material 0.062” (1.57mm) thick using an SMT carrier fixture holding two copper clad PWB’s (Figure 4). This allowed both the uncoated and coated image to be printed at the same time minimizing as many variables as possible. The printer was a DEK Horizon 02i. Print parameters are show below (Table 1).

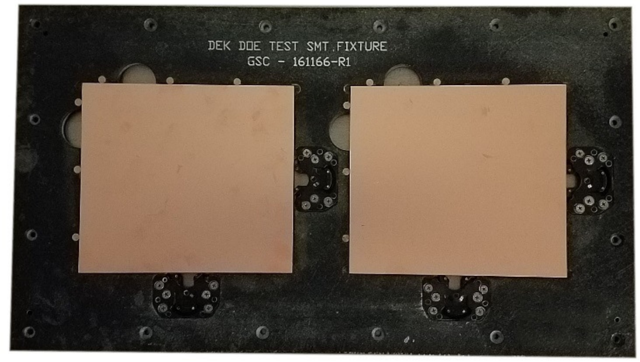

Figure 4: SMT Carrier Fixture.

Table 1: Solder Paste Printer Parameters.

Parameter	Value
Squeegee Length	600 mm
Squeegee Pressure	10 Kg
Squeegee Speed	30 mm/sec
Squeegee Angle	60 degrees
Separation Speed	1.0 mm/sec
Cleaning Solvent	IPA
Solder Paste	NC SAC305 T4

Solder paste volumes were measured using a 3D solder paste inspection system (SPI). The solder paste volume data was analyzed using statistical analysis software and the results were presented.

Seven different materials were evaluated and are listed in the table below (Table 2). Grain size is grouped into 3 categories. Category A includes stainless steel with grain sizes between 1-5 microns. Category B includes stainless steel with grain sizes between 6 and 10 microns and Category C includes stainless steel with grain sizes over 10 microns. Grain size was not measured but was provided by the metal manufacturer. Category A is included in the “Fine Grain” category and grain size was not available for the electroformed nickel material. For the purpose of this paper, “Fine Grain” material is defined as material with a grain size less than 5 microns.

Table 2: Materials Tested.

Material	“FG”	Description	Grain Size Category
1	Yes	Stainless	A
2	No	Stainless	B
3	N/A	Ni	N/A
4	N/A	Ni	N/A
5	No	Stainless	C
6	Yes	Stainless	A
7	Yes	Stainless	A

RESULTS

Transfer Efficiency -Uncoated Metal Stencils

Initially, all 7 materials were printed and the uncoated stencil data was analyzed for all area ratios of apertures. The top performers were identified based specifically on transfer efficiency in this analysis. The results are seen below (Figure 5) and show that materials 1 and 2 exhibit better print transfer efficiencies with uncoated apertures than the other materials.

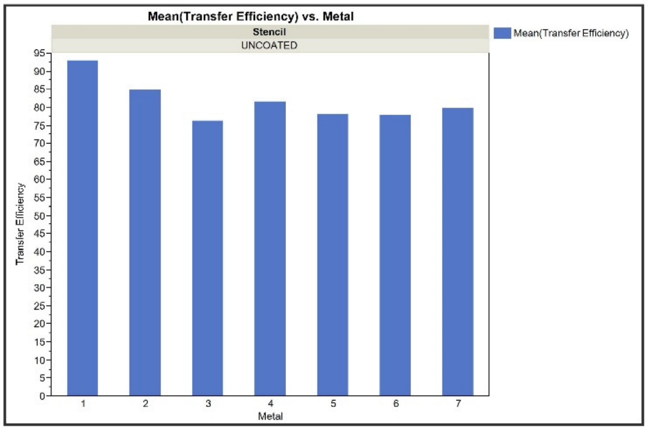

Figure 5: Transfer Efficiency of Uncoated Stencils: All area ratios and metal types.

Since small area ratio printing is key in product miniaturization, it is important to determine which uncoated material performed the best from 0.3 thru 0.5 area ratios. These area ratios are defined as small area ratio printing because they are below the recommendation in IPC7525B standard of 0.66 [2]. The following figure (Figure 6) shows the results for 0.3, 0.4 and 0.5 area ratio apertures only.

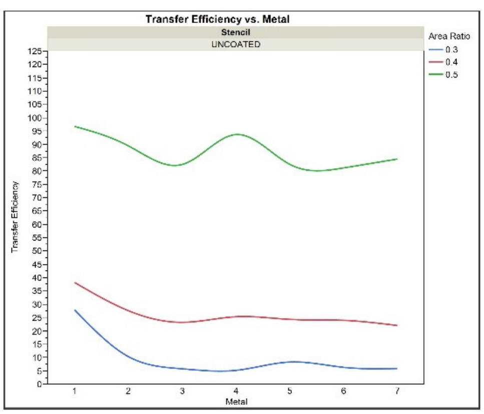

Figure 6: Transfer Efficiency of Uncoated Stencils: All metals, 0.3, 0.4 and 0.5 area ratios.

As shown above, metal 1 has the highest transfer efficiency results versus the other metals for the 0.3, 0.4 and 0.5 area ratio prints. It also outperformed the second-best material, material2, when comparing the means by over 15%. Material 2 shows a 5% improvement over the third best material when comparing mean transfer efficiencies (Table 3).

Table 3: Mean Transfer Efficiency of Uncoated Stencils for 0.3, 0.4 and 0.5 Area Ratios for all metal types.

Material	0.30 Area Ratio	0.40 Area Ratio	0.50 Area Ratio
1	28.04	38.31	96.85
2	10.45	27.71	89.6
3	5.94	23.35	82.46
4	5.31	25.49	93.95
5	8.49	24.44	82.52
6	6.45	24.12	81.32
7	6.05	22.14	84.63

Another interesting observation is that at 0.5 area ratio, the differences in transfer efficiency results increase significantly vs the 0.3 and 0.4 area ratios with materials 1, 2 and 4 easily surpassing the 80% transfer efficiency numbers typically required to pass SPI. Using Tukey-Kramer HSD, material 1 is statistically the best performing material when measuring transfer efficiency on small area ratio apertures (Figure 7) and material 2 are statistically in the second best performing group for transfer efficiency with the highest mean transfer efficiency in that group.

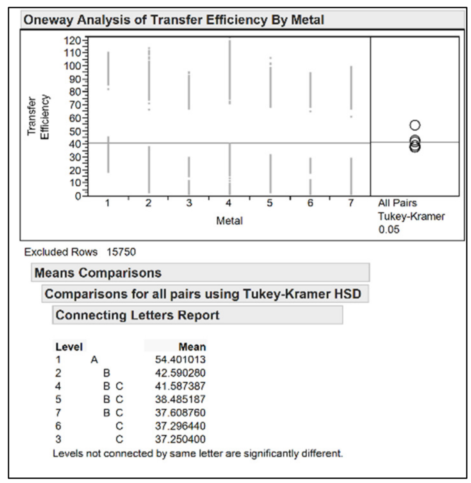

Figure 7: Tukey-Kramer HSD on Transfer Efficiency for Area Ratio 0.3, 0.4 and 0.5.

The final analysis on uncoated stencil foils is to examine larger area ratios to understand if material type affects transfer efficiency. All materials where observed printing at area ratios 0.6, 0.7 and 0.8. The following chart shows the results (Figure 8).

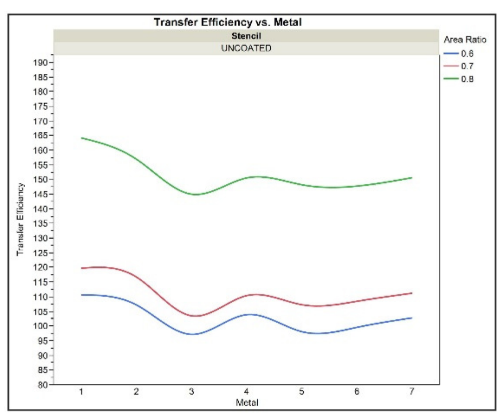

Figure 8: Transfer Efficiency of Uncoated Stencils: All metals, 0.6, 0.7, and 0.8 area ratios.

Once again, it can be observed that metal 1 and 2 outperform the others when measuring transfer efficiency for the larger area ratios. Mean transfer efficiency for metal 1 was greater than the mean of metal 2 by just under 5% and the mean transfer efficiency for metal 2 was 5% better than the next best performing metal 4. Again, we see a large increase in transfer efficiency when moving from 0.6 and 0.7 area ratio printing to 0.8 area ratio printing.

Transfer Efficiency-Ceramic Nano-Coated Metal Stencils

Ceramic nano-coated metal stencils are becoming more widely used in today's assembly environment to achieve the best print possible, especially for low area ratio printing. It has been shown in previously published papers these coatings improve transfer efficiency by 10% up to 24% [3] based on the size of the aperture and the brand and particle size of solder paste being used. To properly evaluate the different metal materials being used to manufacture SMT stencils, it is important to include the ceramic nano-coating technology in this study. The objective is to evaluate if specific material types improve the effect of the coating technology.

Initially, all seven metal foils were analyzed for all area ratios. Again, the top performers were identified based specifically on transfer efficiency. The image below shows the results of both uncoated and coated stencil materials for all area ratios combined (Figure 9).

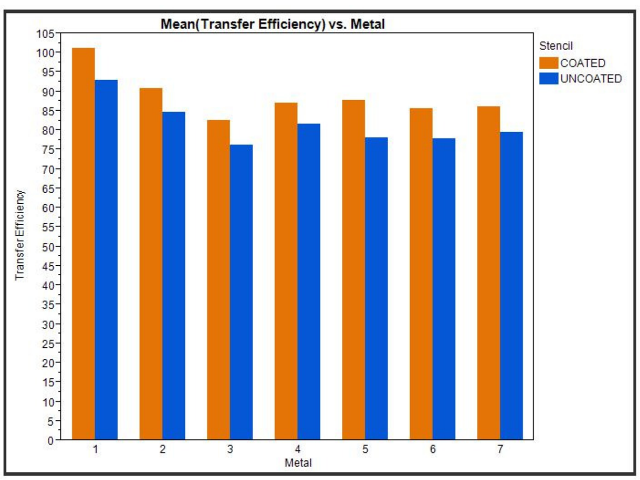

Figure 9: Transfer Efficiency for Coated and Uncoated Stencils for All Metals and All Area Ratios.

The top performers for ceramic nano-coated stencils for all area ratios measured are materials 1 and 2. When measuring the mean transfer efficiency of the coated stencil vs uncoated stencil, material 1 improves transfer efficiency by 8.2%. Material 2 shows an improvement with coating of 6.5% vs the uncoated material. Comparing coated stencil transfer efficiency, material 1 improves transfer efficiency 10.2% more than material 2. Material 2 improves transfer efficiency more than material 4, the third best performer, by just under 4%. One can also see that the improvement in transfer efficiency created by the ceramic nano-coating technology closely follows the release characteristics of the base metal being cut. This phenomenon shows the importance of selecting the best possible base material in the stencil manufacturing environment.

To further evaluate the ceramic, nano-coating technology it is critical to look at small area ratio printing defined in this paper as apertures with area ratios of 0.3, 0.4 and 0.5. The image below (Figure 10) shows the improved release characteristics with the addition of the ceramic nano-coating.

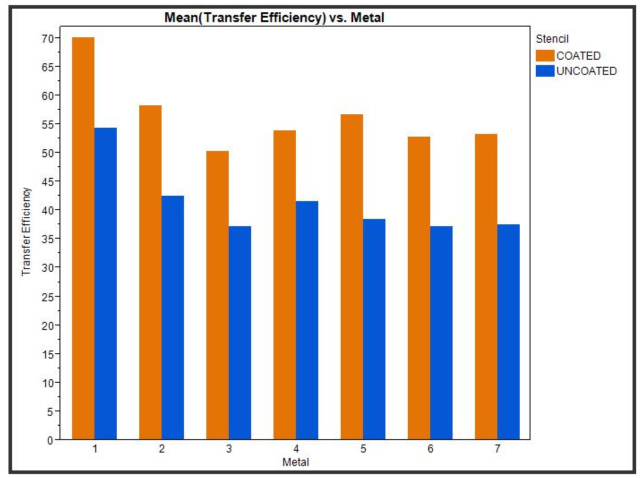

Figure 10: Transfer Efficiency for Coated and Uncoated Stencils for All Metals with 0.3, 0.4, and 0.5 Area Ratios combined.

The coated material exhibiting the best mean transfer efficiency for area ratios of 0.3, 0.4 and 0.5 combined is material 1. When averaging these three area ratios, an increase in mean transfer efficiency with the ceramic nano-coating is 16% versus the uncoated stencil. Material 2 with the coating technology had the second highest mean transfer efficiency improvement of just under 16% as well. Overall, a larger improvement in transfer efficiency is seen on small area ratios with the application of the ceramic nano-coating technology versus the larger area apertures. Again, it should be noted that the improvement in solder paste release from the nano-coated stencil follows the transfer efficiency of the base material especially on small area ratio apertures.

Currently most stencil providers limit lower area ratios to 0.6 to maintain proper release and volume to achieve acceptable solder fillets after reflow. Observing the data in the chart below (Figure 11) one can see that material 3, 5, 6 and 7 are close to 80% transfer efficiency on 0.5 area ratio apertures with no coating (blue bars) and materials 1, 2 and 4 are just at or over 90% with no coating (blue bars). When the ceramic nano-coating is added, the transfer efficiency mean for material 1 increases 28% to 125% (orange bars). With the best base material and the ceramic coating technology, small aperture printing at 0.5 area ratios is now possible.

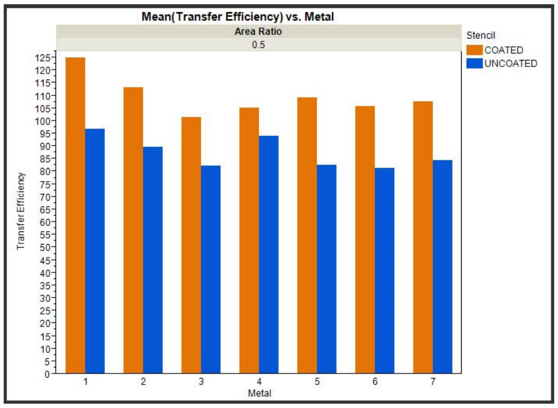

Figure 11: Transfer Efficiency of Coated and Uncoated Stencils for all metals and for Area Ratio of 0.5.

Transfer Efficiency-Grain Size Comparison

Almost all metals are crystalline in nature and contain internal boundaries known as grain boundaries. As new grains are nucleated during processing, atoms line up in a specific pattern common to the crystal structure of the alloy. Each grain eventually impacts others and forms an interference where the atomic orientations are different [4]. These areas are known as grains. Grain size is normally determined by processes such as heat treatment and cooling rates during the alloy extrusion process. Typically, it is accepted that most mechanical properties improve as the size of grains decrease. An example of grain structure is seen in the image below (Figure 12).

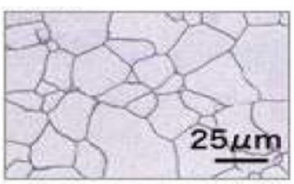

Figure 12: Example of Metal Alloy Grain Structure.

For several years, SMT stencil vendors have offered "Fine Grain" metals to the industry with the benefit of improved print processing. Initially, only one vendor offered this material to stencil manufacturers and over the past several years, more vendors have offered "Fine Grain" metals to the industry. This investigation identifies "Fine Grain" material as foil with grain sizes of less than 5 microns. To better understand print performance with these "Fine Grain" alloys, we have divided grain sizes into three categories. Category A materials have a grain size of 1-5 microns, Category B materials have a grain size of 6-10 microns, and Category C includes materials with grain size more than 10 microns.

The graph below (Figure 13) shows transfer efficiency of all area ratios based on grain size. Both category A, grain sizes 1-5 microns and category B, grain sizes 6-10 microns produce higher transfer efficiency results than category C with grain sizes of higher than 10 microns. The uncoated stencil shows a slight improvement in transfer efficiency for category A vs category B when looking at all area ratios.

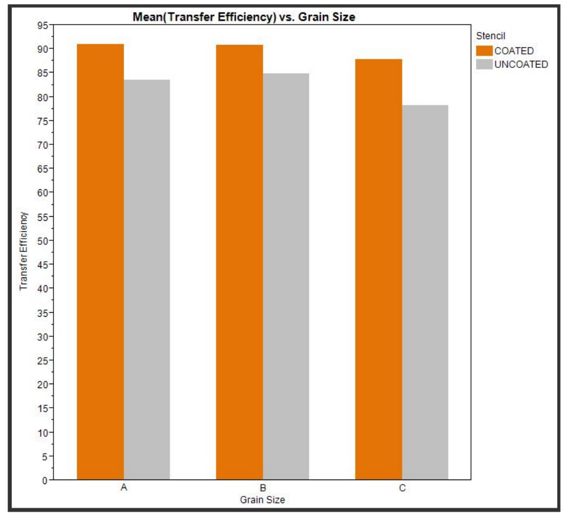

Figure 13: Transfer Efficiency vs Grain Size for all Area Ratios.

Looking more closely at the effects of grain size on print performance, the graph below shows transfer efficiency results for small area ratios, 0.3, 0.4 and 0.5, based on the grain size of the metal (Figure 14). Both categories A and B show very similar solder paste release characteristics and both exhibit improved transfer efficiency versus category C grain sizes. It should also be noted that adding the ceramic nano-coating improves category C transfer efficiency more than the others. Finally, when the transfer efficiency of the two nickel materials are averaged together the nickel material releases solder paste similar to the category C grain size stainless steel prior to coating. However, the nickel alloy does not release paste as well as the stainless-steel alloys with the addition of the coating technology.

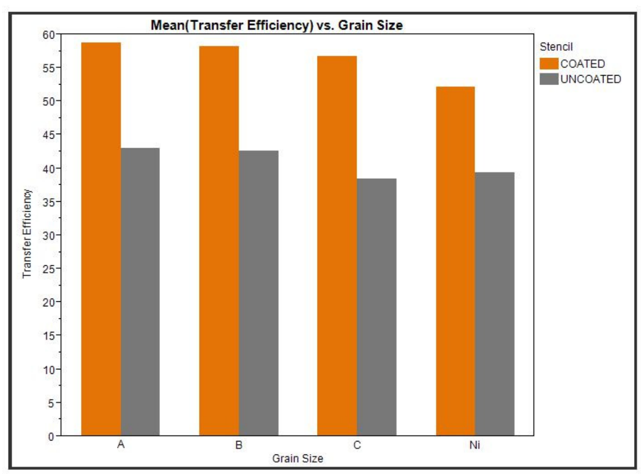

Figure 14: Transfer Efficiency by Grain Size for 0.3, 0.4, 0.5 Area Ratios.

Variation in Print Process

Transfer efficiency is one key indicator of stencil print performance, however, one must also investigate whether specific metals improve variation in the print process. The Coefficient of Variation, or CV is the standard deviation of the print volume measurement divided by the mean of the measurements. Comparing the CV of each material with and without nano-coating will provide another tool for identifying the best performing materials. A CV of 10% or less will be considered acceptable for this comparison and is typically considered good [1].

The following chart (Figure 15) shows CV percentages for the 0.5 area ratio both with and without the coating. When looking at top performing materials, this percentage must be less than 10%.

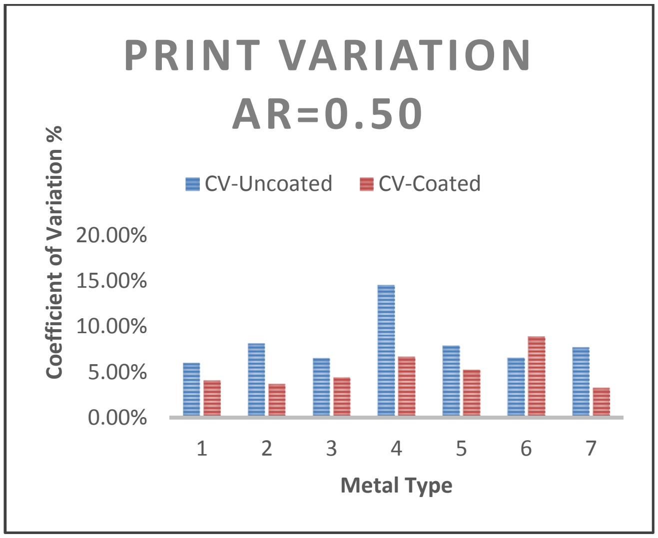

Figure 15: Coefficient of Variation by Metal Type.

Looking at the graph above, it can be seen that uncoated CV percentages are below ten percent except material 4. Although material 4 performed well when observing transfer efficiency, it is the worst performer when looking at print variation. Material 1 once again exhibits the best results when specifically looking at print variation. Another observation when looking at this data is the stencils with ceramic nano-coating all exhibit lower CV percentages except material 6. Material 4 exhibited the largest decrease in CV with the ceramic coating technology lowering the CV by 54%. Overall, CV percentages were lowered for each material by 32% to 57% with the addition of the coating technology. Since material 1 and 2 exhibited overall the best transfer efficiency results and also have CV percentages below ten percent, they are the two top contenders for best performing stencil material when evaluating both transfer efficiency and print variation (Table 4).

Table 4: Transfer Efficiency (TE) and Coefficient of Variation for all metals with 0.5 Area Ratio

Material	TE-Uncoated	CV-Uncoated	TE-Coated	CV-Coated
1	96.85	5.99%	125	4.06%
2	89.6	8.10%	113.4	3.67%
3	82.46	6.48%	101.59	4.38%
4	93.95	14.56%	105.08	6.65%
5	82.52	7.88%	109.3	5.22%
6	81.32	6.54%	105.68	8.88%
7	84.63	7.68%	107.57	3.25%

Aperture Sidewall Images

SEM photographs were obtained for each of the material types and an attempt was made to correlate these images to print performance. The images below are SEM's of aperture sidewalls of the coupons described above. Material 1 was the best performing material for both transfer efficiency and print variation and can be seen in the first image below (Figure 16).

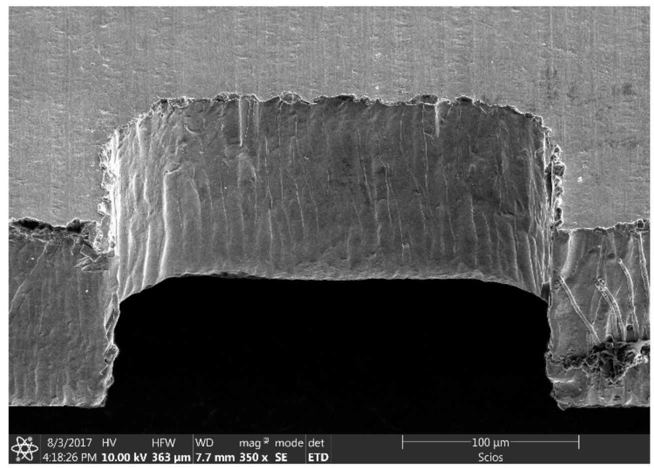

Figure 16: SEM of Uncoated Aperture Sidewall, Material 1

The second best performing material was material 2. An SEM of the aperture sidewall of the coupon is shown below (Figure 17).

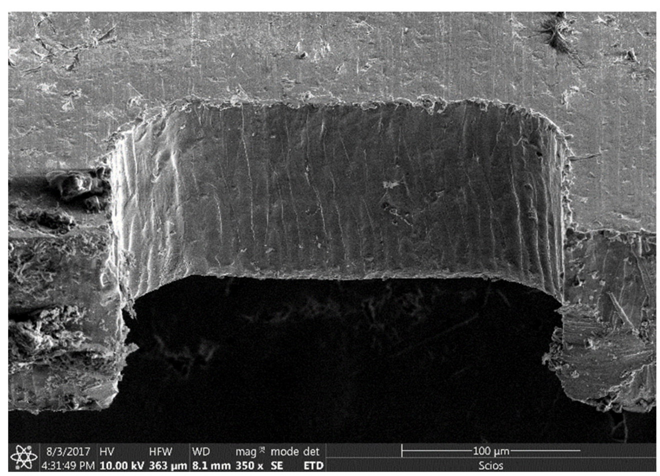

Figure 17: SEM of Uncoated Aperture Sidewall, Material 2

To understand these SEM images, one must understand the laser cutting process. When laser cutting SMT stencils, the laser always penetrates the foil from the bottom or board side of the stencil. This is the side that has the smoothest cut at the foil surface. Paste release is optimized with the smoothest cut side facing the PWB during printing. Initially, the laser penetrates the foil away from the center of the aperture. As the laser beam melts thru the metal, an assist gas pushes the molten metal away from the foil. Once the beam burns thru the metal, it moves toward the edge of the aperture and then follows the path of the aperture design. The laser cuts with a series of energy pulses. You can see these pulses in these SEM photos. As the molten metal is removed by the assist gas, some material may freeze just at the surface and most stencil manufacturers remove this with a secondary process. By properly maintaining the laser settings including focus and energy settings, optimal cut quality will result. For both materials 1 and 2 above, both sidewalls are clean and the corners are smooth. When comparing these two SEM photographs to the worst performing material below (Figure 18) one can see that aperture wall smoothness, or in this case roughness, correlate to lower transfer efficiency and higher coefficient of variation.

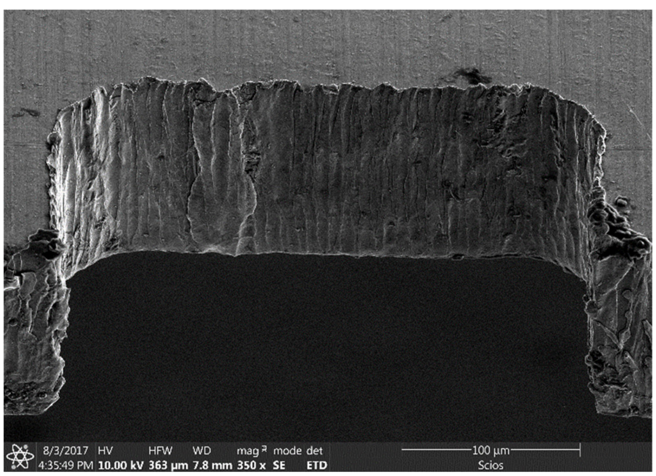

Figure 18: SEM of Uncoated Aperture Sidewall, Material 3

In the image above (figure 18), one can see more defined striations and overall a rougher surface. This surface tends to "hold" the solder paste and prevent good release. Material 5 and 6 were average performers in this analysis. These images are shown below (Figure 19).

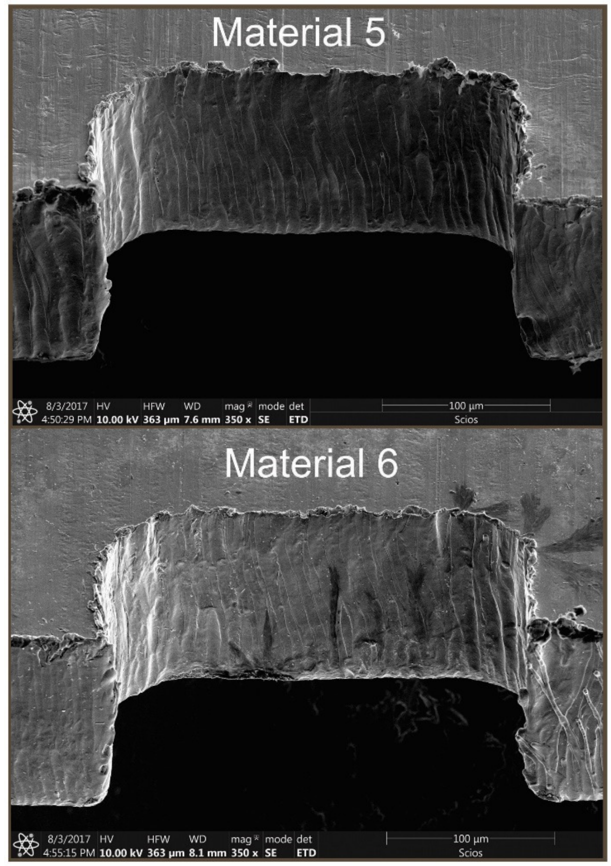

Figure 19: SEM of Uncoated Aperture Sidewall, Material 5 and 6

Finally, the image below (Figure 20) shows the aperture sidewall after coating with the ceramic nano-coating technology. The coating fills in the striations created during the laser cutting process and creates a smooth surface that is both hydro-phobic (repels water based materials) and oleo-phobic (repels oil based materials). This smooth surface not only allows the solder paste to release from the apertures more easily than an uncoated surface, it repels the fluxes in the solder paste to allow the surface of the PWB to easily pull the solder paste from the apertures. The results, as seen in the data presented, are better transfer efficiency and reduced coefficient of variation.

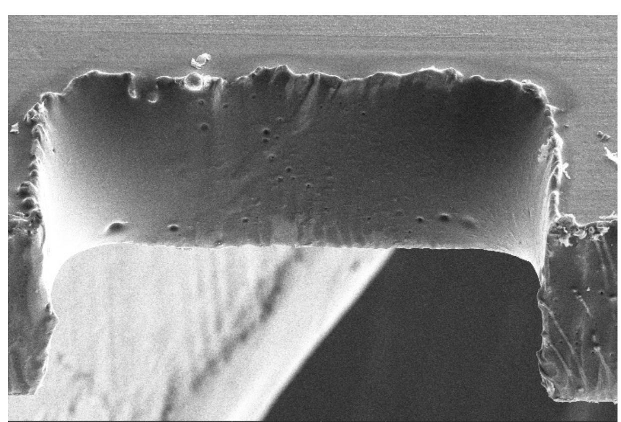

Figure 20: SEM of Ceramic Nano-Coated Aperture Wall

CONCLUSIONS

There are many choices of stencil material for SMT stencil manufacturers to utilize in their process and many of these materials claim to be "Fine Grain". This study looked at seven different materials and quantified those materials for overall print performance. Material 1 was the best overall performer when measuring transfer efficiency and coefficient of variation. This material fell into the "Fine Grain" category. Material 2 was the second-best performer and did not fall into the "Fine Grain" category. It was also observed that some "Fine Grain" materials such as material 6 and 7 did not perform as well as others.

Ceramic nano-coating technology was also investigated and exhibited both improved transfer efficiency on all materials tested. It also reduced coefficient of variation in the print process for all but one material. These improvements in transfer efficiency also followed the base material results. One can conclude that choosing the best base material and then applying the nano-coating technology produced the best performing stencil.

Finally, it was shown thru SEM analysis that laser cut wall quality changed by only changing the base material. Certain materials exhibited smoother wall quality surfaces after the laser cutting process and showed improved transfer efficiencies. Others exhibited a rougher aperture side wall and exhibited lower transfer efficiencies. Overall, it was shown that by choosing the best base material and applying a ceramic nano-coating technology, transfer efficiencies can be optimized and print variation reduced in the assembly process.

FUTURE WORK

No future work is currently planned.

ACKNOWLEDGEMENTS

I would like to thank Andrea Motley, our summer intern, for the hours of print testing to obtain the data needed for this paper.

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