Advanced Flexible Substrate Technology for Improved Accuracy, Definition, and Conductivity of Screen Printed Conductors

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Abstract
One of the major concerns with screen printing of low temperature curing polymer thick film(PTF) pastes onto common flexible PET substrate materials is the overwhelming spread of the paste beyond the design line width after printing. Industry observation and controlled testing have shown this spread can be as much as 80% over the circuit design's intended line width. This issue prevents designers from increasing circuit density and/or reducing circuit real estate without incorporating other, more involved and more costly patterning methods. In many cases, flexible circuit fabricators desiring finer more accurate circuit elements may have to subcontract parts out of house in order to incorporate other patterning methods and in-turn lose control of both cost and lead time to the hands of their subcontracting partners.

This paper will provide results of numerous in-house and field testing, comparing printed line width control, edge definition, and improved conductivity of printed polymer Ag conductors on different flexible PET substrates with testing done on a company developed screen emulsion stencil material and substrate material.

Introduction
A new screen emulsion stencil material exhibiting high image resolution characteristics was developed to provide improvements in printed accuracy and definition of high end industrial and electronics screen printing applications. While the response from the Printed Electronics industry related to this new screen stencil material was positive, user feedback identified that the biggest factor inhibiting greater accuracy of printed circuit elements was actually the flexible substrate materials currently used in the printed electronics industry. High accuracy and definition of printed circuit elements provides the opportunity for increased density, reduction of circuit footprint, ability to finer feature sizes, reduced paste consumption, and even better conductivity. However, regardless of the accuracy and clarity of a circuit image reproduced in a printing screen's stencil component, the accuracy of the resulting printed image significantly degradesas the printed paste noticeably spreads on the surface of the flexible substrates commonly used in the Printed Electronics industry.This recognitionhas led to the development and testing of a new advanced flexible PET substrate level solution for improving accuracy of screen printed circuit elements.

The Screen Printing Process
The screen printing process is the most commonly used method of paste deposition for creating circuit elements such as conductive traces, dielectric layers, and resistors.In the screen printing process, an open weave mesh is stretched and elongated to a specific level of tension and secured to a stable framework. A water soluble, photo-imageable stencil coating is normally applied to the underside of the tensioned screen mesh. This coating is then imaged with the desired print designusing opaque masking (typically in the form or a photopositive film) and ultraviolet light in the 300 to 400 nanometer spectral range. As the UV light passes through the non-opaque areas of the masking, itcrosslinks the photosensitive emulsion coating rendering it water tolerable. The areas of the design which represent the desired print areas are opaque on the photo-mask. These opaque areas block the UV light from striking the photosensitive coating, preventing these sections from crosslinking and keeping them water soluble. A water spray development process is then applied to the exposed screen and the areas of the stencil coating which were masked from the UV light and remained water soluble eventually dissolve and rinse away, creating openings in the stencil coating in the geometries of the print features.

The imaged printing screen is normally secured to either a printing machine or a printing fixture. The substrate is placed immediately below the screen, typically on a vacuum stage that is X, Y and Theta adjustable for registration purposes. The screen is mounted directly over the substrate nest, and elevated a specific distance (gap) above the substrate surface. This gap distance is approximately equal to $1/200^{th}$ of the inside dimension of the screen frame.

This gap, termed the screen "off-contact" distance, is one of the crucial factors of the screen printing setup. Screen printing, along with metal stencil printing, are the only contact printing processes which require the ink or paste to move completely through the printing plate (the screen or metal stencil), from the far side down through the imaged pattern openings and out the opposing side nearest to the substrate surface. Printing with a metal stencil can be successfully accomplished while printing directly on contact with the substrate surface, however screen printing cannot. The presence of the mesh filaments in a screen creates substantial surface area within the imaged pattern openings. The mesh surface area competes with the substrate surface for adhesion of the printing ink. When screen printing is attempted in an on-contact mode, some of the paste remains with the screen mesh and does not completely transfer from the screen to the substrate, often leaving voids or peaks in a partial ink deposit. Incomplete in transfer in the on-contact print method is the main reason for the "off-contact" distance requirement in the screen printing setup. In an off-contact printing setup, the squeegee pushes down and deflects the screen in a single line of contact against the substrate surface and begins to travel laterally, forcing ink into the imaged pattern openings in the screen. The screen mesh tension combines with the off-contact gap to create enough counter force behind the moving squeegee to pull the screen mesh up and out of the ink deposit left behind on the substrate (Figure 1).

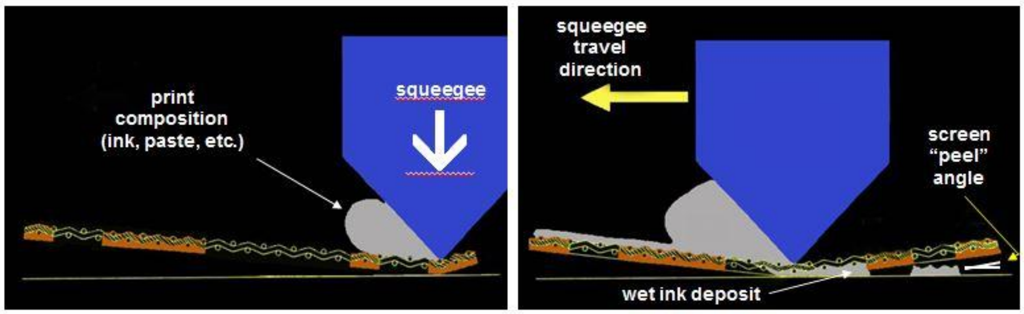


Figure 1- Paste transfer via the off-contact screen printing process

Thick Film Paste Technology

Conductive inks or pastes formulated for electronics applications are a suspension of a functional phase (conductive particles), a binder, vehicle, and perhapsother additives.The binder is used to create adhesion between the printed ink and the substrate. The vehicle component is typically an organic composition composed of resins and solvents (and any required modifiers) which gives the ink printability. While many precious and noble metals are used in electronic materials , silver is the most common conductive component in inks used for low temperature curing polymer thick film materials. The majority of these materials incorporate flake morphology, in some cases monospherical powders, or a mix of flake and powder are also used. The size and volume of the solids in the paste are a major factor when selecting a screen mesh to print that paste.

These pastes exhibit specific behavior when subject to an applied shear stress, such as stirring, or squeegeeing during the screen printing process. Viscosity is often defined as a fluid's resistance to flow and is measured under controlled and standardized conditions. Viscosity of materials tends to be significantly affected by certain variables, such as temperature. Rheology can be defined as the flow of matter under the influence of an applied stress. In the case of printing inks and pastes, rheology is used to describe the behavior of ink viscosity during printing. When considering printing inks or pastes, viscosity is more a snapshot of a specific moment, where rheology could be considered a home movie of an ink's behavior during printing over a specific window of time.

Most printing inks are formulated to be "Pseudoplastic", or shear thinning, where the viscosity decreases as the shear rate increases. This is beneficial to screen printing, as these types of pastes drop in viscosity and become more fluid once the squeegee begins to shear the ink during the print stroke. The more fluid paste can flow more freely as it travels into and out of the open mesh cells in the patterned areas of the screen during printing.

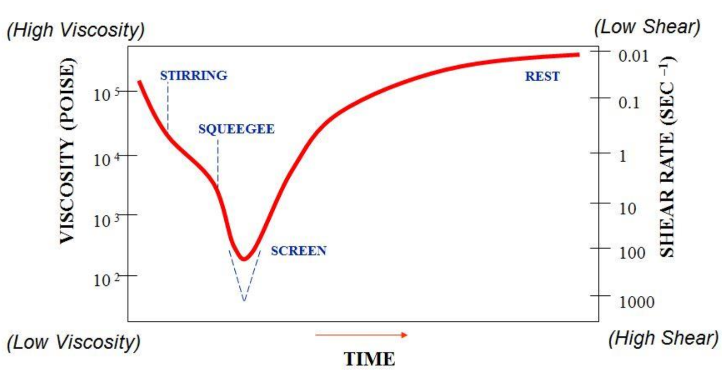


Figure 2 – Pseudoplastic Rheology: Behavior of Ink Viscosity During Printing

The formulation of these shear thinning materials also have a “recovery” side to their rheological curve (Figure 2), causing the paste to quickly return to its original “rest” viscosity once the shear stress being applied to the paste is ceased. This recovery part of the rheological curve prevents the paste from continuing to flow, creating the ability to retain some level of print definition rather than an undefined mass of ink. The length of the recovery time of a given paste can help the printed paste level out and prevent mesh marks and other imperfections on its surface. However, while helpful to achieve a smoother printed surface, slower recovery time can also lead to increased ink spread.

Considering, the wide range of viscosity recovery times of different PTF paste formations can increase the amount of ink spread over that which normally occurs on common flexible PET substrates.

Experimental Method

Testing of the newly developed screen emulsion stencil and advanced flexible PET substrate materials designed to improve accuracy of screen printed circuit elements was performed both in-house and in the field.Considering that both of these new materials were formulated to improve printed image accuracy, all print testing was performed using both materials simultaneously. The testing involved criteria such as image size reproduction accuracy, edge definition, and resolution for the new screen emulsion, and accuracy, definition, resolution, printed profile, and line resistance of conductive traces printed onto the new PET substrate.

Screen Technology

A printing screen was needed to perform the print tests. This required the selection of an appropriate mesh type prior to fabricating the screen. Criteria for mesh selection includes:
a) Minimum artwork size requirements (smallest line or space size)
b) Desired Wet Ink Film Thickness (“WIFT”)
c) Ink/mesh relationship (Can the proposed ink pass through the chosen mesh without clogging?)
d) Screen cost (capability versus dollars)

To aid in the mesh selection process, a chart of mesh types used in the Printed Electronics industry was created to easy comparison (Table 1).

Table 1 –Screen Mesh Types Used in Printed Electronics Applications

Mesh Type	Mesh Count	Thread Diameter	Mesh Opening	Mesh Thickness	Open Area	Mesh WIFT	Suggested Min Line Width
SS	290	20	68	45	60%	27	75
PET	305	33	47	50	32%	16	150
SS	325	28	50	59	41%	24	150
SS CAL	325	23	54	48	50%	24	100
Polyarylate	330	23	54	43	49%	21	100
PET	355	35	31	55	19%	10	180
SS	360	16	55	36	60%	22	40
SS CAL	360	16	55	32	60%	19	40
PET	380	30	33	45	24%	11	180
SS	400	18	46	39	51%	20	50
SS CAL	400	18	45	29	51%	15	50
PET	420	27	30	40	25%	10	180
SS CAL	500	18	32	29	41%	12	40
SS	590	15	30	30	49%	15	35
SS CAL	640	15	25	21	40%	8	30
SS CAL	730	13	22	18	40%	7	20

Due to its higher strength, stainless steel mesh typically has smaller wire diameters than polyester mesh having the similar mesh counts. This is identified in the "open area" percentage column in Table 1, and visually apparent in Figure 3 below which displays a 400 count, 18µmwire diameter stainless steel wire cloth (50.1% open area) compared to a 420 count polyester mesh with 27µm thread diameter (25% open area).

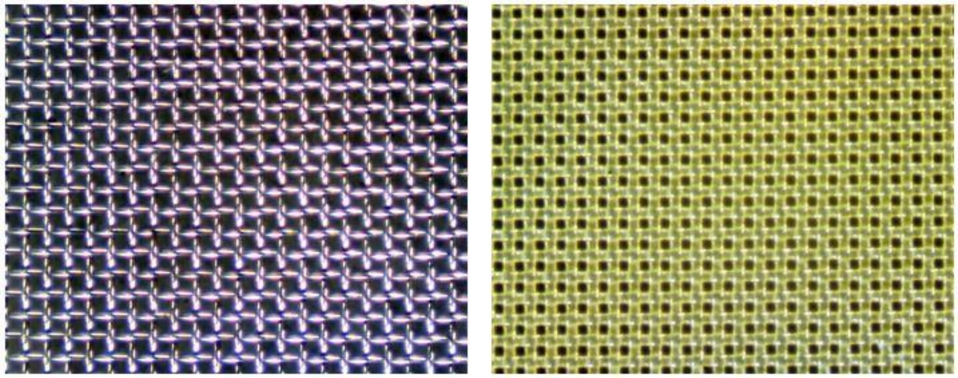


Figure 3 – More Open Stainless Steel Wire Mesh versus. Less Open Polyester Mesh

When mesh counts are similar, mesh with larger thread diameters will exhibit smaller openings with a more closed porosity (open area). The particle size in most low temperature Ag PTF pastes are typically between 1 to 4µm, with a solids content between 60% and 90%. The higher open area and larger mesh openings of the 400 stainless steel wire mesh offers less obstruction to paste flow compared to a polyester mesh of similar thread count per inch. The smaller diameter of the 400-18µm wire mesh permits smaller artwork sizes to be imaged into the screen stencil compared to the 420 count polyester. While all of the stainless steel mesh types finer than the 400-18µm mesh are also capable of printing the finest features on the test artwork (30µm), they are substantially more expensive compared to the 400 mesh, rendering them somewhat cost prohibitive when larger area screens are required. For these reasons, a calendared 400 stainless steel mesh with 18µm wire diameter was selected for the print testing.

The screen stencil component (emulsion) must also be capable of photographically reproducing the finest features of the intended print design. The newly developed stencil material was formulated with high resolution capability and is able to resolve the minimum test artwork features (30µm) with great accuracy. A 25 micron capillary film version of the new stencil material was selected for use on the 400-18µm screen mesh as it would provide a 8µm to 10µm EOM (emulsion over mesh) thickness to aid in suitable printed wet ink film thickness (WIFT), and also provide a smooth screen surface to achieve a sufficiently gasket-like seal to the substrate surface to restrict ink bleed.

Test Pattern

A test pattern was designed to evaluate the desired criteria of both the new screen emulsion and the new coated PET substrate. The test artwork incorporated lines and spaces, right angles, concentric circles and 45° biased lines and spaces. The artwork was arranged in rows and columns, and line sizes ranged from 100µm to 30µm, and the spacing between the lines varied as lines got narrower. This test design was imaged into the test screen's emulsion stencil as depicted in Figure 4.

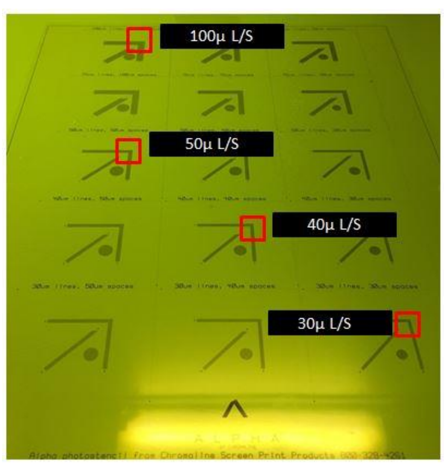


Figure 4 –Measurement Areas of Screen Stencil Imaged With Print Test Pattern

The photomask used to image the test screen was a photopositive film, photo-plotted at 30,000 ppi from a production CAD file. The line widths on the photo-plotted test positive were within 1µm of designed sizes in the CAD file. Following screen exposure, the sizes of the images in the screen stencil were typically within 1µm of the size of the corresponding feature on the photo-plotted film positive.

Substrates Tested

Three different types of flexible PET substrates were included in the print testing:

1) Substrate A (common industry material)

Print treated PET, with a primer for ink adhesion, pre-stabilized, and optically clear

2) Substrate B (also a common industry material)

PET, surface treated for ink adhesion and high surface tension, pre-stabilized, hazy / translucent

3) Substrate F (newly developed)

Coated PET, with ink adhesion promoter and ink spread inhibitor, pre-stabilized, hazy / translucent

Print Testing

Screen print testing was conducted at various stages using different silver loaded PTF conductor pastes. In all cases to date, "flat bed" screen printing was used and all of these systems were sheet fed substrate insertion printing systems. The sheet fed substrate placement methodwas advantageous for this testing as it allows for staging separate stacks of as many different substrates as needed for comparison and permits inserting them into the printing machine in any consecutive yet unbiased sequence.

Printer setup parameters used were:

a) Flood Stroke: 500 mm/second @ 20 kg pressure
b) Print stroke: 400 mm/second @ 30 kg pressure
c) Off contact distance: 5.5 – 6.0 mm
d) Squeegee: 75/95/75 Shore A scale durometer, 10° attack angle, 16" length w/ factory edge

Common characteristics of the PTF pastes used in testing were silver conductor paste, viscosity of 10,000 – 13,000 cps, shear thinning rheology, with a fine Ag flake morphology typically under 4µm in size.

Print Test Results

The print test results show that the newly developed substrate "F" provides printed feature sizes which accurately reproduce the size of the corresponding images in the print screen. This result is consistent throughout the different line widths used on the test artwork. The high printed accuracy is due to the company developed coating applied to the surface of substrate F. The same lines and spaces were printed on substrates A and B using the same screen and paste display substantial line spread. Table 2 displays the sizes of the cured 100µm line widths printed on the 3 different test substrates.

Table 2 - sizes of the cured 100µm line widths printed on the 3 different test substrates.

Description	Substrate A	Substrate B	Substrate F
Target Line Width	100µm	100µm	100µm
Min Line Width	164µm	136µm	96µm
Max Line Width	189µm	148µm	109µm
Average Line Width	178.5µm	142.7µm	101.4µm
Ave Paste Spread Over Target Width	+ 79%	+ 43%	+ 2%

The 100µm line and space images in the test screen are presented in Figure 5 for reference. Photos of the corresponding cured print results for the 100µm lines and spaces appear in Figures 6 through 8.

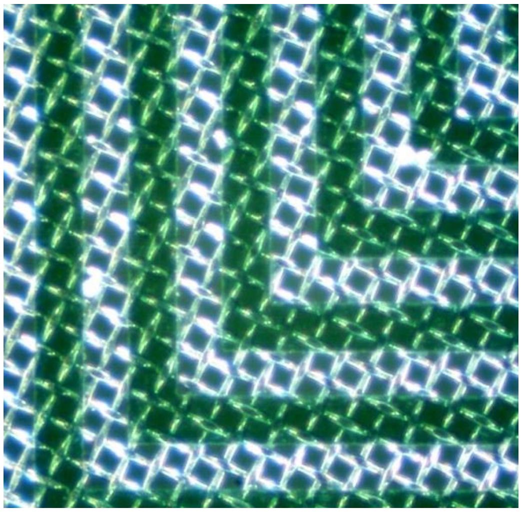


Figure 5 – 100µm image in test screen.

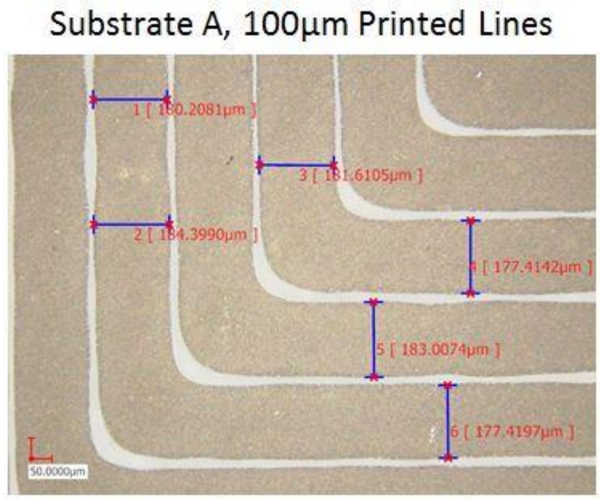


Figure 6 – Cured 100µm L/S Printed on Substrate A.

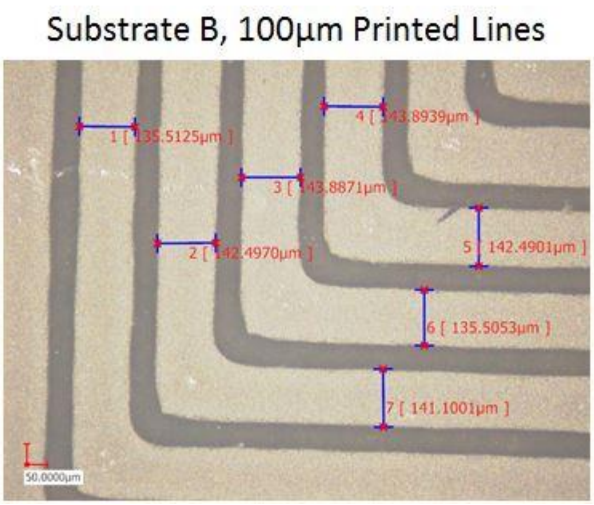


Figure 7 – Cured 100µm L/S Printed on Substrate B.

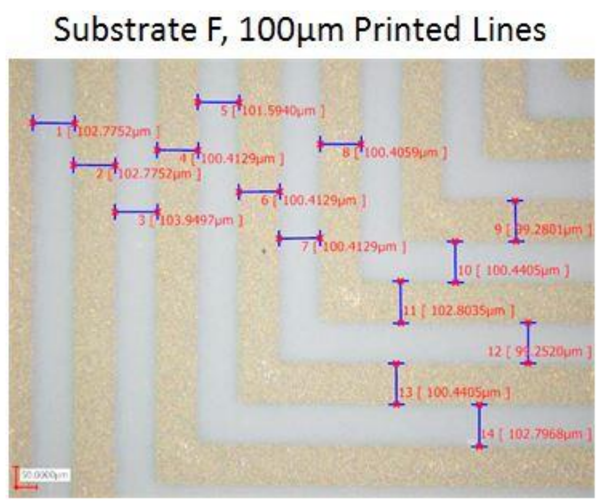


Figure 8 – Cured 100µm L/S Printed on Substrate F.

In the randomly selected areas measured for the cured 100µm lines and spaces, ink spread on Substrates A and B averaged between 43% to 79% over the target linewidth of 100 microns. Due to the properties of the coated surface of Substrate F, the paste spread on Substrate F was measured to be no greater than 9%, with an average of just 2% at these same locations.

Print test results for the 50 micron line and space sections showed similar results, with spread on Substrates A and B so significant that the paste actually migrated far enough that it overcame the pitch distance and shorted adjacent lines, and in some cases flowed into a common mass similar to a ground plane, rendering them unmeasurable.

Table 3 - Sizes of the cured 50µm line widths printed on the 3 different test substrates.

Description	Target Line Width	Min Line Width	Max Line Width	Average Line Width	Ave Paste Spread Over Target Width
Substrate A	50µm	unmeasurable	unmeasurable	unmeasurable	unmeasurable
Substrate B	50µm	unmeasurable	unmeasurable	unmeasurable	unmeasurable
Substrate F	50µm	44µm	54µm	49.1µm	- 2%

Table 3 displays the sizes of the cured 50µm line widths printed on the 3 different test substrates. Line widths on Substrates A and B were undeterminable due to substantial paste spread. The cured lines on Substrate F remained within an average of 2% of the target 50 micron line width.Figure 9 displays the 50 micron lines in the test screen stencil. Figures 10 -12 display the cured 50 micron line and space sections on the 3 tested substrates.

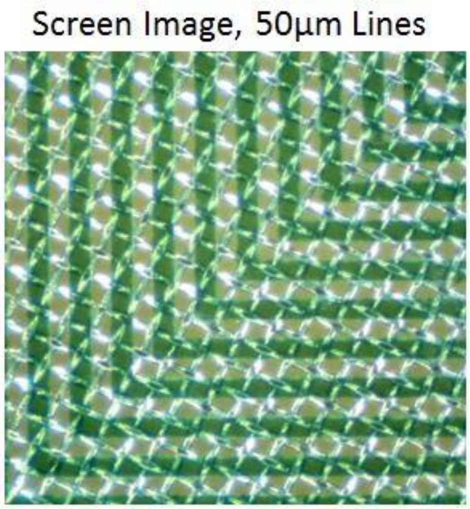


Figure 9 – 50µm image in test screen.

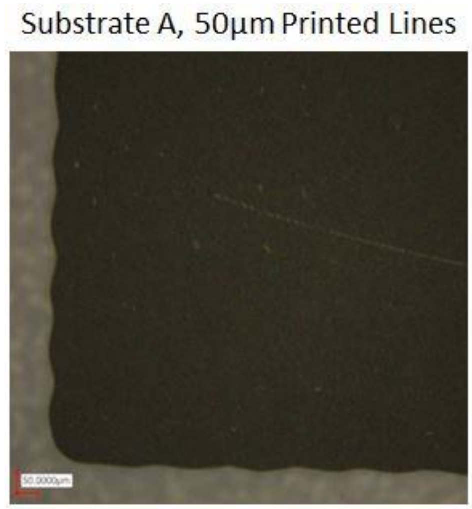


Figure 10 – Cured 50µm L/S Printed on Substrate A.

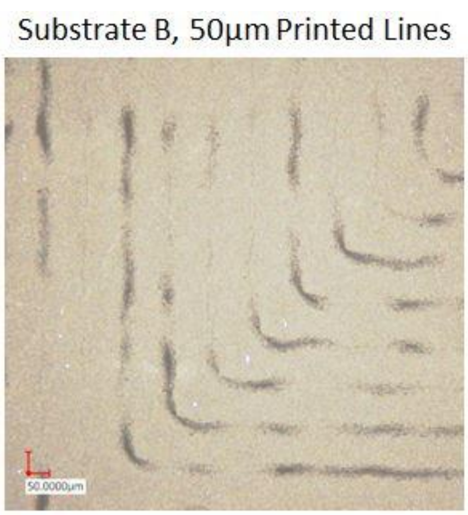


Figure 11 – Cured 50µm L/S Printed on Substrate B.

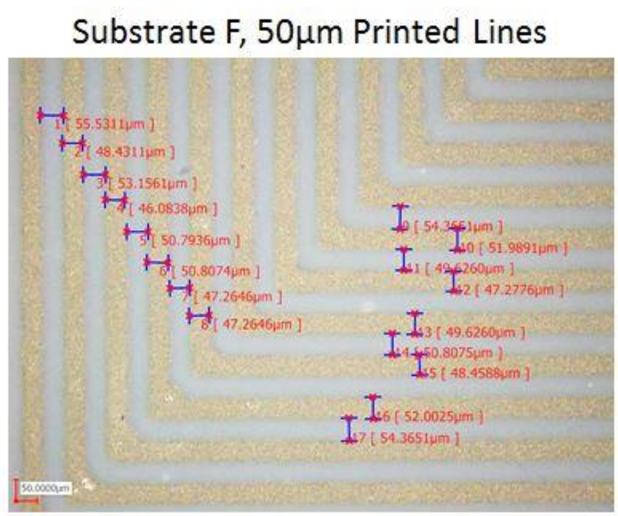


Figure 12 – Cured 50µm L/S Printed on Substrate F.

Test print results for the 40 and 30 micron sections displayed similar results to that of the 50µm wide test sections, with Substrates A and B exhibiting paste spread too significant to permit measurements. The 40 and 30 micron size cured prints on Substrate F were well defined and exhibited an average of less than 4% paste spread (Tables 4 and 5).

Table 4 - Sizes of the cured 40µm line widths printed on the 3 different test substrates.

Description	Target Line Width	Min Line Width	Max Line Width	Average Line Width	Ave Paste Spread Over Target Width
Substrate A	40µm	unmeasurable	unmeasurable	unmeasurable	unmeasurable
Substrate B	40µm	unmeasurable	unmeasurable	unmeasurable	unmeasurable
Substrate F	40µm	34µm	46µm	40.9µm	+ 2%

Figure 13 displays the 40 micron lines in the test screen stencil. Figure 14 displays the 40 micron line and space measurements of the cured paste on Substrate F. The printed and cured 40 micron lines were averaged less than 3% of the target line size in the test design.

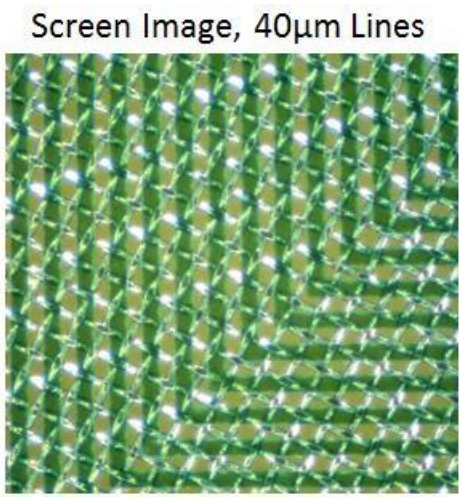


Figure 13 – 40µm image in test screen.

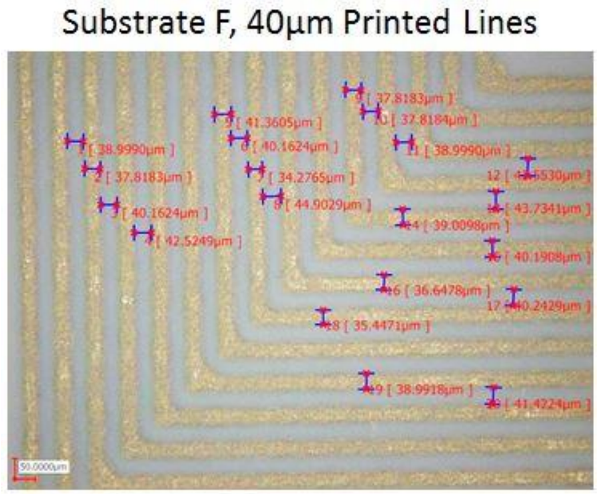


Figure 14 – Cured 40µm L/S Printed on Substrate F.

Table 5 - Sizes of the cured 30µm line widths printed on the 3 different test substrates.

Description	Target Line Width	Min Line Width	Max Line Width	Average Line Width	Ave Paste Spread Over Target Width
Substrate A	30µm	unmeasurable	unmeasurable	unmeasurable	unmeasurable
Substrate B	30µm	unmeasurable	unmeasurable	unmeasurable	unmeasurable
Substrate F	30µm	26µm	37µm	30.8µm	+ 3%

Figure 15 displays the 30 micron lines in the test screen stencil. Figure 16 displays the 30 micron line and space measurements of the cured paste on Substrate F. The printed and cured 30 micron lines were averaged less than 4% spread over the target line size in the test design.

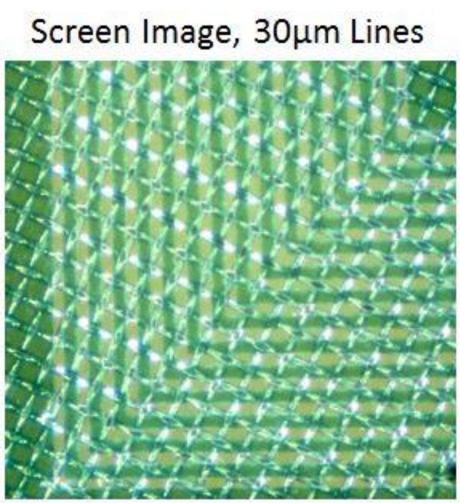


Figure 15 – 30µm image in test screen.

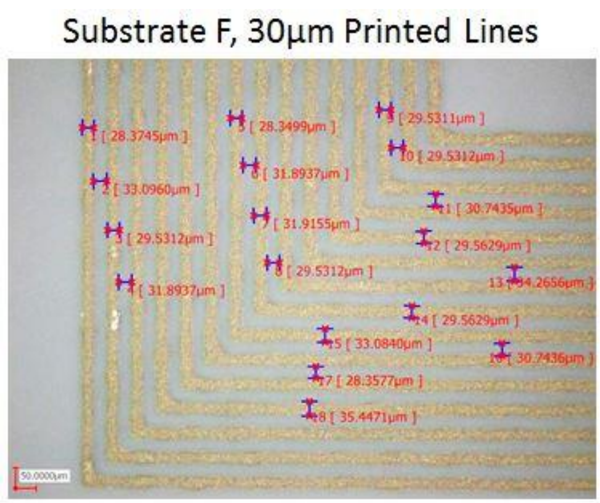


Figure 16 – Cured 30µm L/S Printed on Substrate F.

It is theorized that the higher resolution line sizes (50µm, 40µm, and 30µm) both imaged into the newly formulated screen emulsion stencil and in turn printed onto the newly developed Substrate F are a resulting byproduct of the increased reproduction accuracy characteristics designed into the performance characteristics of both materials.

Figure 17 displays a comparison of concentric circles with 40µm lines and spaces and 30µm lines with 50µm spaces printed onto Substrates A and F with the same paste through the same test screen using consecutive print strokes.

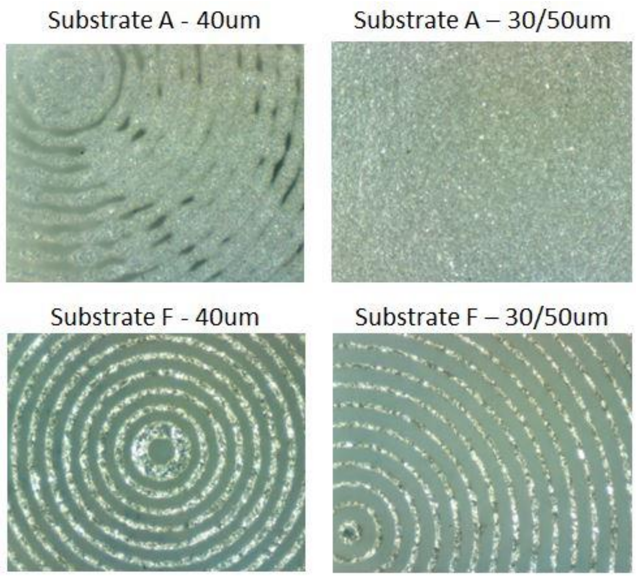


Figure 17–Comparison of Screen Printed High Resolution Concentric Circles on Substrates A and F.

3-D Printed Profile Data

The printed silver traces were reviewed using a production 3D optical microscope to capture profile data.

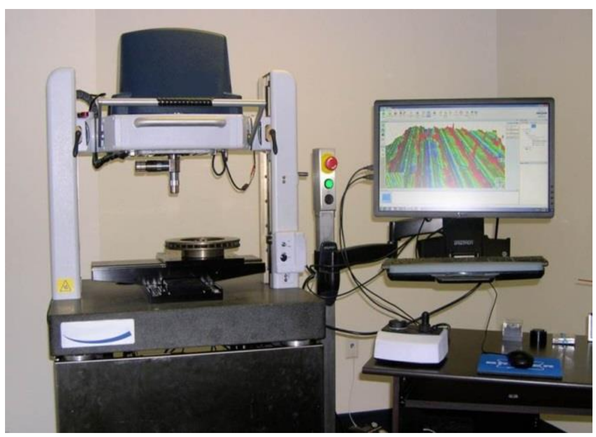


Figure 18 – Production 3D optical microscope.

The significant spread on Substrates A and B prevented capturing clean profile images, as depicted in Figures 19 and 20.

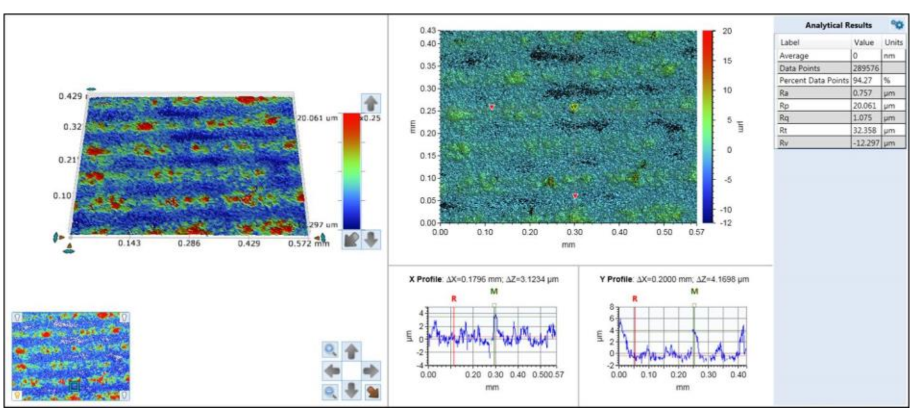


Figure 19 –3D Microscope Data of 40µm Lines and Spaces Printed on Substrate A.

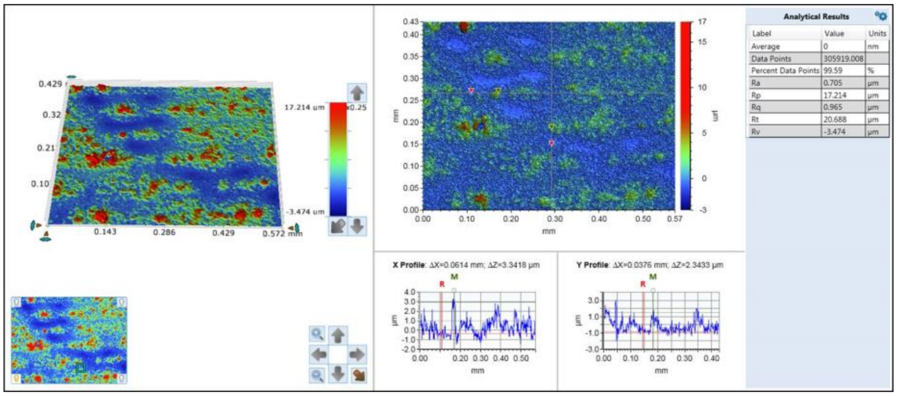


Figure 20 – 3D Microscope Data of 40µm Lines and Spaces Printed on Substrate B.

Figure 21 displays the same 3D microscope data for silver traces printed on Substrate F. Note the distinctly defined profile displayed in the “Y Profile” graph within Figure 21.

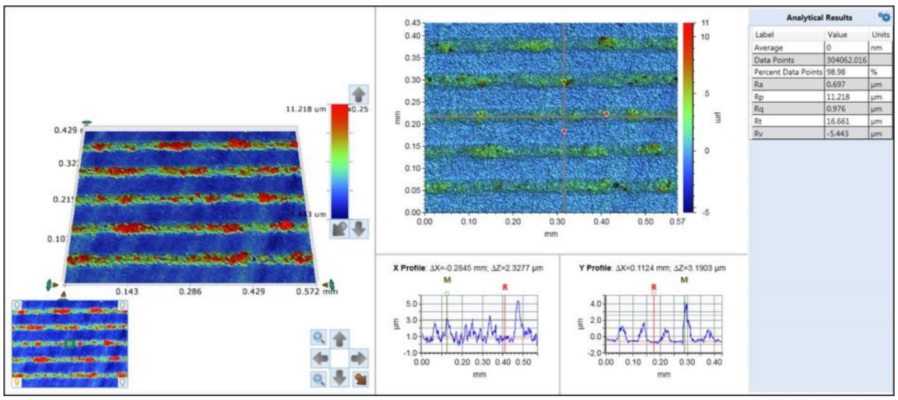


Figure 21 – 3D Microscope Data of 40µm Lines and Spaces Printed on Substrate F.

The production 3D optical microscope was also used to capture 3-dimensional images of the 100µm and 50µm lines printed on Substrate F and provide additional profile and thickness data (Figures 22 and 23).

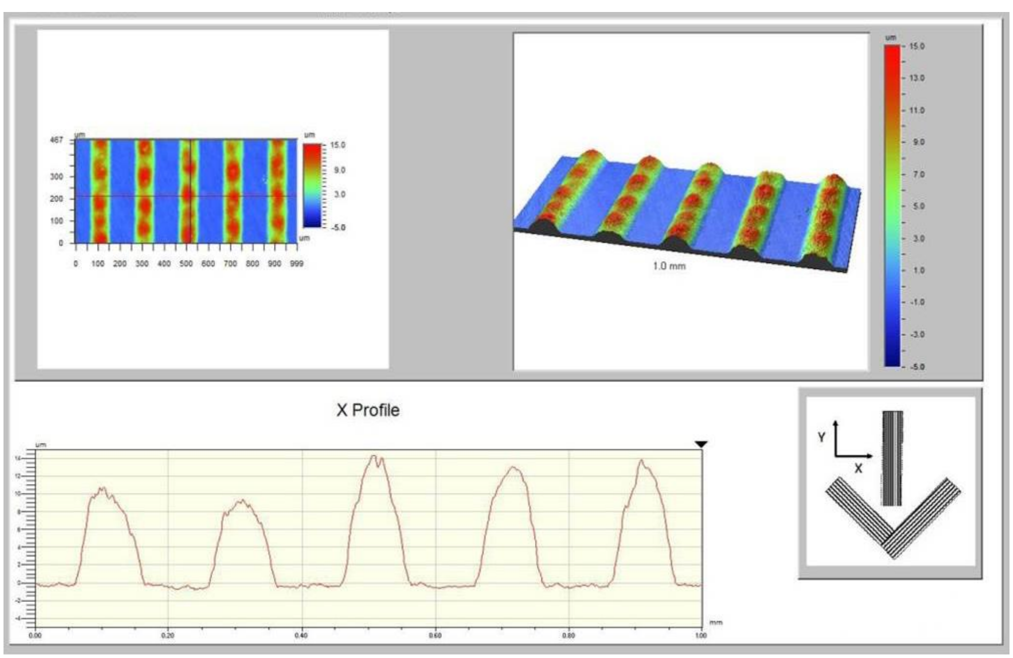


Figure 22 –3D Microscope Data of Cured Profile and Height of 100µm Lines on Substrate F.

The cured 100µm lines on Substrate F averaged approximately 10µm in height while the cured 50µm wide lines averaged approximately 8µm in cured thickness.

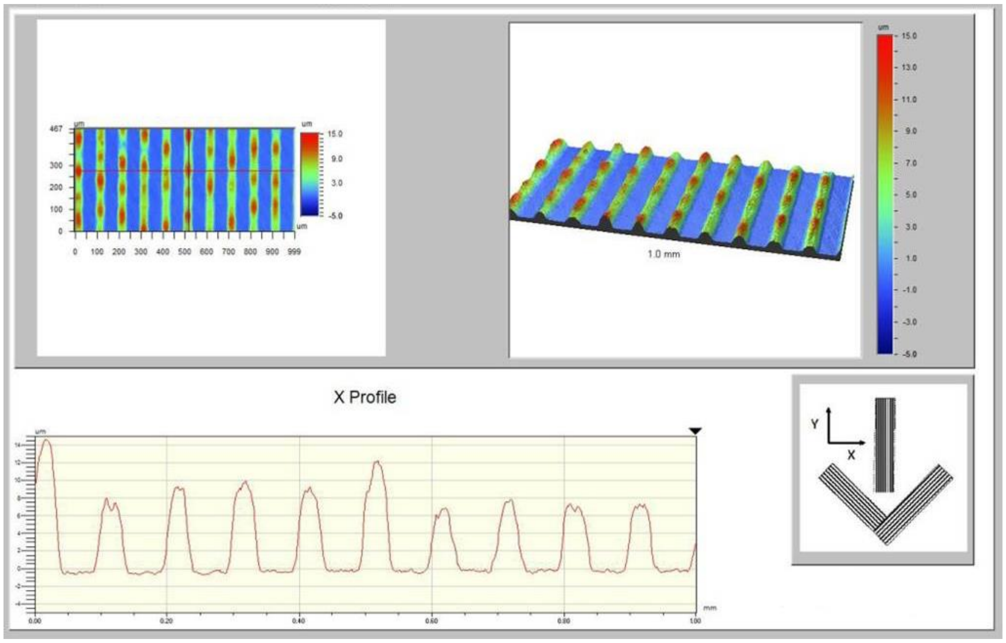


Figure 23 –3D Microscope Data of Cured Profile and Height of 50µm Lines on Substrate F.

Screen printed testing of 1000µm wide lines of a copper based conductive paste on Substrate F was performed, and printed profile and line width data appears in Figure 24. The screen printed copper conductive paste retained a more desirable printed profile on Substrate F compared to Substrate A.

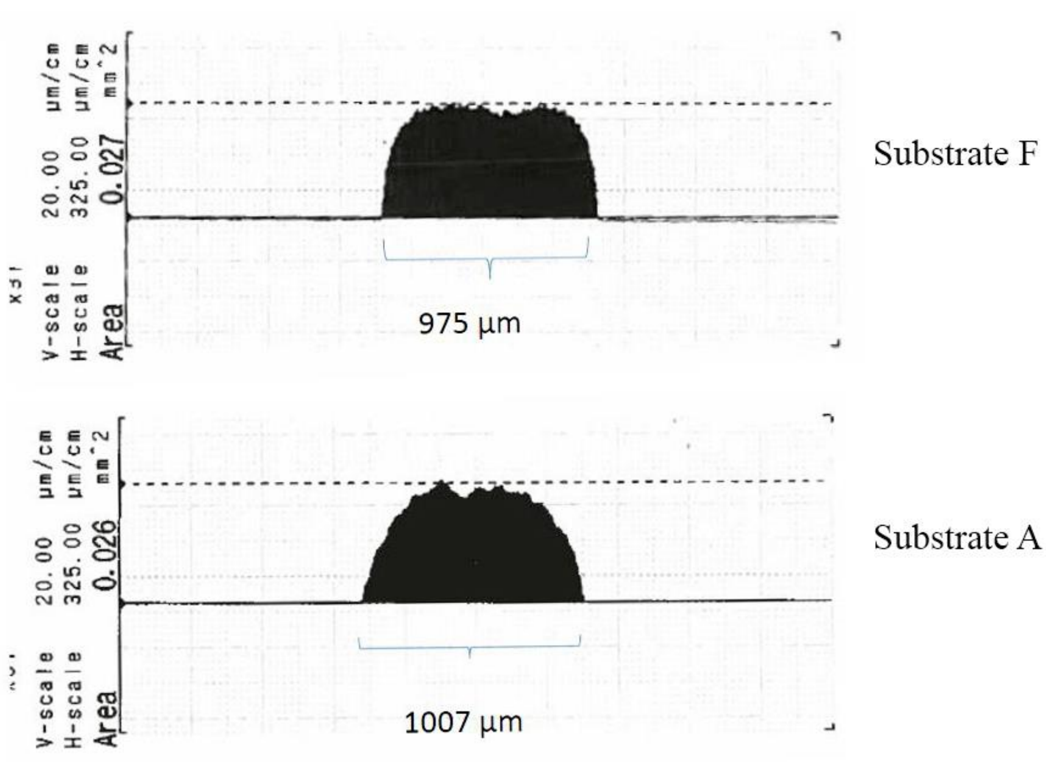


Figure 24 – Screen Printed 1000µm Wide Copper Trace Profile Measurements on Substrate F compared with Substrate A

Resistance Measurements
Line resistance and volume resistivity was measured on both Substrate A and Substrate F. Additional data such as cross-sectional area, and the height and width of the cured traces was also monitored for comparison and its relationship to line resistivity.

Experience suggests that traces printed moments apart with the same paste reservoir through the same screen should have relatively identical deposition volumes. The production 3D microscope was used to calculate the cross-sectional area of the cured Ag traces on both Substrates A and F to confirm this industry recognized perception. Figure 25 confirms that the consecutively printed silver traces on Substrates A and F have similar cross-sectional areas, suggesting the volume of paste deposited on both substrates was relatively the same.

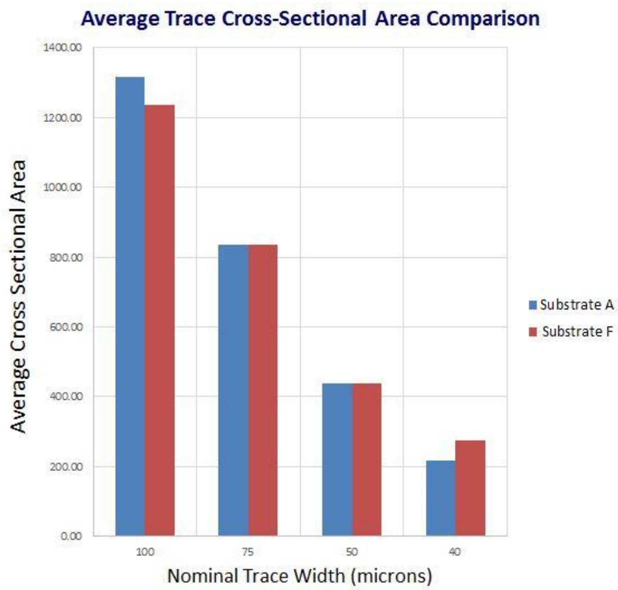


Figure 25 - Average Trace Cross-Sectional Area is Relatively Identical on Substrates A and F

However, as shown in Tables 2, 3, 4, and 5, the paste spread of the printed trace widths was significantly greater on Substrate A compared to Substrate F. Trace width measurements from the production 3D microscope also confirm that the standard deviation of those wider trace widths on Substrate A was significantly greater than that of the more accurate trace widths measured on Substrate F. This is illustrated in Figure 26.

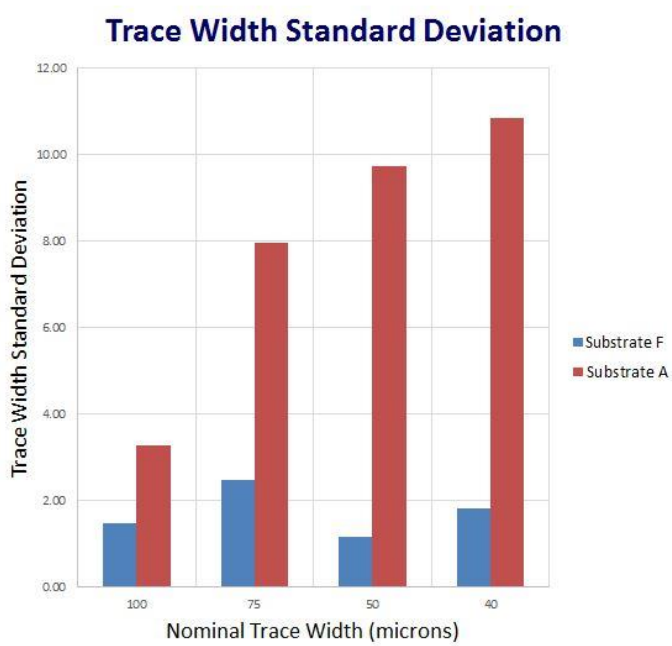


Figure 26–Standard Deviation of Printed Trace Widths on Substrates A and F

Resistivity was measured for the cured traces on both Substrates A and F. This is displayed in Figure 27.

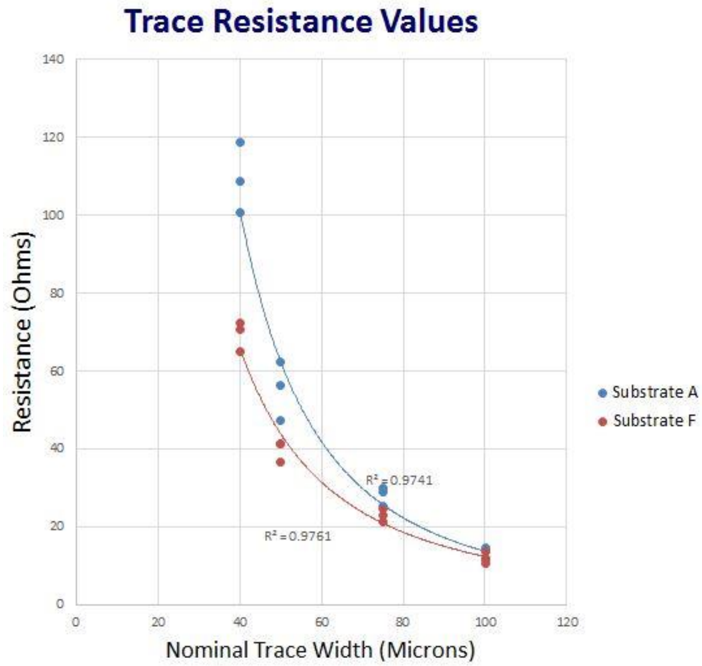


Figure 27–Line Resistance Measurements on Substrates A and F

Figure 27 advises that lineresistance values were consistently higher on Substrate A than on Substrate F, but that the delta in the line resistance measurements between Substrates A and F decreases as the trace width becomes wider.

Volume resistivity measurements for both Substrates A and F appear in Figure 28.

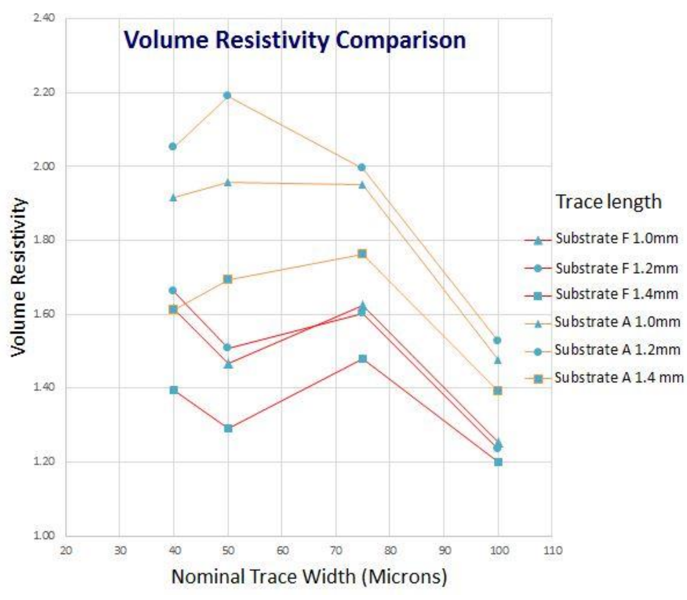


Figure 28–Volume Resistivity Values for Substrates A and F

Figure 28 shows that volume resistivity is higher on Substrate A regardless of line width, but the delta in resistivity decreases as the trace width increases. Volume resistivity values for Substrate A were 14% to 45% greater than thoseofSubstrate F.

Figure 25 indicates that the same volume of the same paste was printed through the same screen onto both Substrates A and F. Based on this data, the resistance values of identically cured, relatively equal volumes of the same paste would initially be expected to be very close, if not equal.

The data in Figure 26 confirms that Substrate A showsa significantly higher standard deviation in trace width than Substrate F. Standard deviation for Substrate F remained relatively constant regardless of line width. The higher standard deviation of paste spread on Substrate A suggest that the printed line widths on Substrate A are not only greater in width compared to corresponding lines printed on Substrate F, but that the amount of line spread varies significantly as well. The smaller variation in line widths on Substrate F for all line sizes tested permits more efficient use of the same amount of printed paste.

A hypothesis for understanding the lower resistance values measured on Substrate F is that the reduced spread of the printed paste confines the conductive particles in narrower, more consistentwire-like lines, rather than permitting them to spread with the increased line widths. Additionally, as the vehicle and solvents in the paste are drawn into the coating on Substrate F, it is theorized that this activity also creates a tighter "packing" of the conductive particles leading to better conductivity for the same deposited volume of the same paste. Figure 29 illustrates this concept of a more confined, tighter packing of the conductive particles in paste printed on Substrate F.

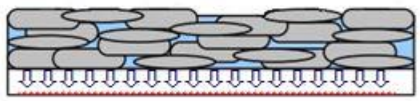


Figure 29–Depiction of tighter conductive particle packing in paste printed on Substrate F

Ink Jet Print Testing

Test results showing improved printed accuracy similar to those reported here were consistently achieved while test printing with more than 10 different commercial Ag conductive ink formulations, including some formulated specifically for Ink Jet printing. Improved print size accuracy has also been seen in initial Ink Jet print testing of conductive traces onto Substrate F compared to Substrates A and B. Further investigation of Ink Jet deposition of conductive paste onto Substrate F is still needed to generate statistically sufficient data.

Summary and Conclusions

Printed Electronics circuit designs continue to move towards tighter line pitch and reduced line widths as a means to increase functional density and reduce overall circuit area. Feedback from Printed Electronics manufacturers suggests that the biggest inhibitor to greater accuracy of printed circuit elements is the standard flexible substrate materials currently used in printed electronics fabrication. Recognition of these factorsled tothe development of a new flexible PET substrate and high accuracy screen stencil material, specifically designed to reproduce printed image sizes with an increased degree of accuracy. While improvements to screen printing presses, squeegees, screen mesh, and conductive paste technology have evolved in recent years, the concept of a substrate level solution to improve printed accuracy is much less common.

The results reported here of both the field and in-house testing of the combination of both the advanced substrate and screen emulsion stencil in comparison to the standard PET substrates currently in industry use suggest the intention of the development of these new electronicsscreen printing related materialshave been realized.

Test results provided in this paper show a significant increase in conductivity (14% to 45%) for the same volume of the same conductive paste when printed on Substrate F. This is theorized to be due to the more accurate and consistent 3-dimensional profile of conductive traces when printed on Substrate F, resulting in tighter packing of conductive particles when the fluids in the paste are drawn into the substrate's surface coating. This increase in printed conductivity seen with Substrate F also creates the opportunity to achieve the same level of conductivity currently achieved on Substrate A by printing a calculated lesser amount of the same paste, or by printing the same volume of a less conductive paste on substrate F. Either of these scenarios create the possibility of material cost savings.

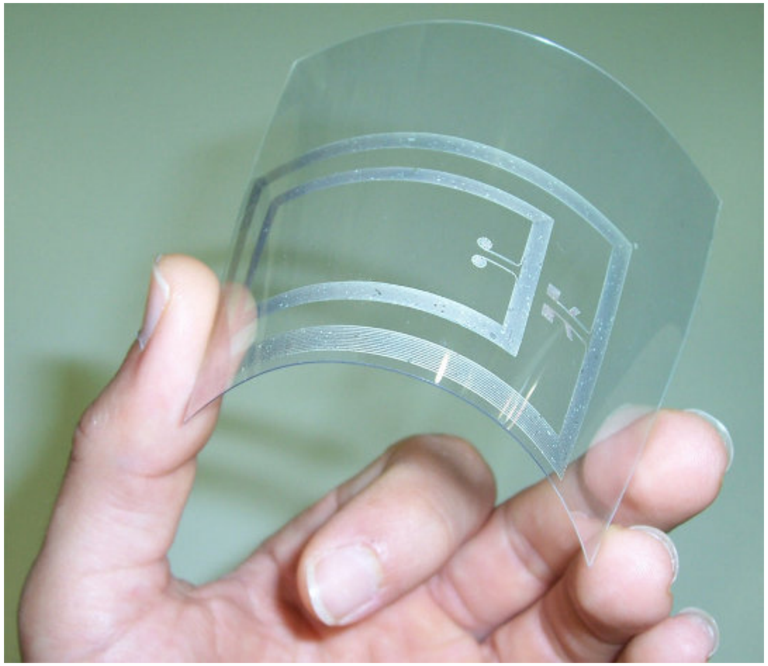
Acknowledgments

The author thanks the involved company team members for their expertise and support throughout the duration of the testing and analyses of the materials presented in this paper, and to the many allied industry suppliers and customers who dedicated time, resources, and /or materials relating to the testing described herein. Figure 24 was provided courtesy of Intrinsiq Materials, Inc.

Advanced Flexible Substrate Technology for Improved Accuracy, Definition, & Conductivity of Screen Printed Conductors

Art Dobie
Chromaline Screen Print Products

Screen Printed Flexible Circuits



Flexible Flat Cables

Printed Sensors

RFID Tags

Medical Applications

Displays

Smart Garments

more

Why Screen Printing? Screen Printing is a mature and easily scalable process which many circuit makers already use successfully in-house.

Flexible Substrate Printing Limitations

Printing Accurate Circuit Element Sizes on Flex is Difficult!

Ink spreads substantially on common PET substrates.

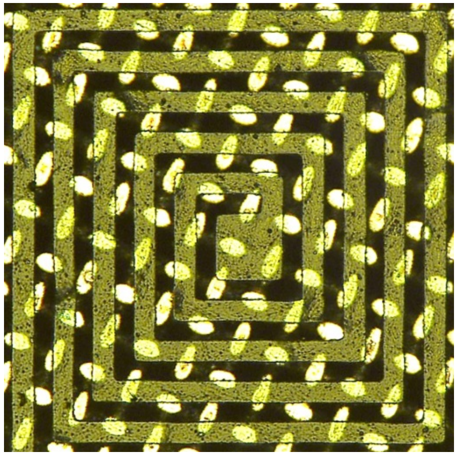
Ink spread inhibits increasing circuit density or reducing circuit real estate without involving other, more involved and more costly patterning methods.

Many flexible circuit fabricators would need to subcontract parts out of house in order to incorporate other patterning methods and in-turn lose control of both cost and lead time.

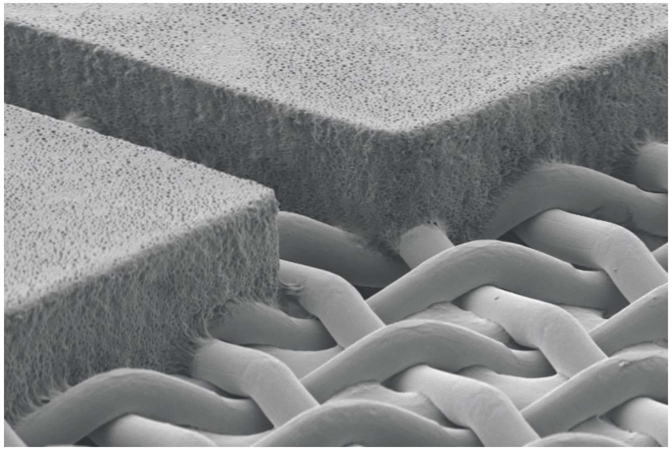
Desire: improve print quality, accuracy, & resolution on flexible substrates

Develop a screen stencil material solution capable of reproducing printable image features with very high accuracy and definition, and high resolution capability.

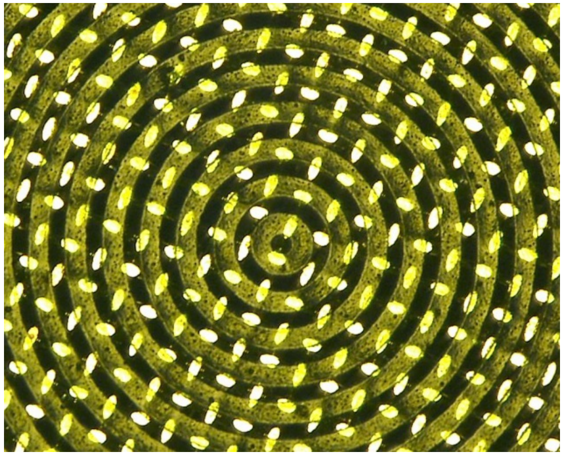
Develop a screen stencil material solution capable of reproducing printable image features with very high accuracy and definition, and high resolution capability.



20µ square serpentine



Edge definition @ 500x



20µ concentric circles

"Advanced Flexible Substrate Technology for Improved Accuracy, Definition, and Conductivity of Screen Printed Conductors"

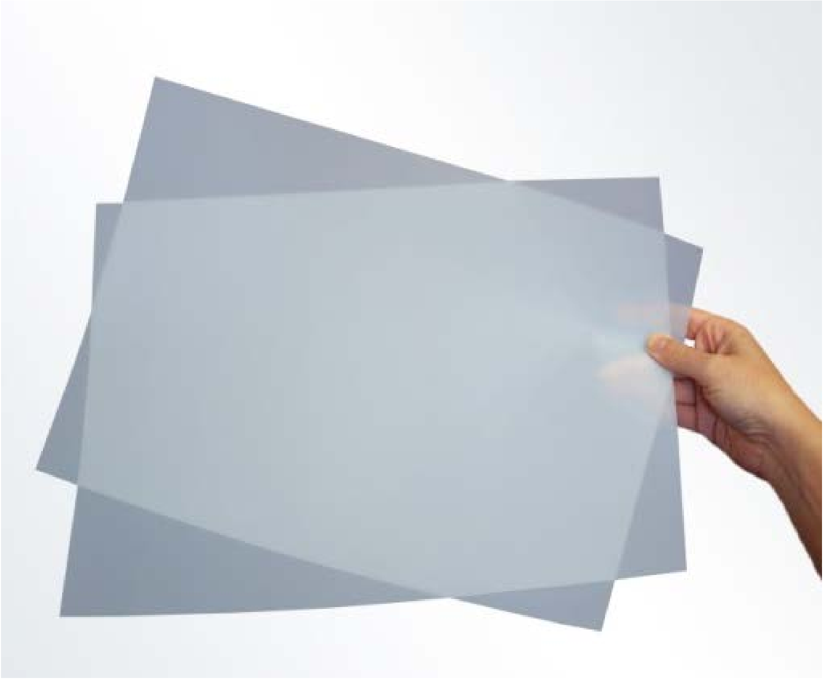
Desire: improve print quality, accuracy, & resolution on flexible substrates

Part A: Develop a screen stencil material solution capable of reproducing printable image features with very high accuracy and definition, and high resolution capability.

Desire: improve print quality, accuracy, & resolution on flexible substrates

Part B: Develop a substrate level solution capable of maintaining image size accuracy of printed circuit elements on flexible material by inhibiting ink spread.

Part B: Develop a substrate level solution capable of maintaining image size accuracy of printed circuit elements on flexible material by inhibiting ink spread.



Newly developed Substrate ("F")

Coated PET

- Ink adhesion promoter
- Print spread inhibitor

– Pre-stabilized

– Hazy / translucent

"Advanced Flexible Substrate Technology for Improved Accuracy, Definition, and Conductivity of Screen Printed Conductors"

Materials Testing: *2 years and ongoing*

Screen Stencil Materials: *(emulsion, capillary film)*

- Screen Image:
  - Resolution
  - Accuracy
  - Edge Definition
  - EOM (capillary film)

Substrate Material: *(PET)*

- Print Testing:
  - Printed Accuracy
  - Printed Definition
  - Printed Resolution
- Measurements:
  - Profile
  - Resistance

Screen & Prepress for Testing

Factors which influenced mesh selection

a) Minimum artwork size requirements
(smallest lines & spaces)

b) Desired Wet Ink Film Thickness ("WIFT")

c) Ink/mesh relationship
(Can the ink pass through the chosen mesh?)

d) Screen cost *(capability vs dollars)*

Smallest Feature Size of the Test Artwork

30µ L/S

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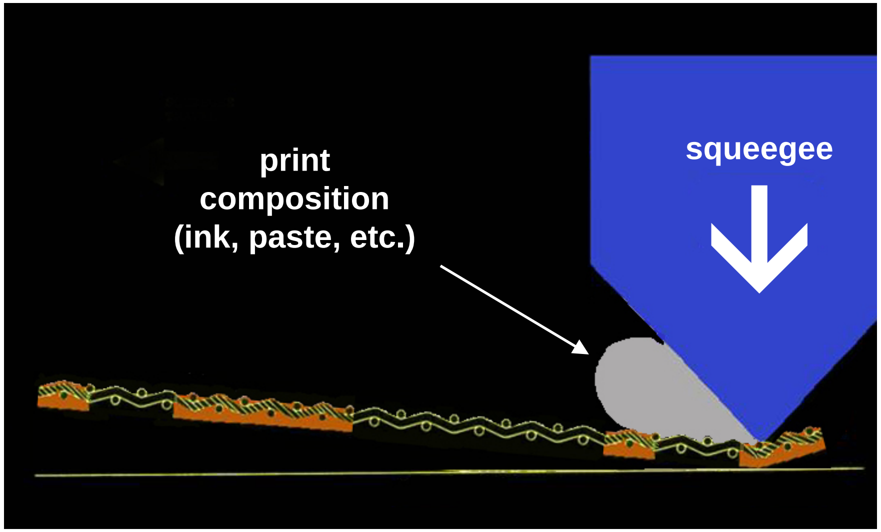
Screen & Prepress for Testing

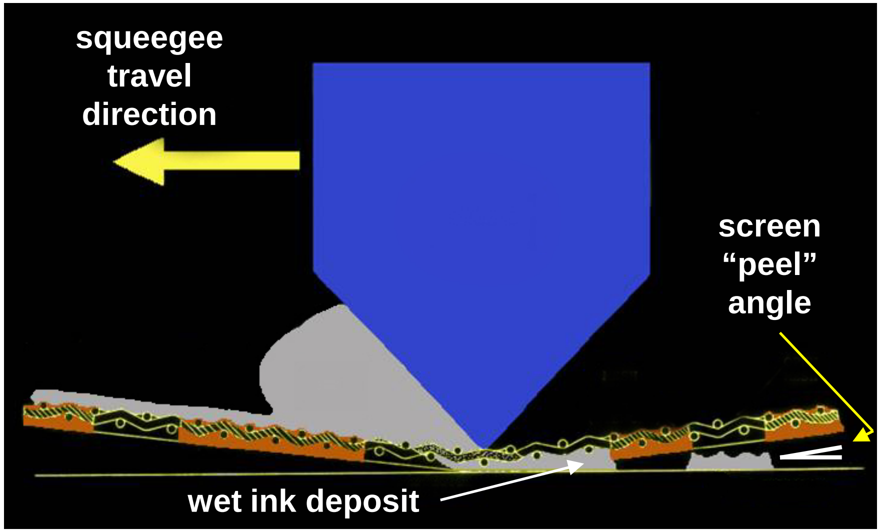
Artwork vs Screen Aspect Ratio

30µ Lines & Spaces:

Requires a thin mesh, which results from using mesh with small filament diameters.

Ink Transfer in Screen Printing

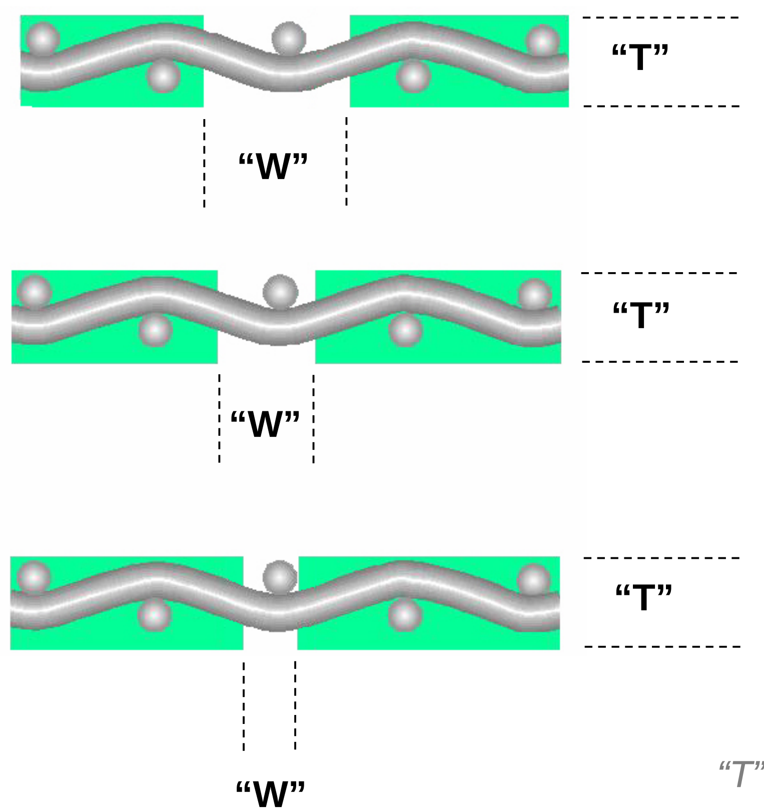




The screen is elevated a specific height above the substrate. The squeegee moves downward, deflecting the screen into a single line of contact with substrate, and then travels laterally. The mesh tension of the elevated screen "peels" up behind the traveling squeegee, leaving ink in position on substrate.

Screen Printing is the only "contact" printing process that requires the ink to pass through the printing plate from back to front.

Printable Line Width vs. Screen Thickness: *"Aspect ratio"*



"W" is greater than "T"
Optimal

"W" = "T"
Practical Limit

"W" is smaller than "T"
Very difficult, if not impossible

"T" based on total screen thickness (mesh + emulsion thickness)

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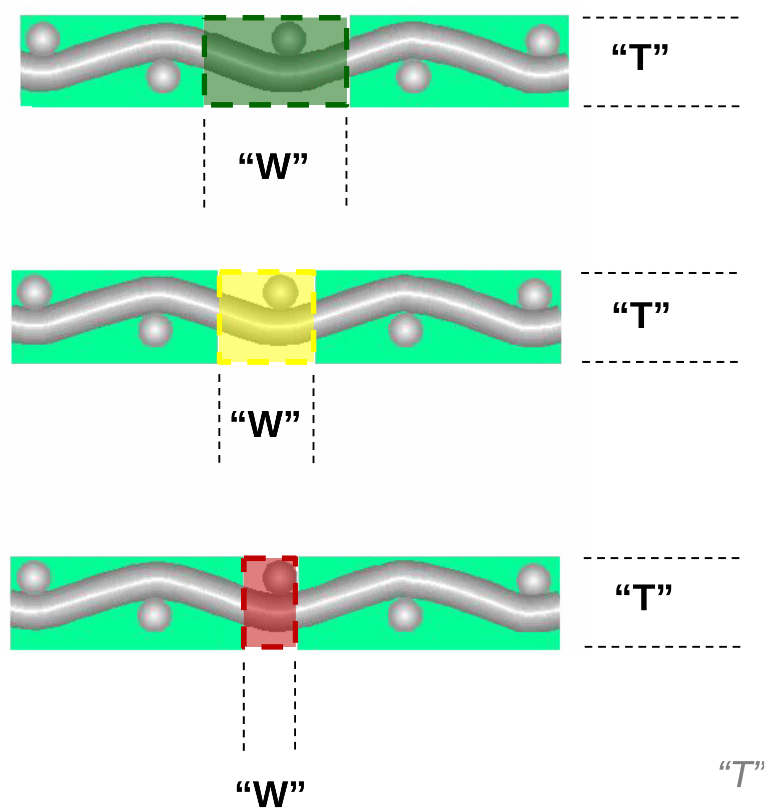
Printable Line Width vs. Screen Thickness: *"Aspect ratio"*



"W" is greater than "T"
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"W" is smaller than "T"
Very difficult, if not impossible

"T" based on total screen thickness (mesh + emulsion thickness)

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Printable Line Width vs. Screen Thickness: *"Aspect ratio"*

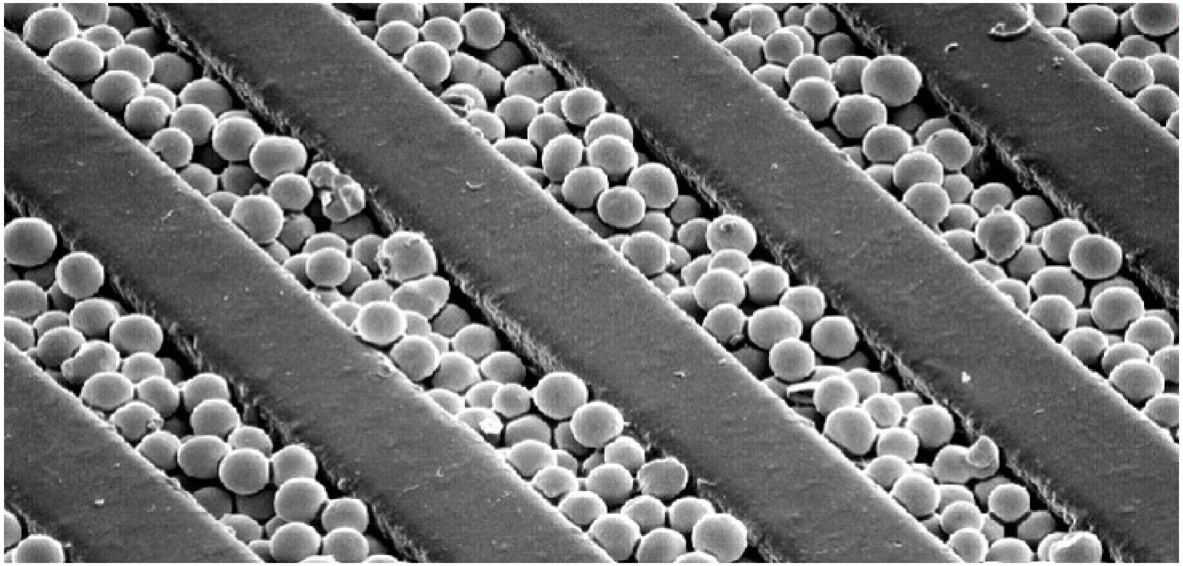
It's easier to print a factory…

…than a house,

or a skyscraper!

Screen & Prepress for Testing

Ink/mesh relationship *(Can the ink pass through it?)*



For proper passage and to avoid sifting, the mesh openings should be approximately <u>4x</u> the size of the largest particle in the paste.

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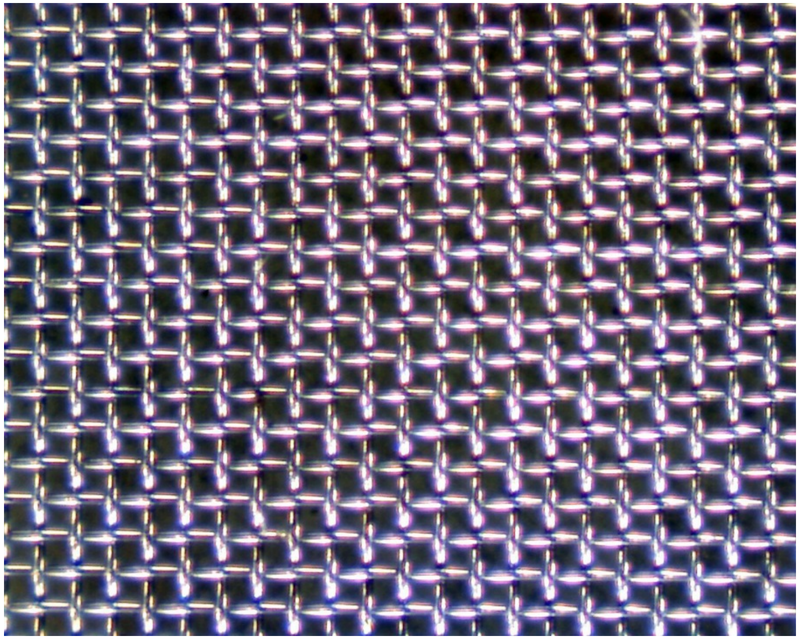
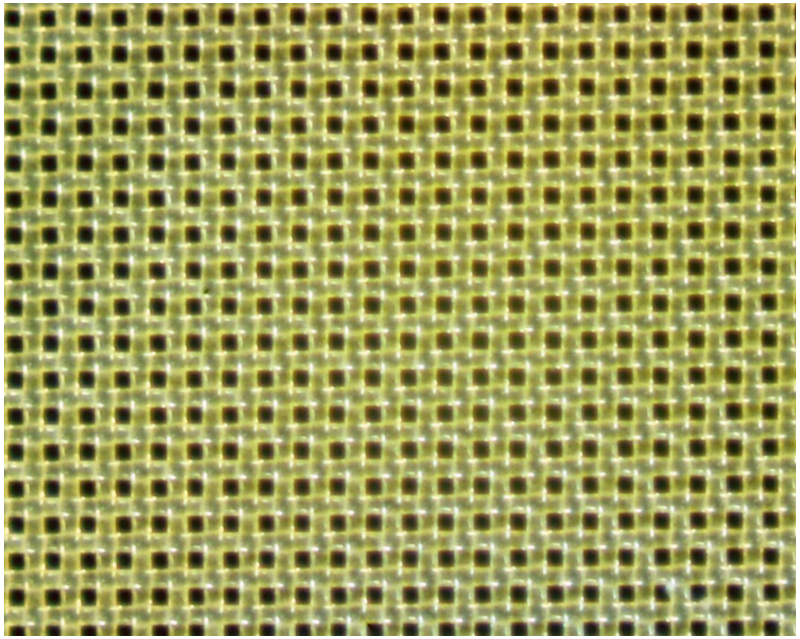
Screen & Prepress for Testing

Ink/mesh relationship *(Stainless Steel vs PET)*



400 Stainless Steel Mesh;
Plain Weave, 18µ wire dia.,
51% open area, 45µ opening
Max particle: 11µ



420 Polyester Mesh;
Plain Weave, 27µ thread dia.,
23% open area, 29µ opening
Max particle: 7µ

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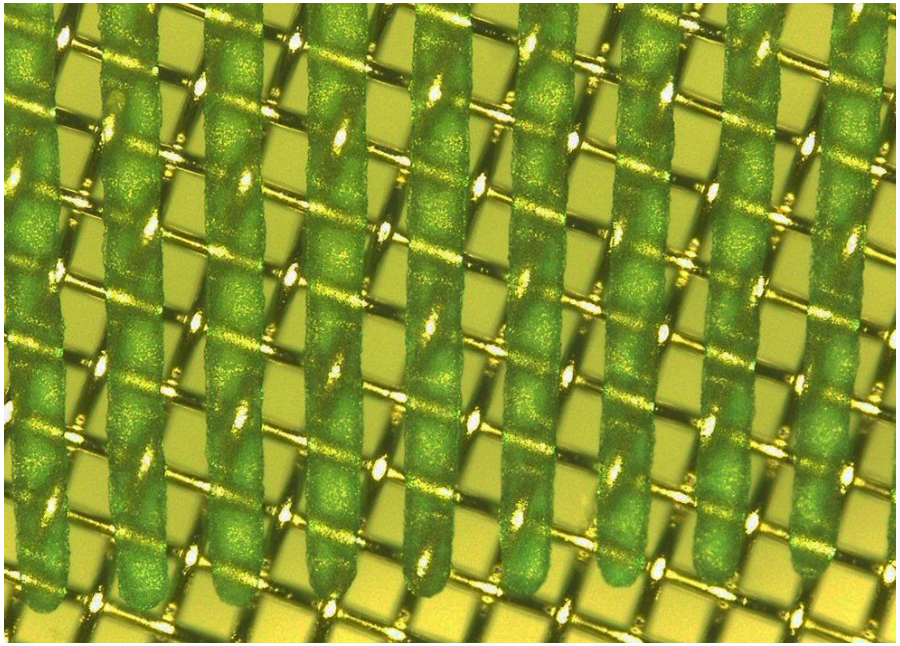
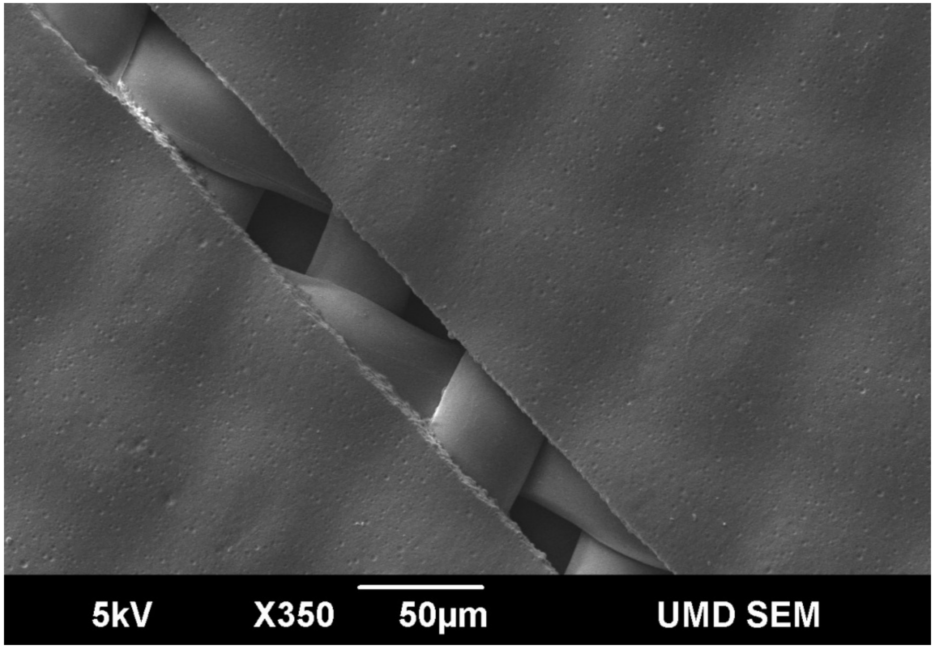
Screen & Prepress for Testing

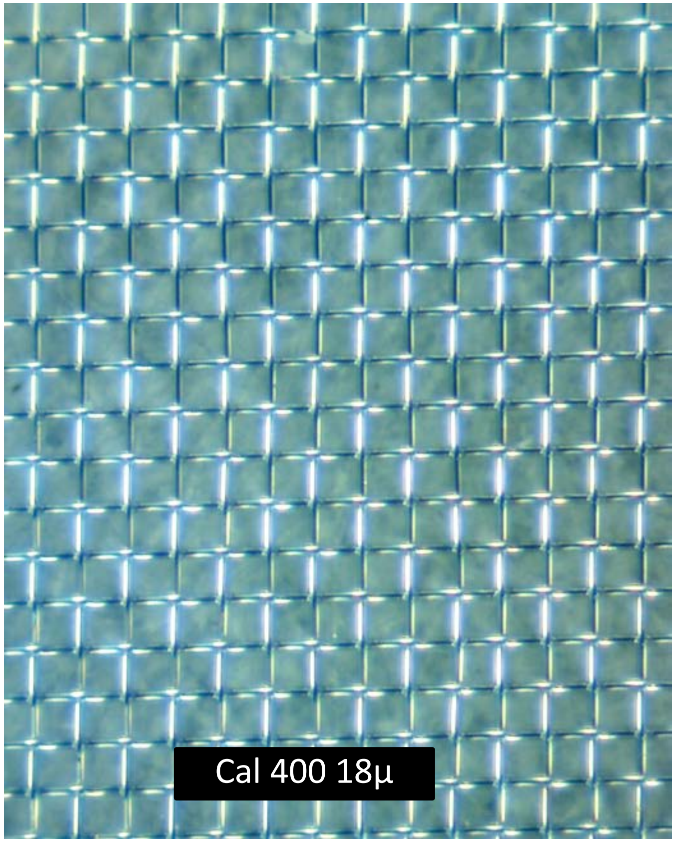
Ink/mesh relationship *(Stainless Steel vs PET)*





The larger PET thread size interferes with paste flow through the line channel.
SS alloy allows for thinner wire size and less obstruction to paste flow.

Screen & Prepress: Mesh Selection



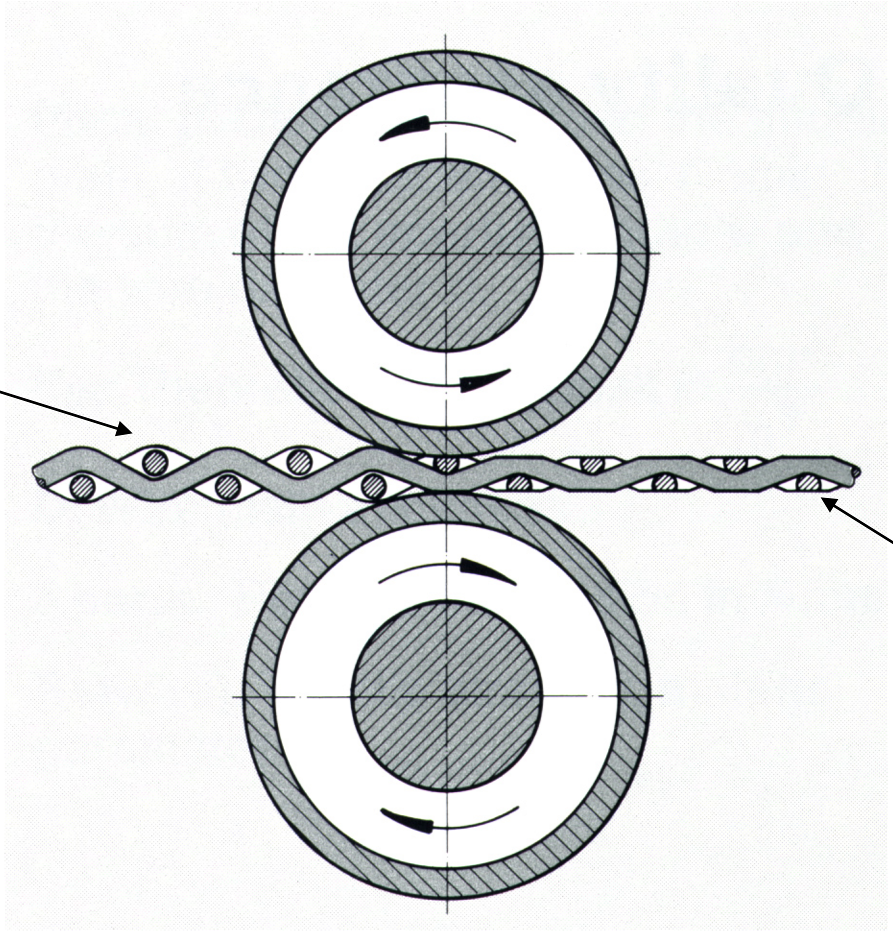
51% open area
29µm thickness

Although higher count/smaller diameter mesh types provide exceptional resolution capability, these were not used for print testing due to their significantly higher cost.

Calendared 400 – 18µ stainless steel wire mesh was selected based on US PE market acceptance (although there is still a wide level of "sticker shock" relating to the cost of this mesh type).

Wire Cloth Calendaring Process

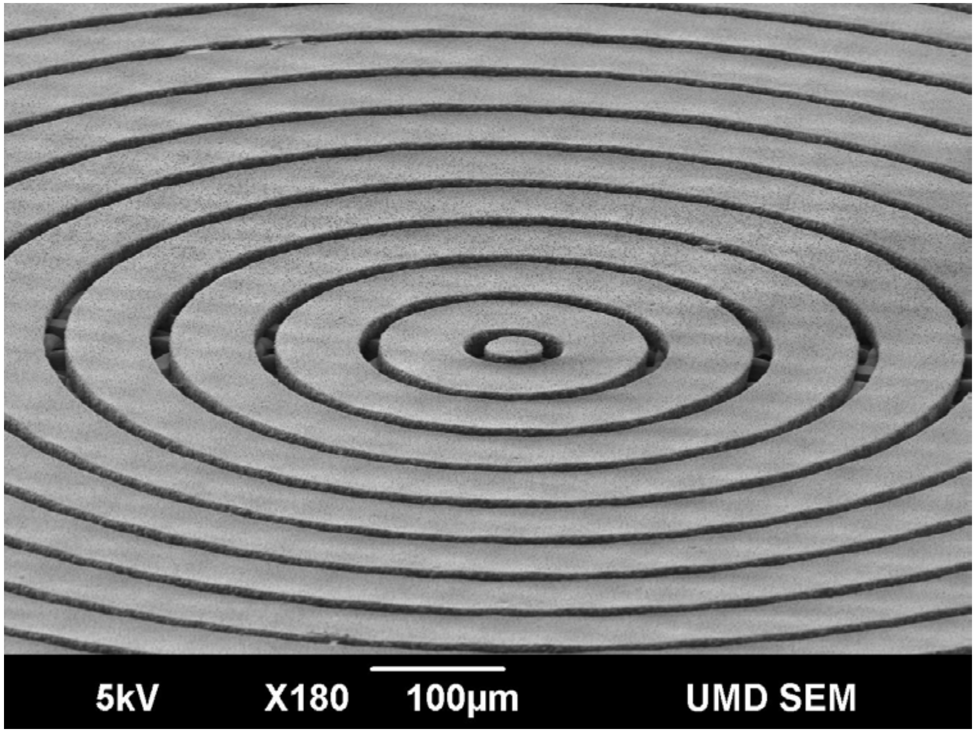
"As woven" mesh in



"Calendared" mesh out

Screen & Prepress: Stencil Selection

Factors which influence emulsion selection



Can the emulsion resolve all of the features in the artwork, specifically the smallest sizes?

Image reproduction accuracy and clarity is critical to achieving a sharp, clean and dimensionally acceptable print.

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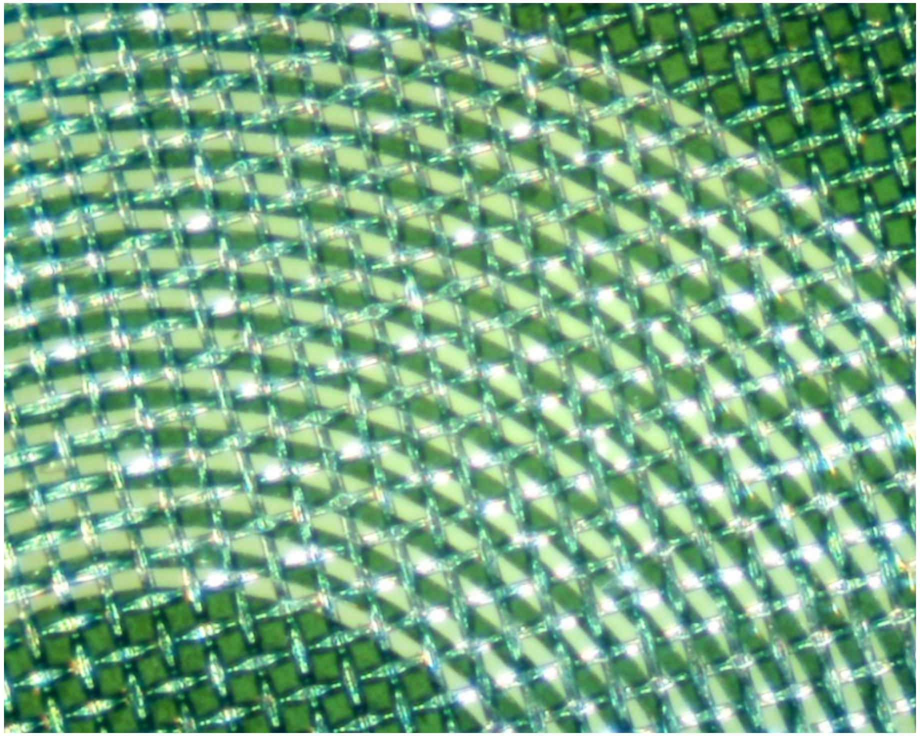
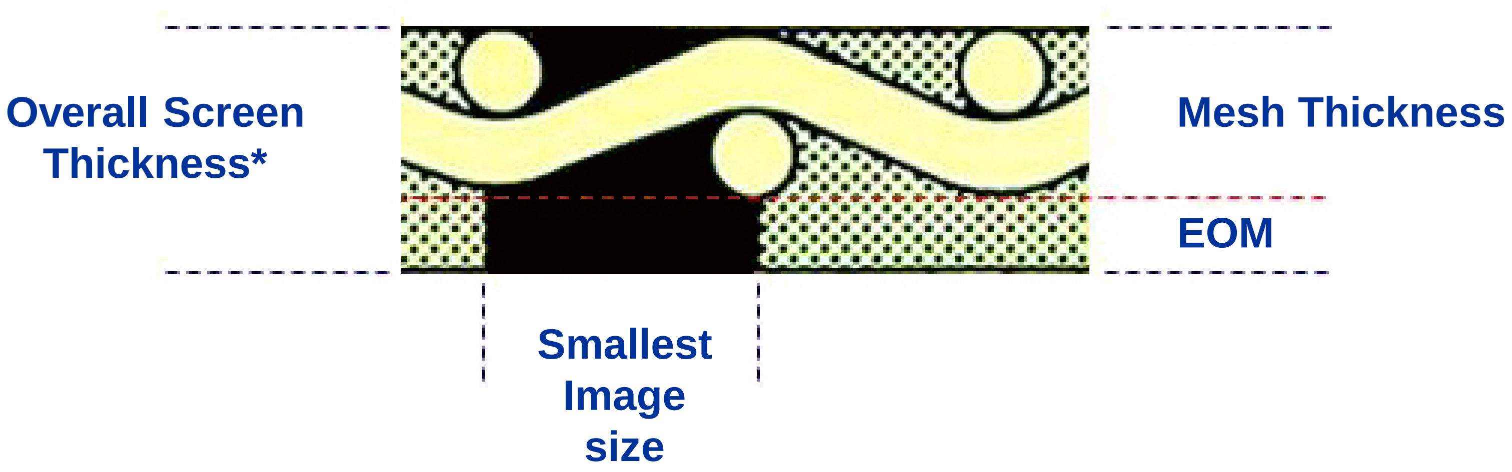
Screen & Stencil System



For the test printing we used the newly developed 25µ thick Capillary Film applied to Calendared 400-18µ stainless steel wire mesh. This enabled us to reproduce the smallest features (30µ) of the test artwork in screen-making. The EOM typically measured at ~ 10µm.

Aspect Ratio: Overall Screen Thickness vs Feature Size

Screen Printing is the only "contact" printing process that requires the ink to pass thru the printing plate from back to front.



**Overall Screen Thickness = Mesh Thickness + EOM*

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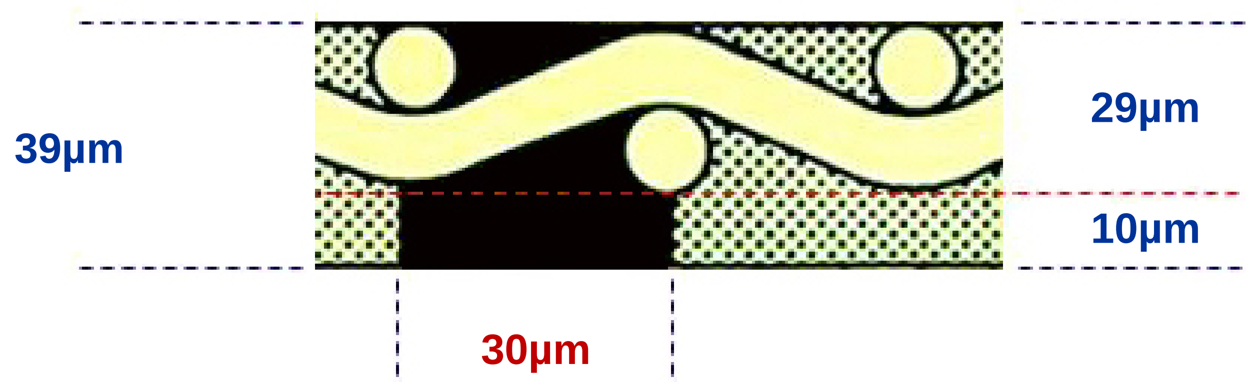
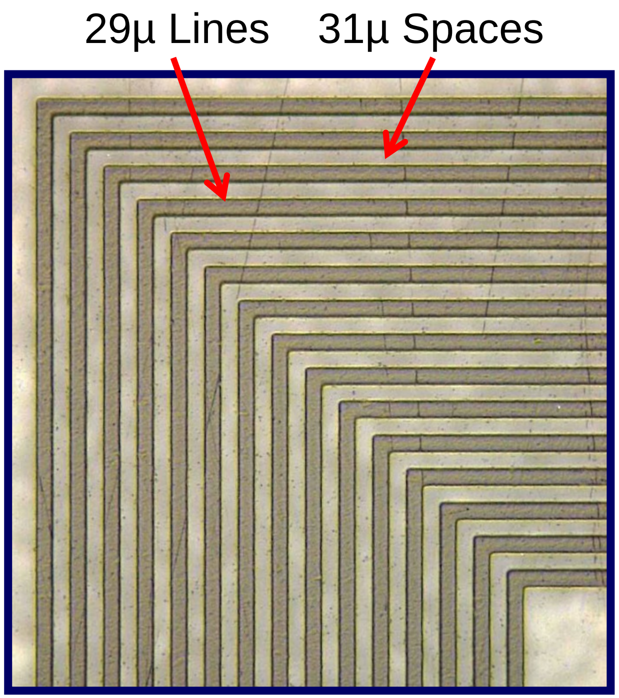
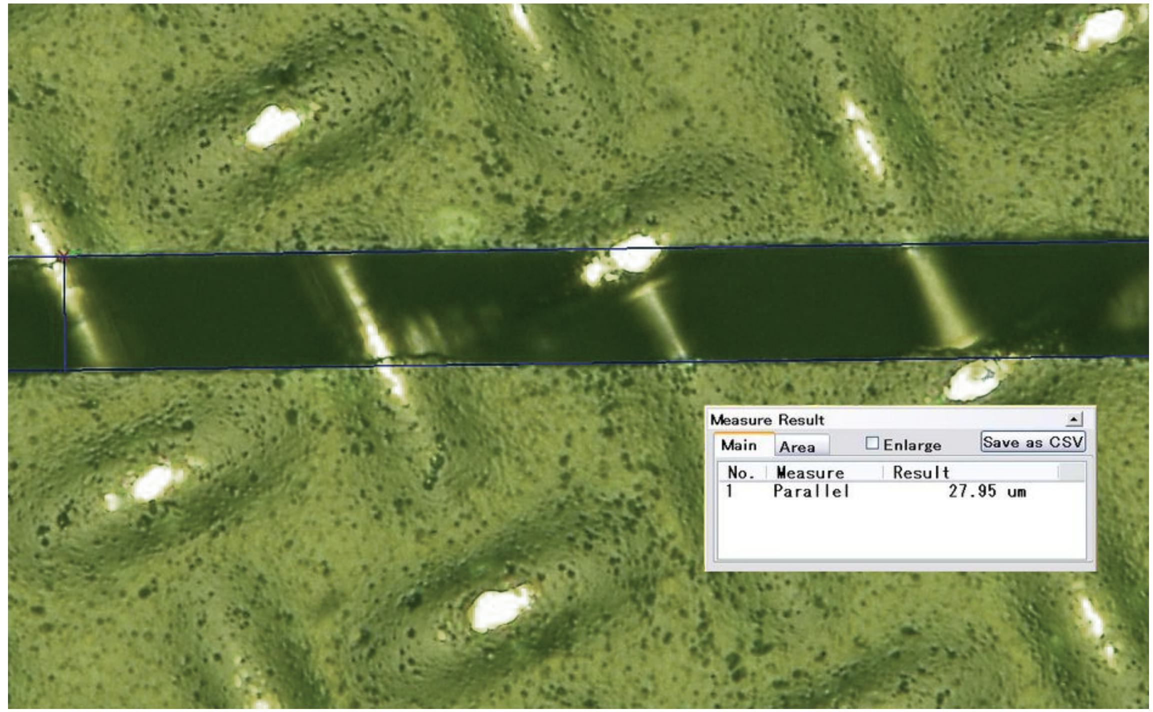
Aspect Ratio: Overall Screen Thickness vs Feature Size



- *The calendared mesh thickness of the CAL 400-18µ mesh was 29µ.*
- *Overall screen thickness for the CAL 400-18µ mesh with 10µ EOM was 39µ.*
- *The smallest feature on our test artwork was 30µ.*

Screen Stencil Image





Our 30µ designed lines measured at 29µ on the phototool (25,000 ppi) and ~28 microns in the screen stencil.

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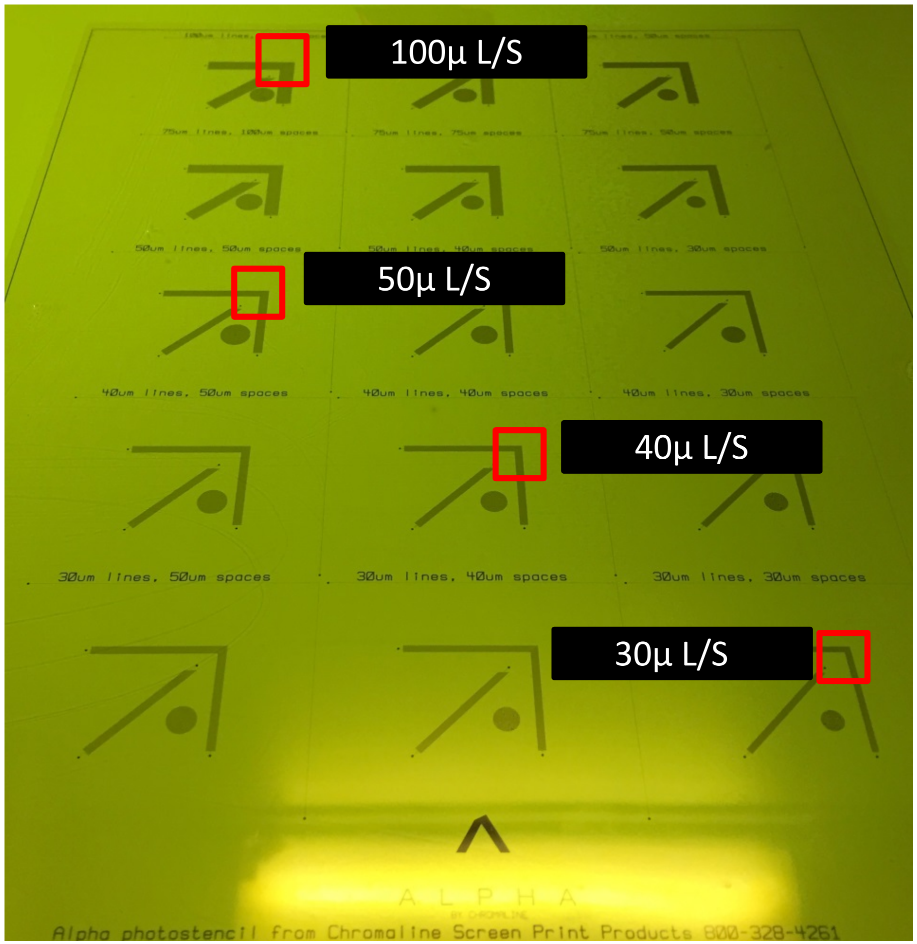
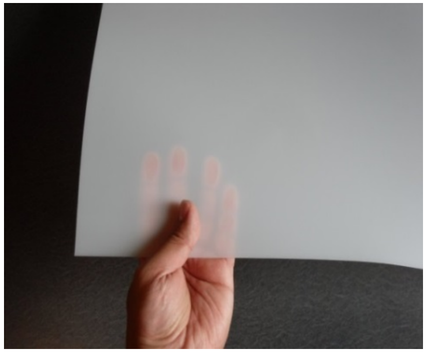
Screen & Printed Areas Typically Measured

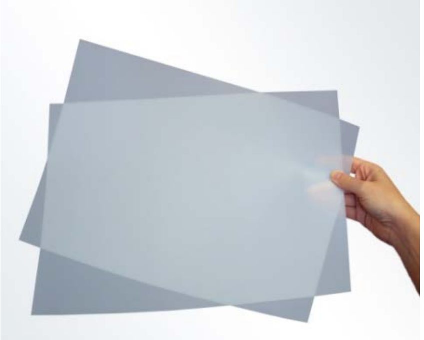


Flexible PET Substrates Tested

- Substrate A (common industry material)
  - Print treated PET
    - Primer for ink adhesion
  - Pre-stabilized
  - Optically clear



- Substrate B (common industry material)
  - Surface treated PET
    - Ink adhesion
    - High surface tension
  - Pre-stabilized
  - Hazy / translucent

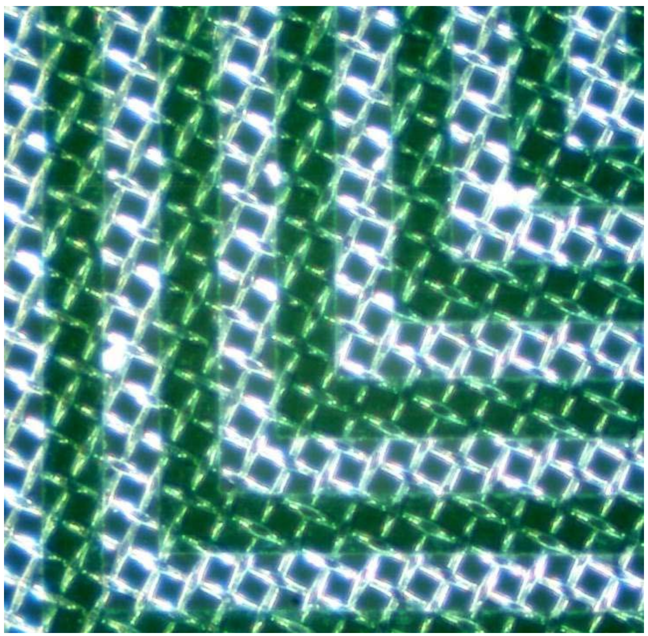


- Substrate F (newly developed)
  - Coated PET
    - Ink adhesion promoter
    - PSR – Print Spread Retention
  - Pre-stabilized
  - Hazy / translucent

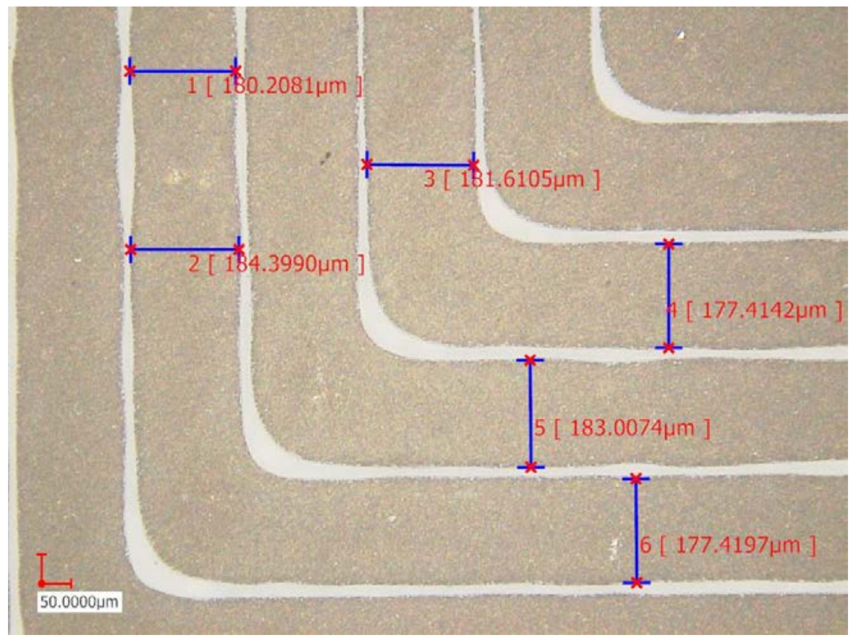
100µm Traces/Spaces *(Ag Paste)*

Substrate A, printed image sizes

Screen



Print



<u>Average</u>
178.5µm
79% spread

<u>Range</u>
164µm - 189µm

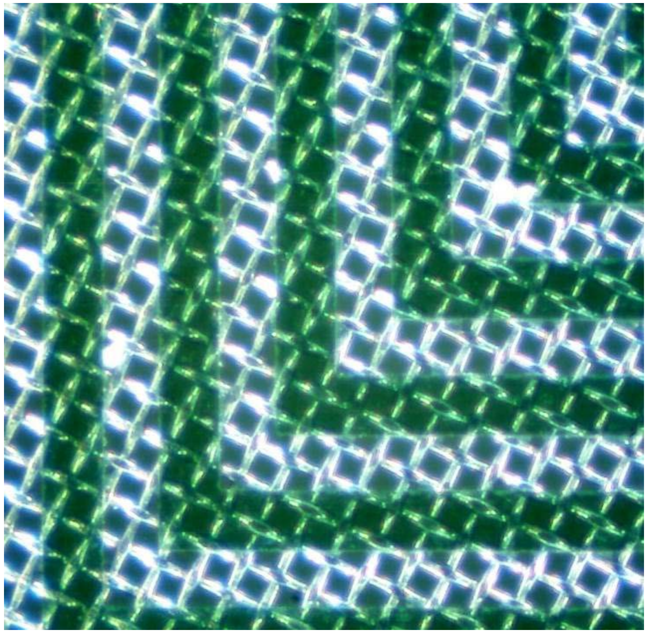
<u>Max Spread</u>
89%

Squeegee direction

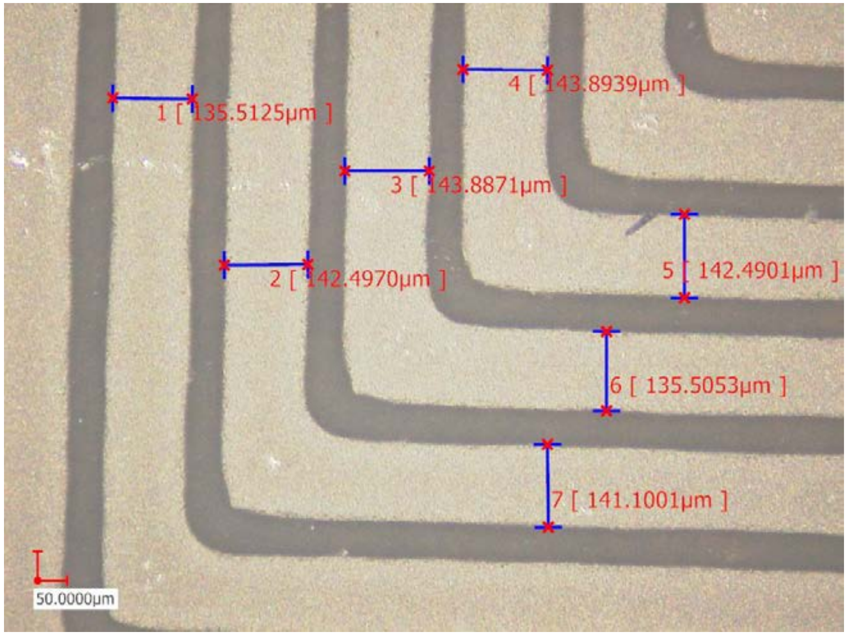
100µm Traces/Spaces *(Ag Paste)*

Substrate B, printed image sizes

Screen



Print



<u>Average</u>
142.7µm
43% spread

<u>Min. - Max.</u>
136µm - 148µm

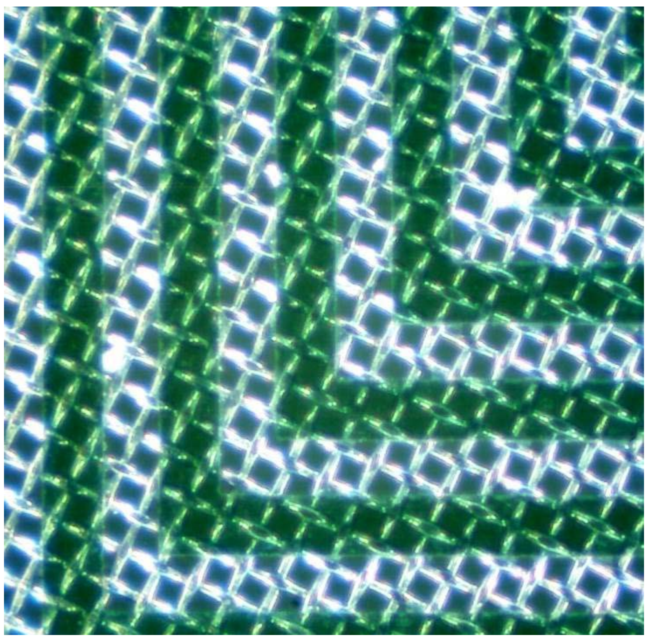
<u>Max Spread</u>
48%

Squeegee direction

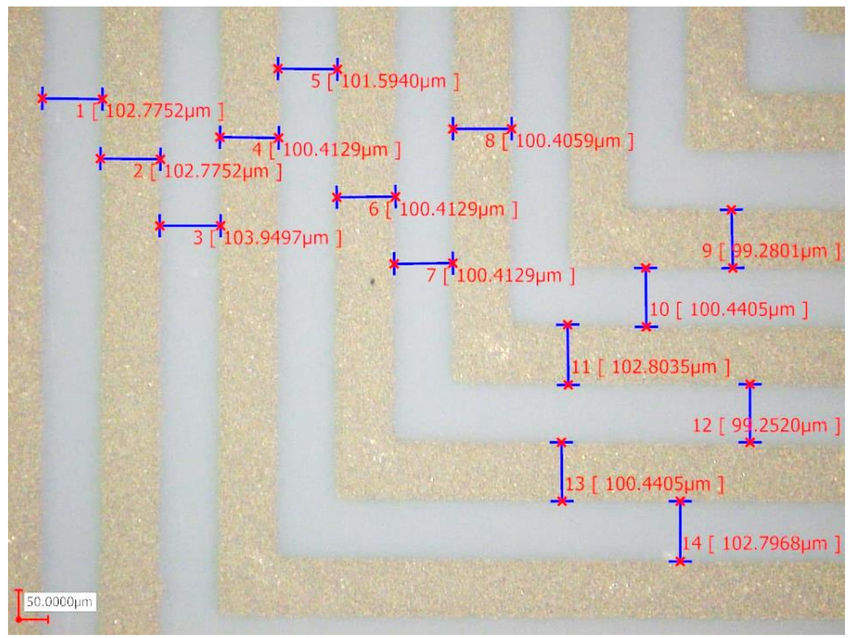
100µm Traces/Spaces *(Ag Paste)*

Substrate F, printed image sizes

Screen



Print



<u>Average</u>
101.4µm
< 2% spread

<u>Min. - Max.</u>
96µm - 109µm

<u>Max Spread</u>
9%

Squeegee direction

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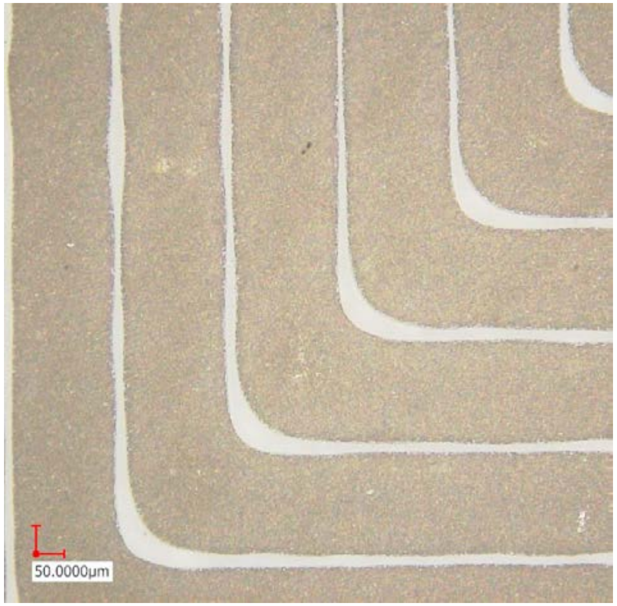
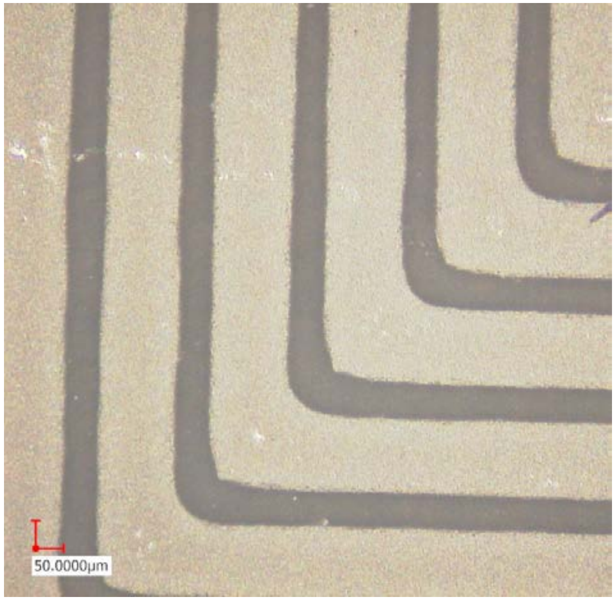
100µm Traces/Spaces *(Ag Paste)*

Substrate A



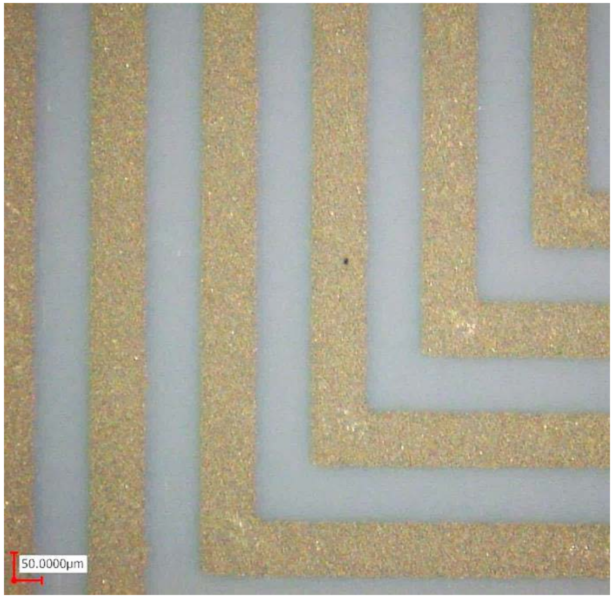
164µm - 189µm

Substrate B



136µm - 148µm

Substrate F



96µm - 109µm

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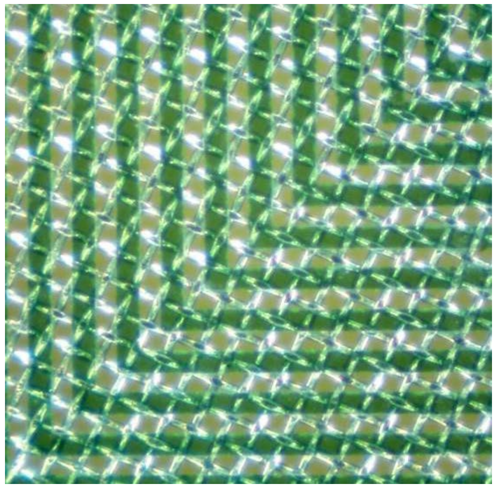
50µm Traces/Spaces *(Ag Paste)*

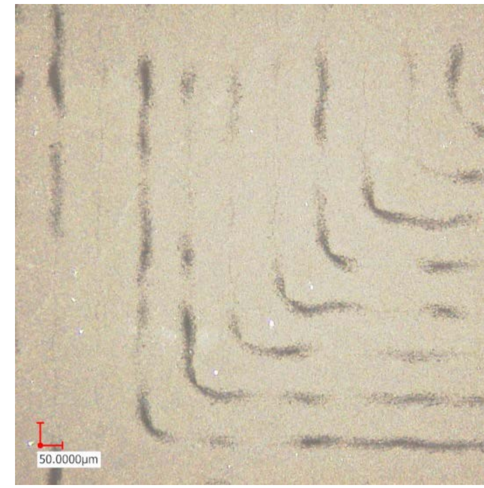
Screen

49µm



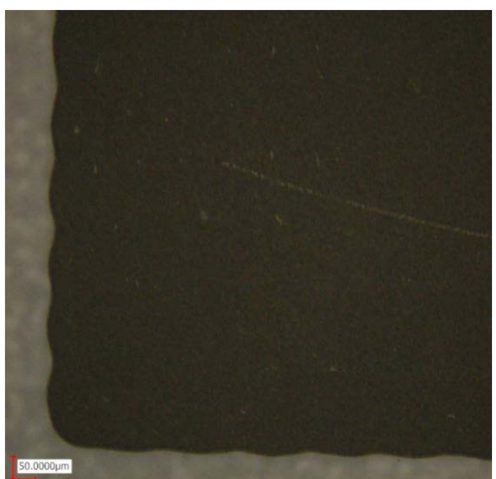
Substrate B

>50µm, shorting



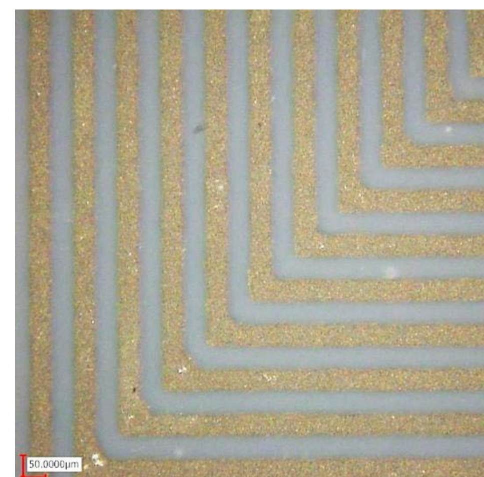
Substrate A

>50µm, shorting



Substrate F

44um - 54um



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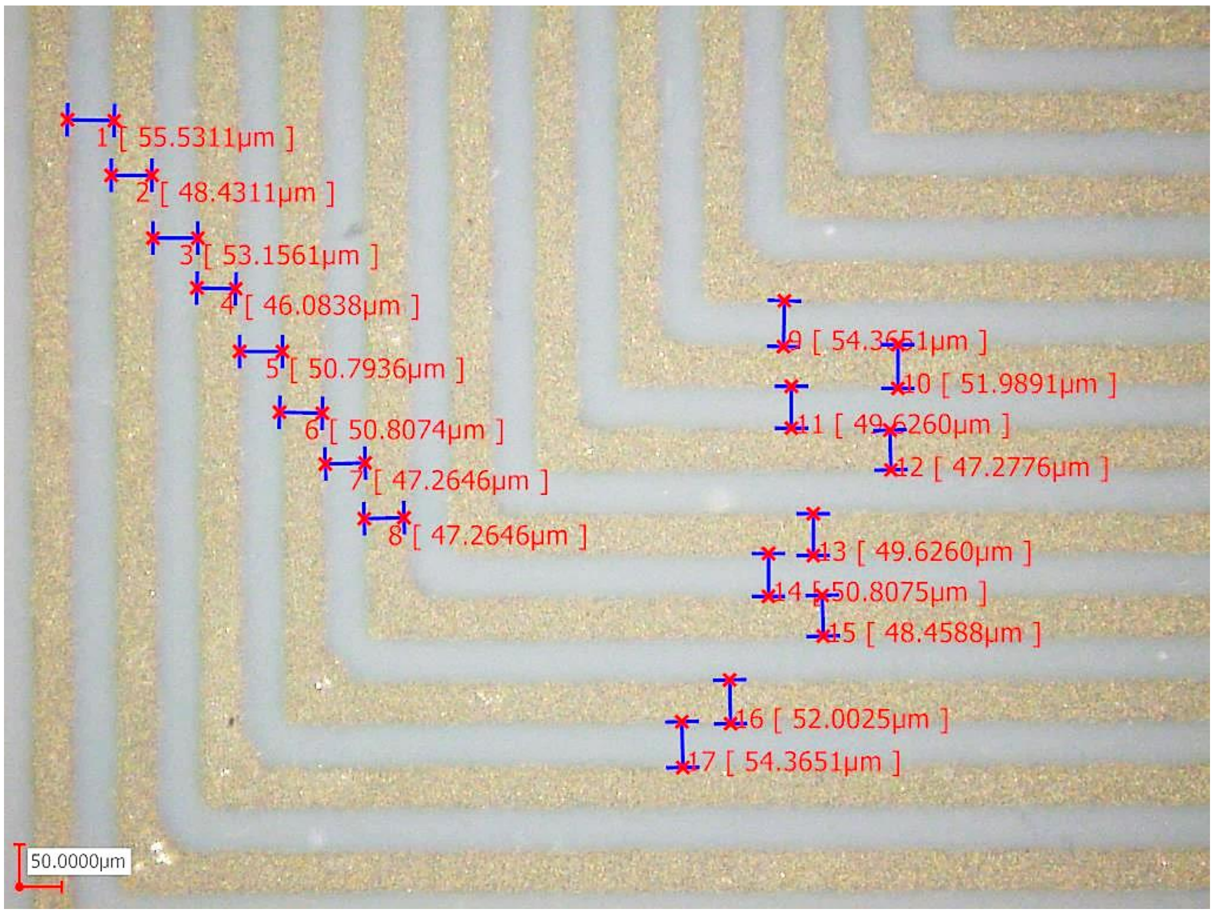
50µm Traces/Spaces *(Ag Paste)*

Substrate F, Paste Spread



<u>Average</u>
49.1 um
< 2% shrink

<u>Min. - Max.</u>
44um - 54um

<u>Max Spread</u>
8%

Squeegee direction

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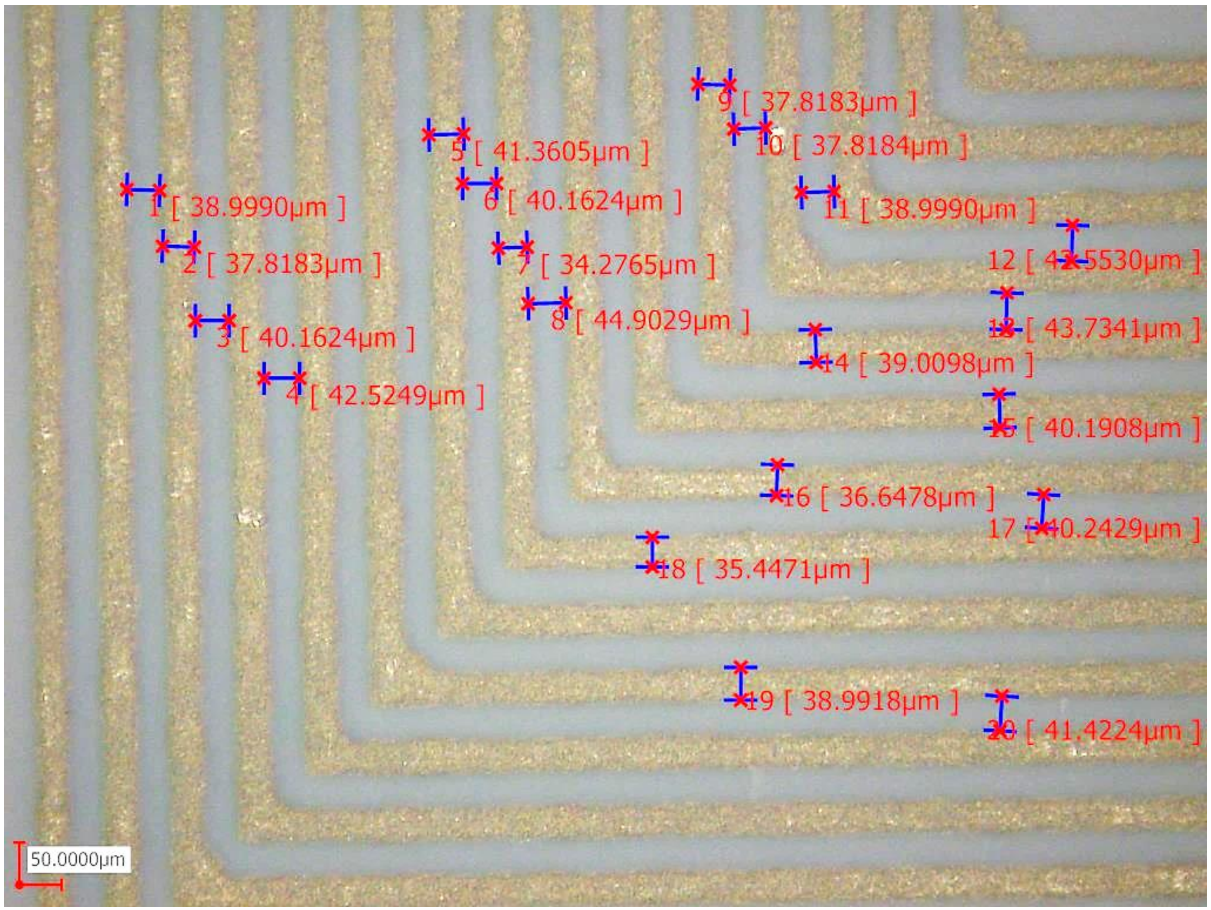
40µm Traces/Spaces *(Ag Paste)*

Substrate F, Paste Spread



<u>Average</u>
40.9µm
~ 2% spread

<u>Min. - Max.</u>
34µm - 46µm

<u>Max Spread</u>
15%

Squeegee direction

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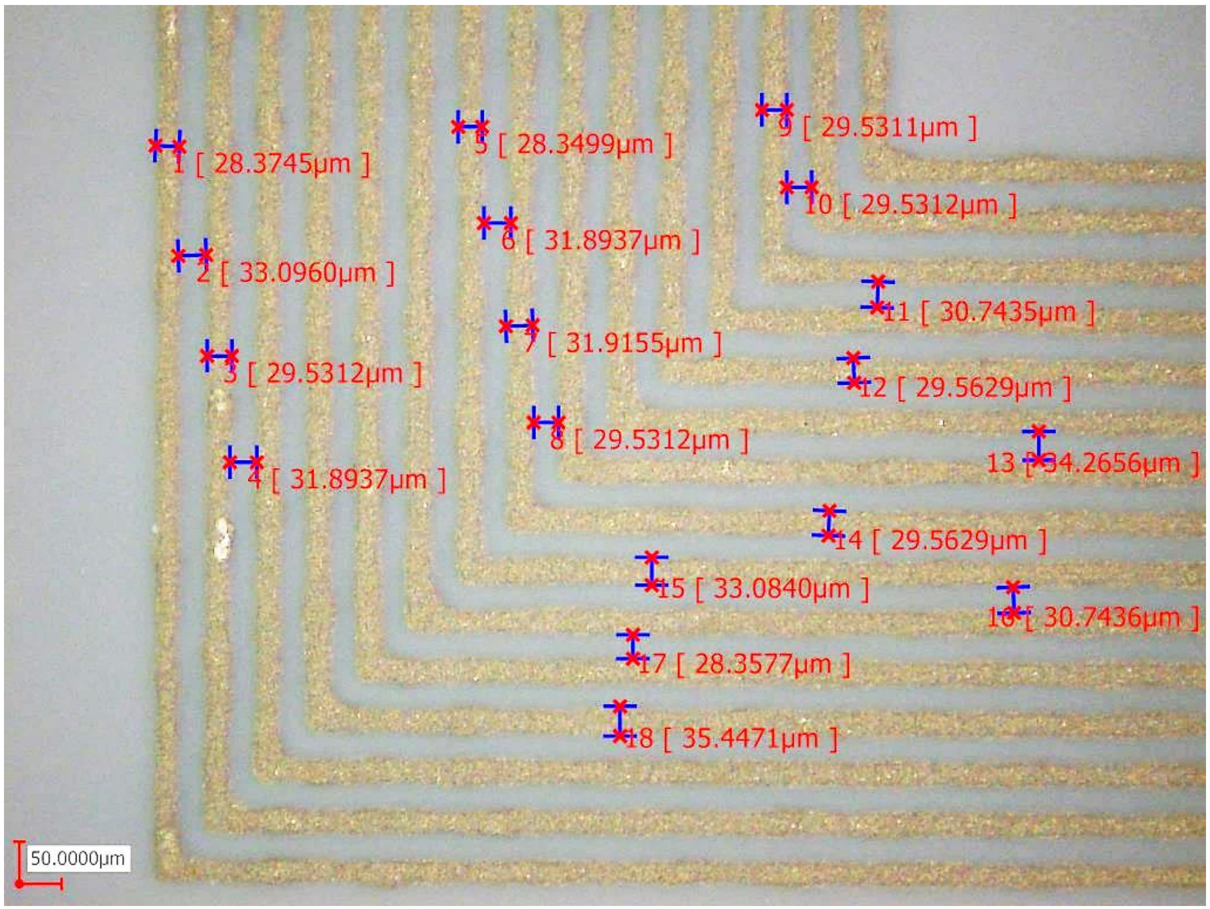
30µm Traces/Spaces *(Ag Paste)*

Substrate F, Paste Spread



<u>Average</u>
30.8 um
~ 3% spread

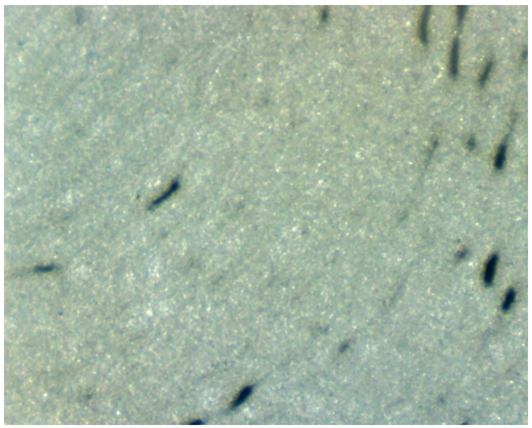
<u>Min. - Max.</u>
26um - 37um

<u>Max Spread</u>
23%

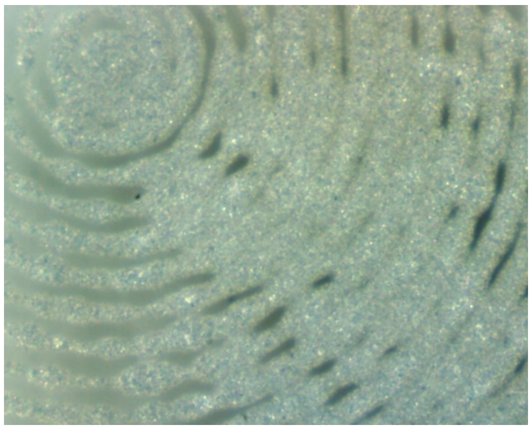
Squeegee direction

50, 40, & 30um Concentric Circles

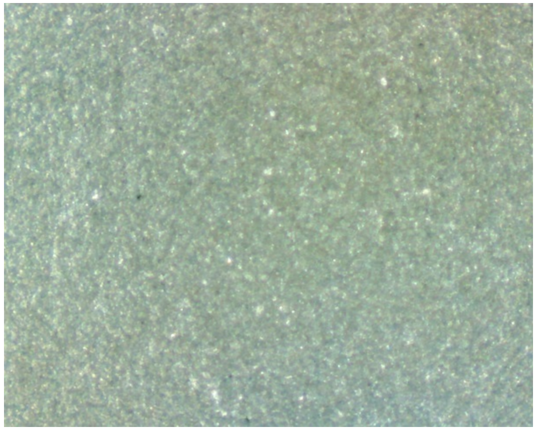
Substrate A - 50um



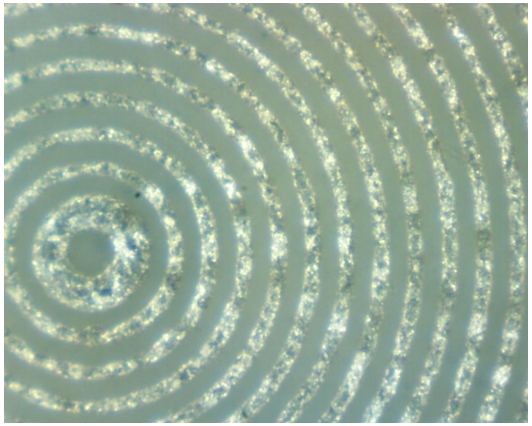
Substrate A - 40um



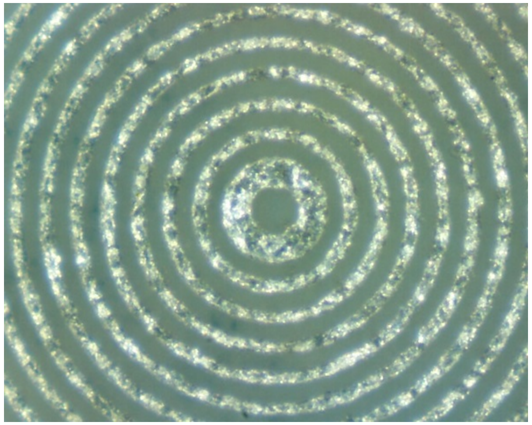
Substrate A – 30/50um



Substrate F - 50um



Substrate F - 40um



Substrate F – 30/50um

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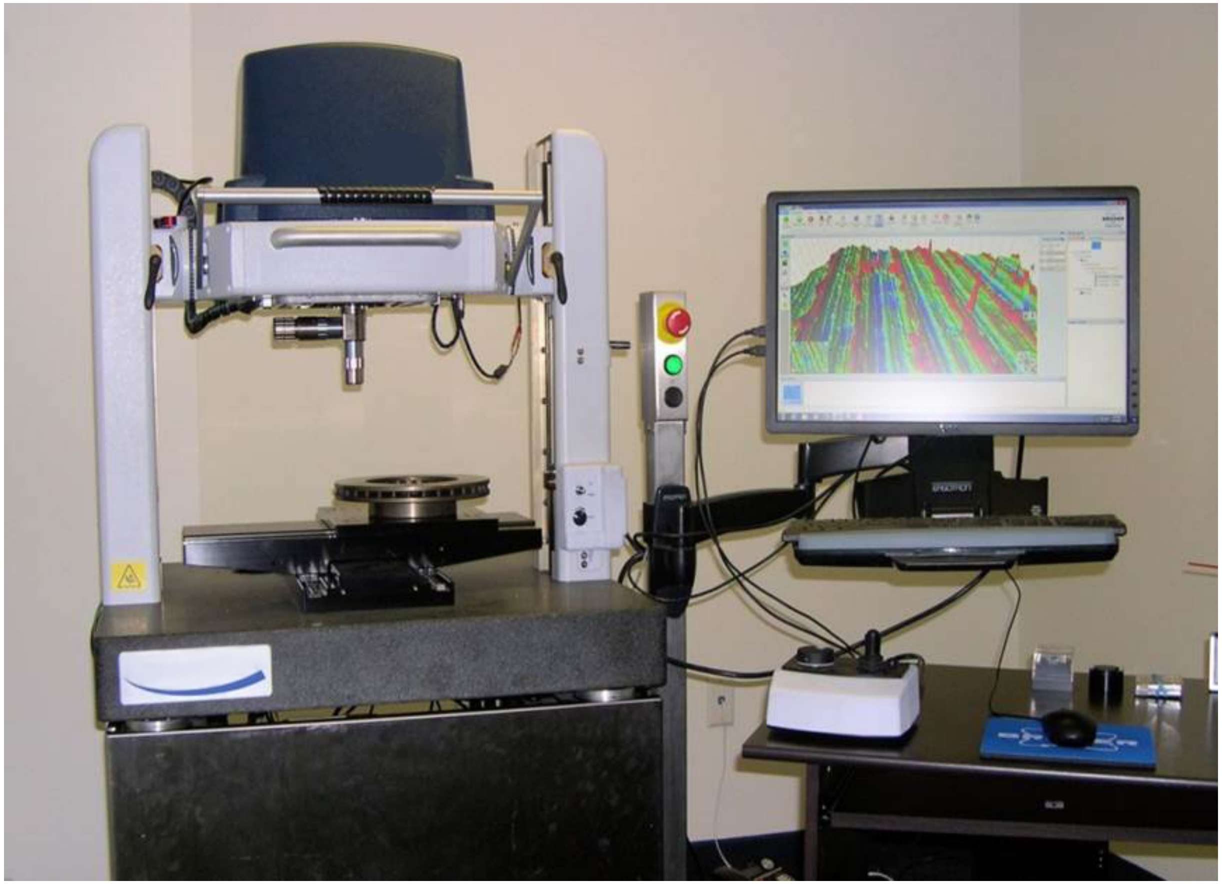
3D Surface Micro-Texture Measurement & Analysis Data

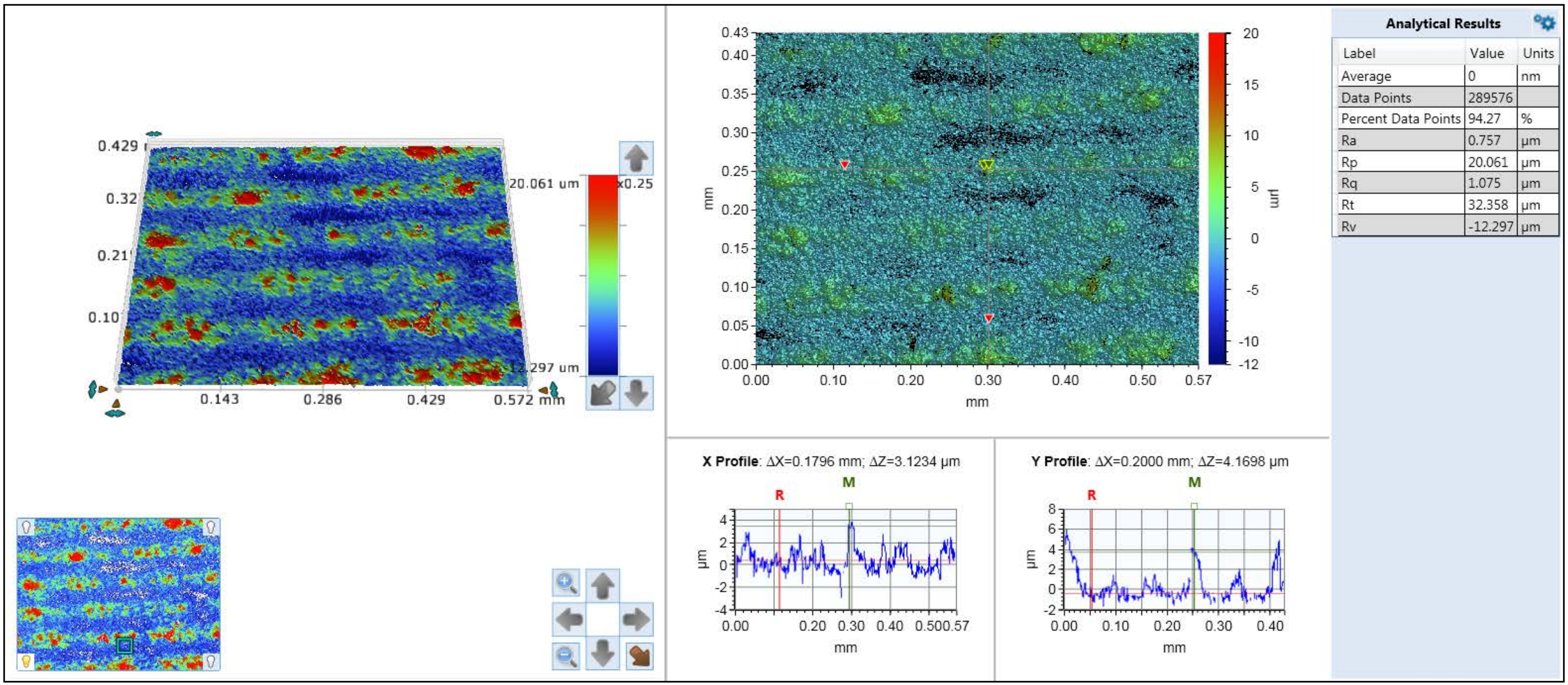
Production 3D Optical Microscope



Production Optical Microscope Measurement Data

Substrate A – Location 1

Squeegee direction

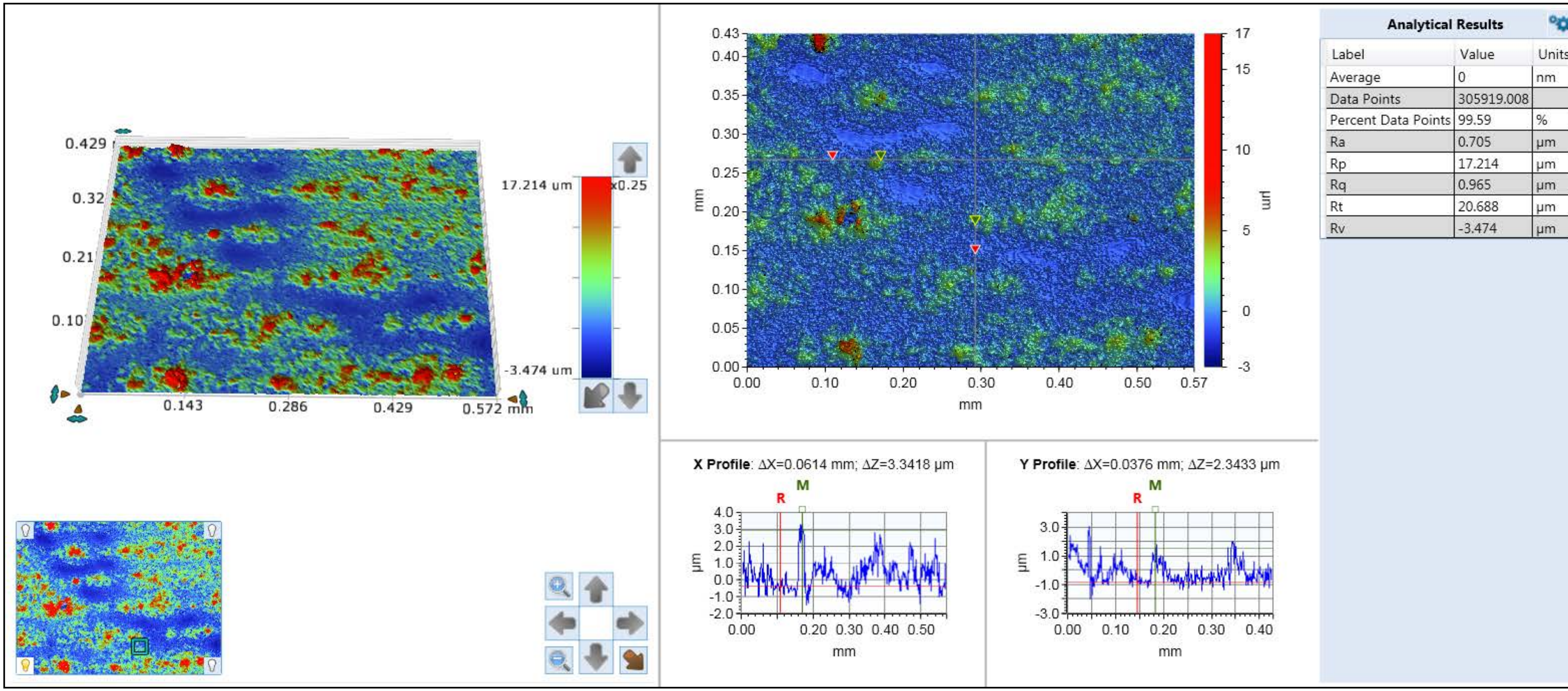


Label	Value	Units
Average	0	nm
Data Points	289576	
Percent Data Points	94.27	%
Ra	0.757	µm
Rp	20.061	µm
Rq	1.075	µm
Rt	32.358	µm
Rv	-12.297	µm

Production 3D Optical Microscope Measurement Data

Substrate B – Location 1

Squeegee direction

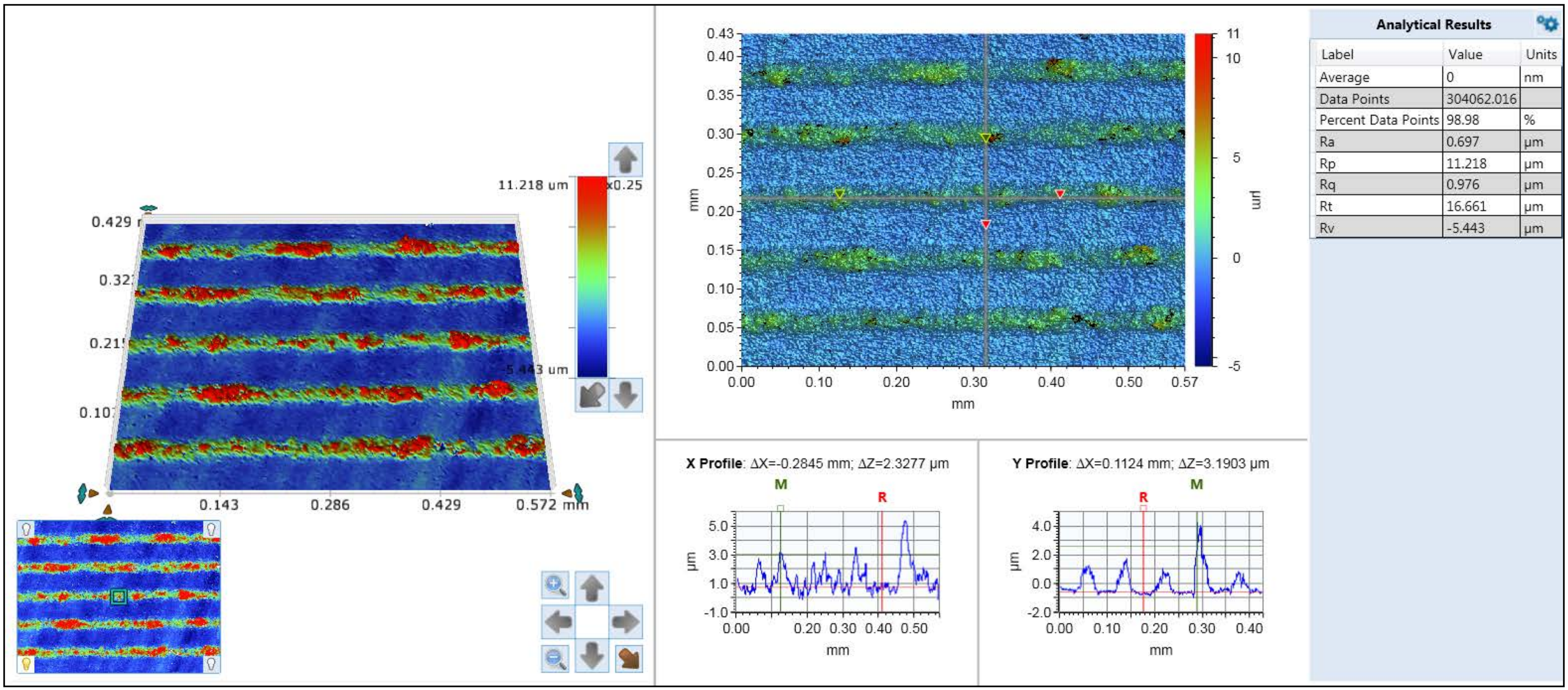


Label	Value	Units
Average	0	nm
Data Points	305919.008	
Percent Data Points	99.59	%
Ra	0.705	µm
Rp	17.214	µm
Rq	0.965	µm
Rt	20.688	µm
Rv	-3.474	µm

Production 3D Optical Microscope Measurement Data

Substrate F – Location 1

Squeegee direction



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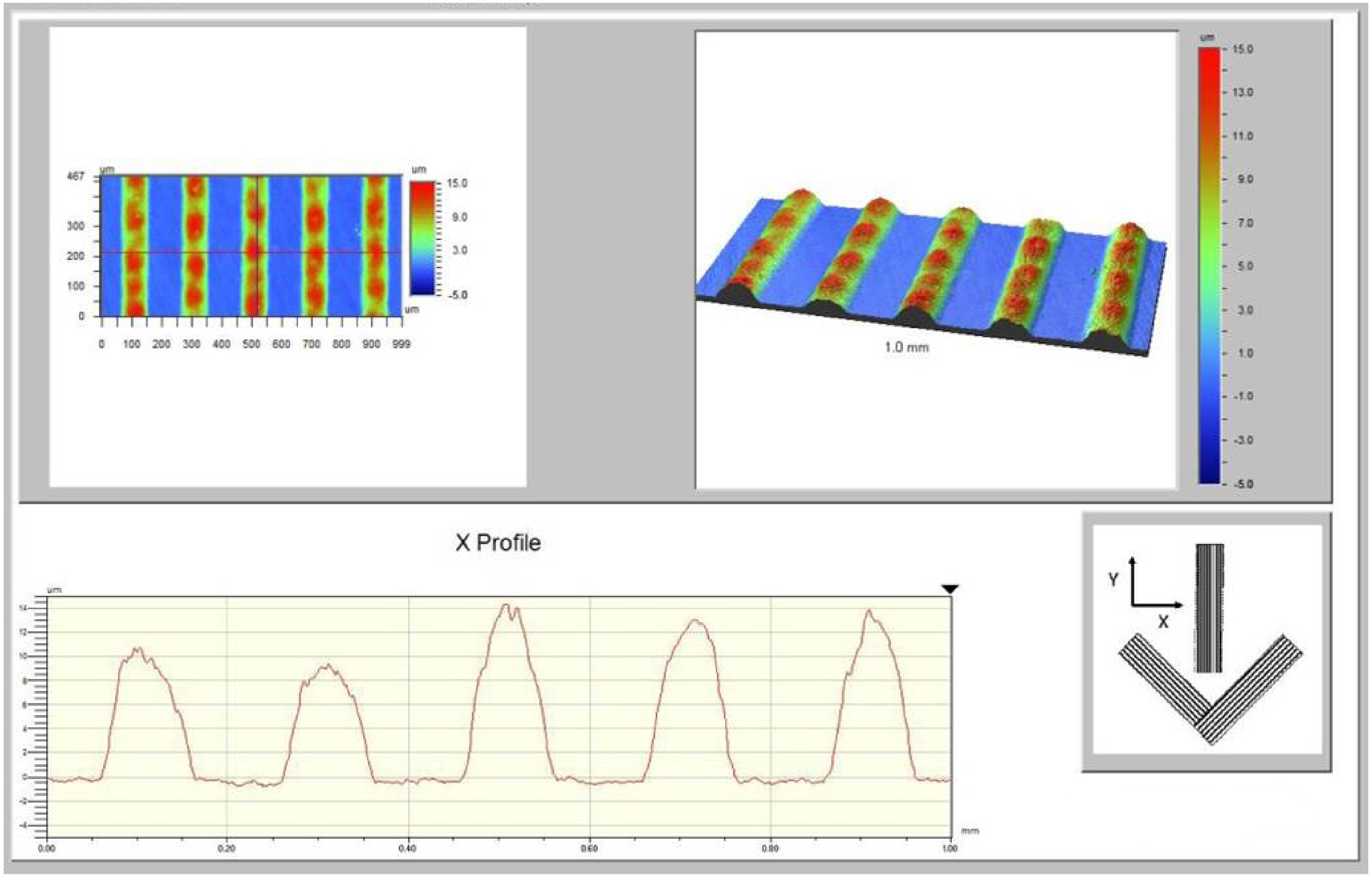
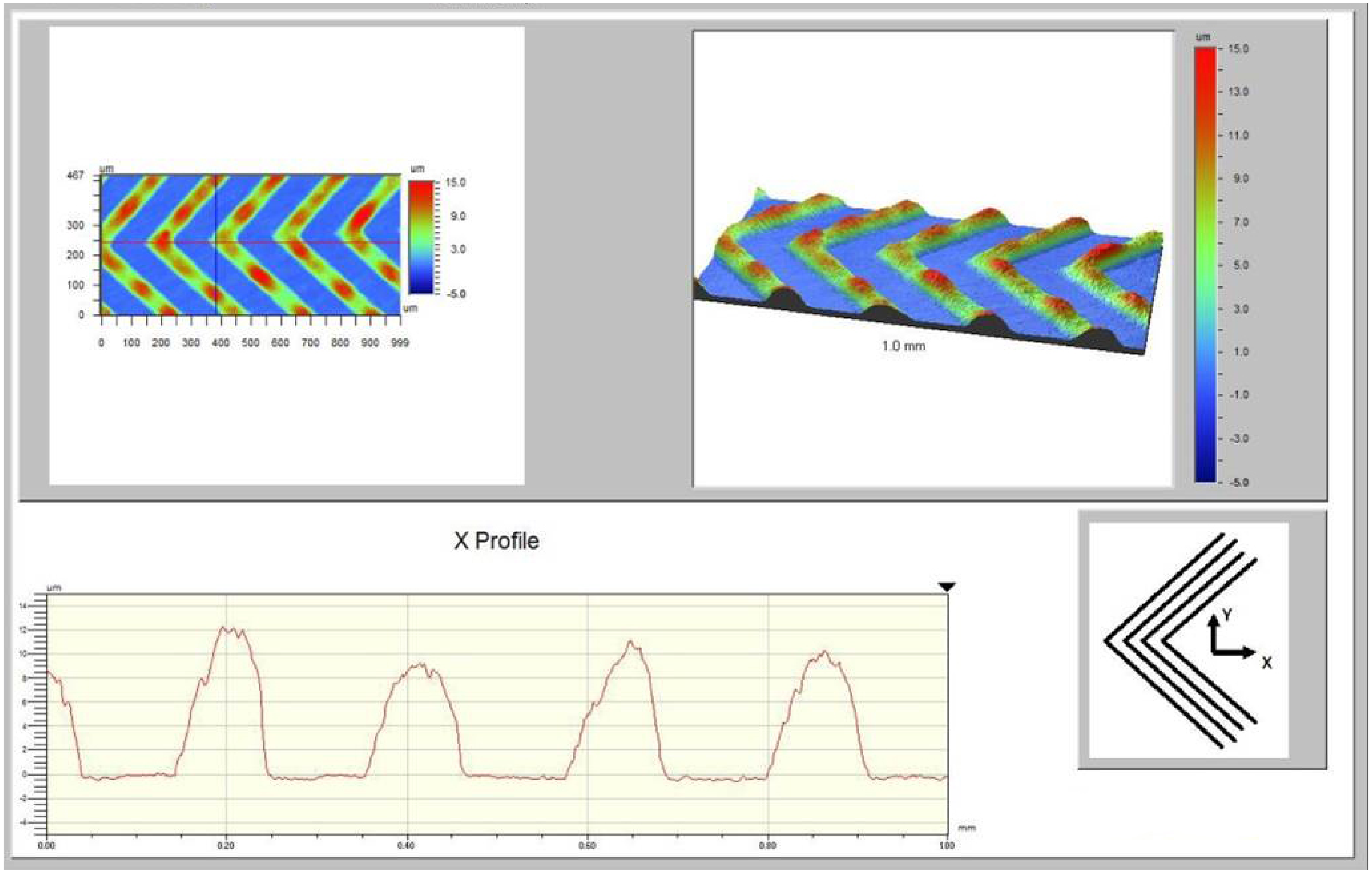
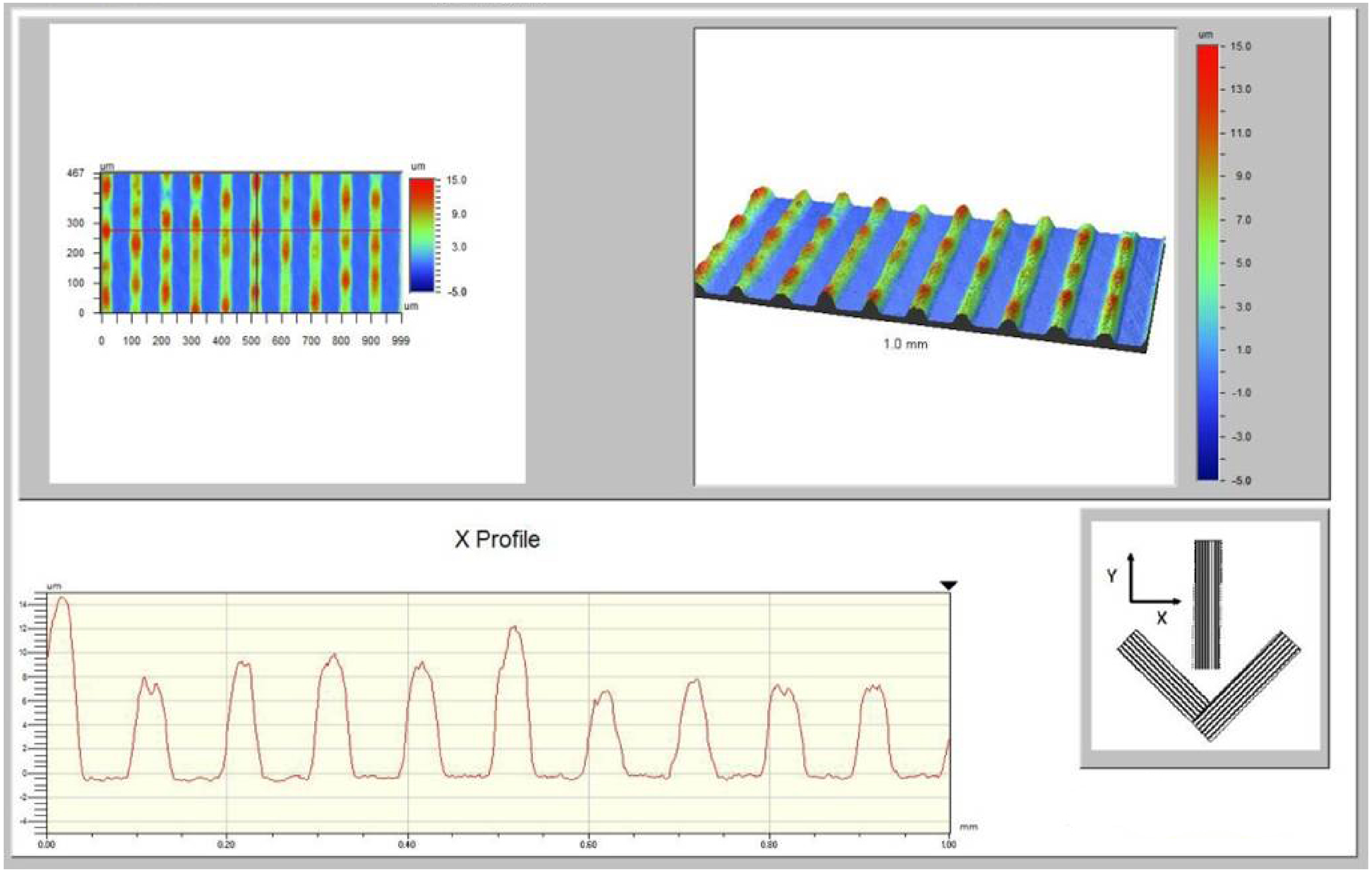
Substrate F, Production 3D Optical Microscope X-Axis Profile: 100µ lines & spaces



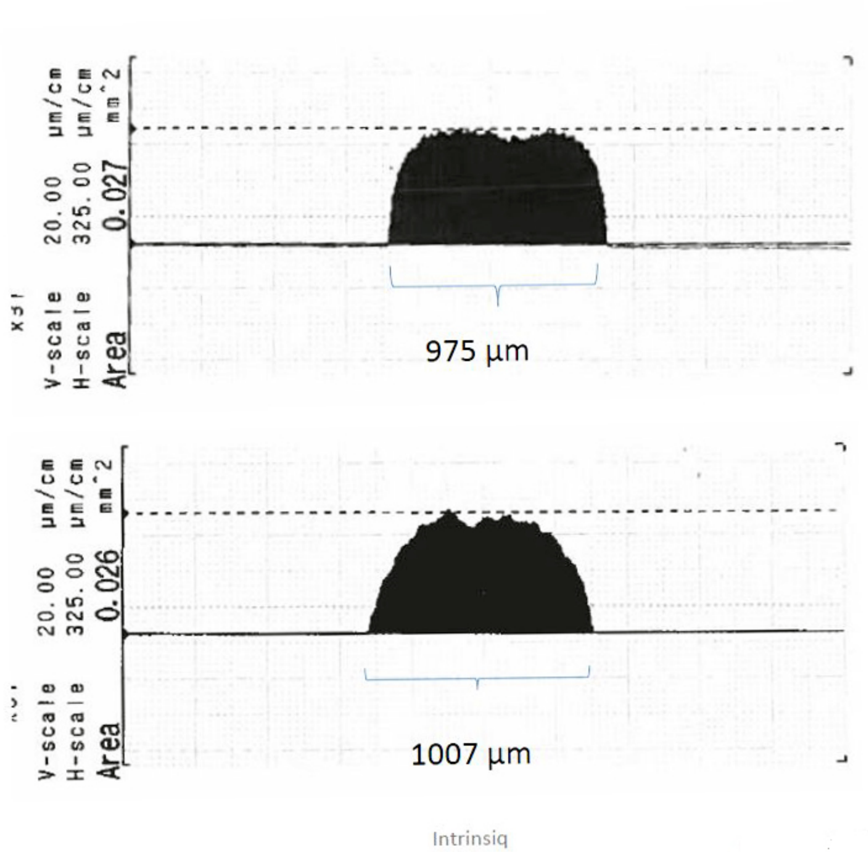
Substrate F, Production 3D Optical Microscope X-Axis Profile: 75µ right angles



Substrate F, Production 3D Optical Microscope X-Axis Profile: 50µ lines & spaces



Profiles of Screen Printed Copper Conductors



Substrate F

Substrate A

Cross-sectional measurement data of1000µm wide screen printed copper conductor traces [1]

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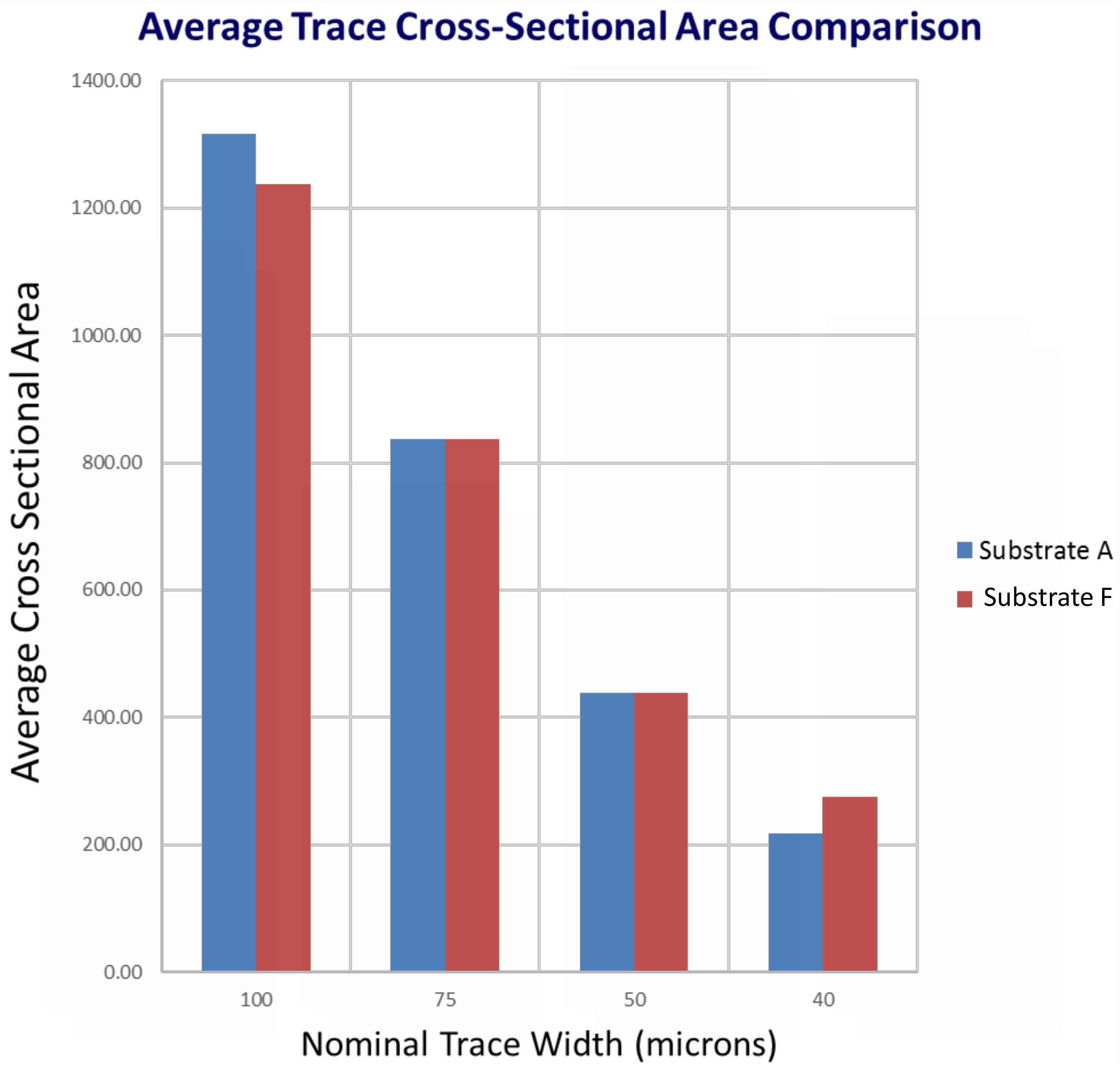
- Average trace cross-sectional area is very similar between Substrate A and Substrate F



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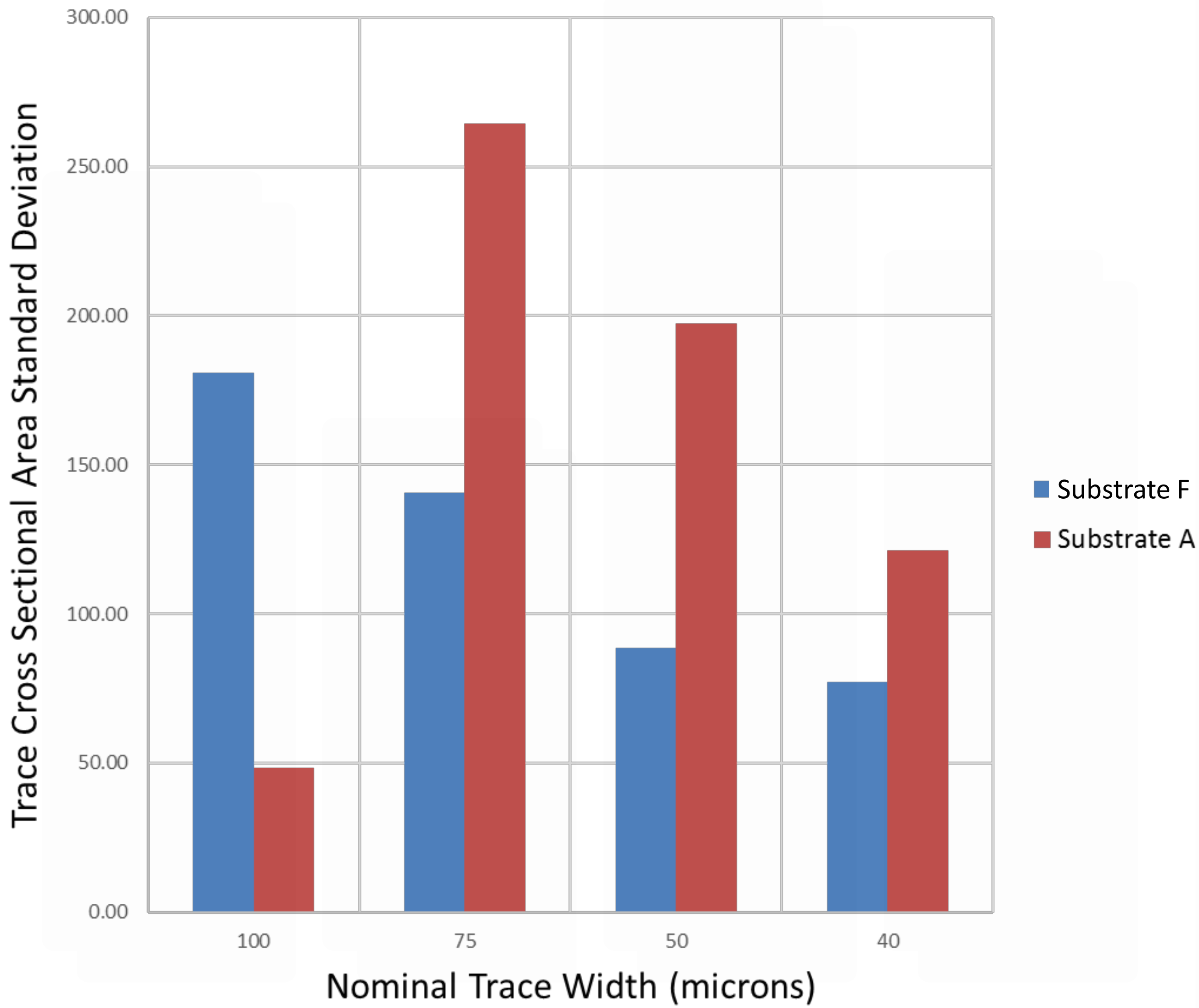
Trace Cross-Sectional Area Standard Deviation

- Standard Deviation of the trace cross-sectional area for Substrate A is greater than that of Substrate F



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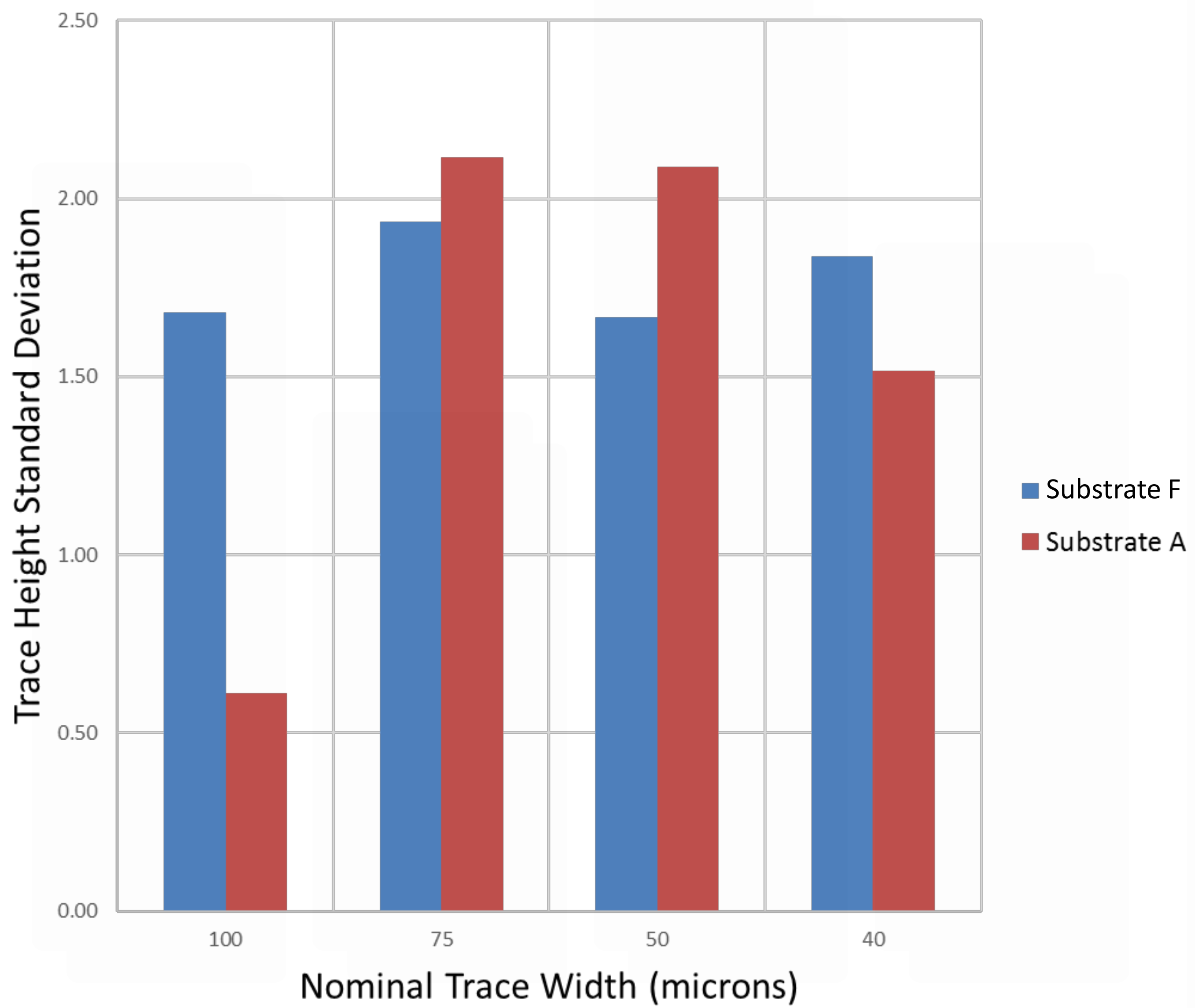
Trace Height Standard Deviation

- Substrate F does not appear to influence trace height standard deviation
- This trend is most likely dictated by screen/paste/press conditions



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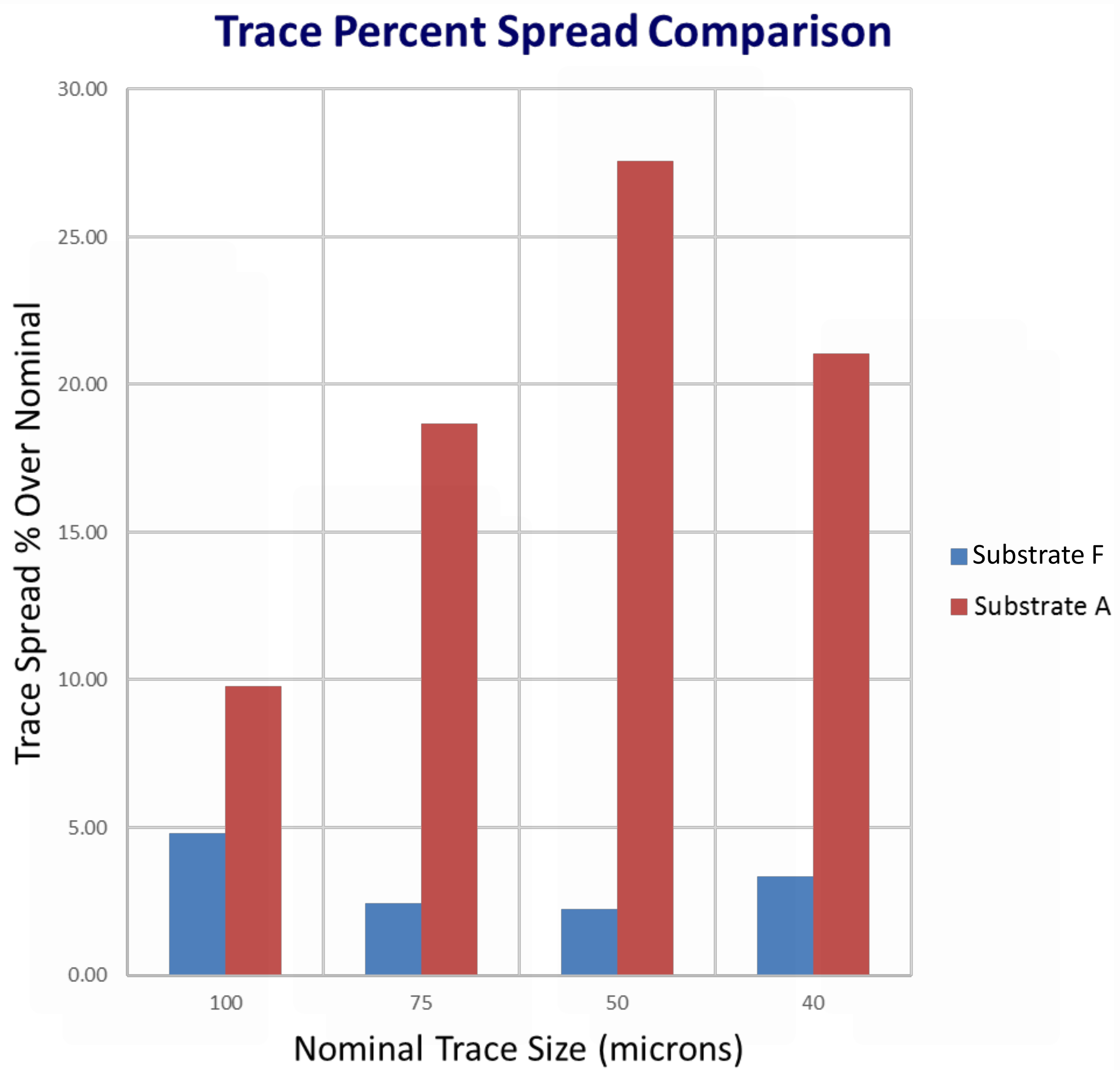
- Percent Spread is less than 5% over nominal across all traces printed on Substrate F

- Substrate A spread varies from 8 to 28% over nominal with increasing spread as trace width decreases



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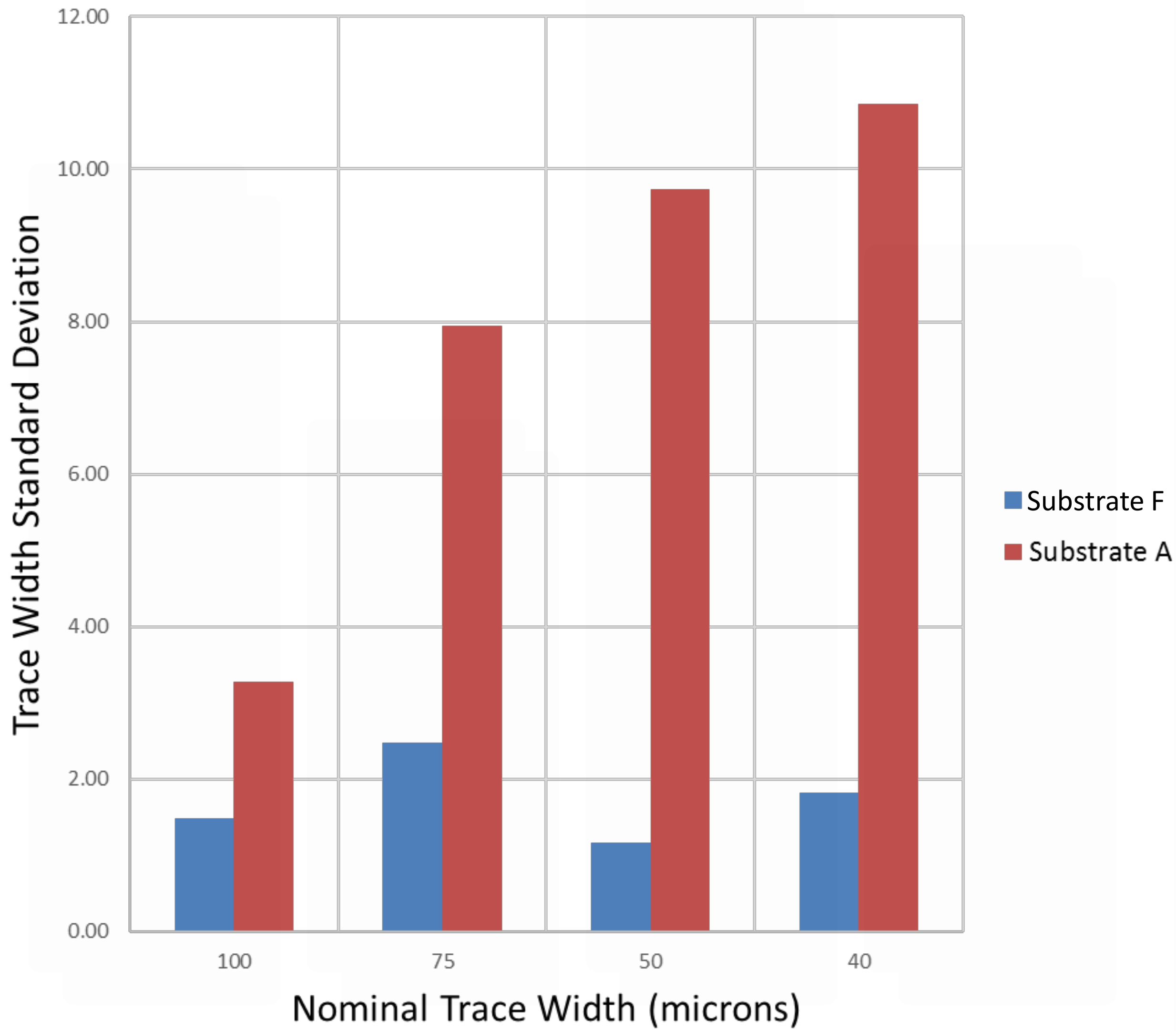
Trace Width Standard Deviation

- Substrate A has significantly higher standard deviation of trace width
- Standard Deviation increases as trace width decreases for Substrate A.
- Standard deviation for Substrate F is relatively constant



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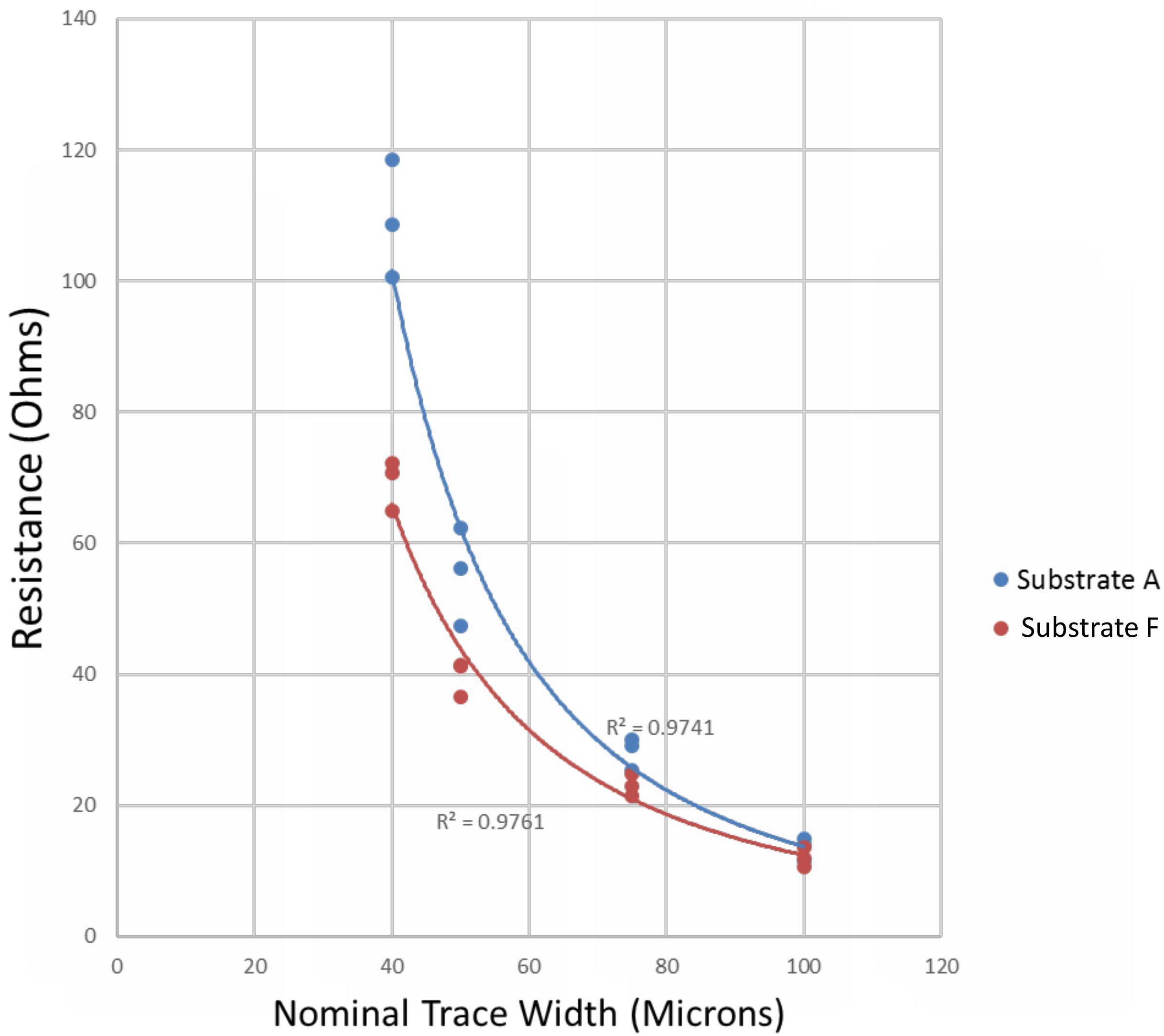
Trace Resistance Values

- Trace Resistance Values were higher on Substrate A
- Trace Resistance Delta decreases with increasing trace width



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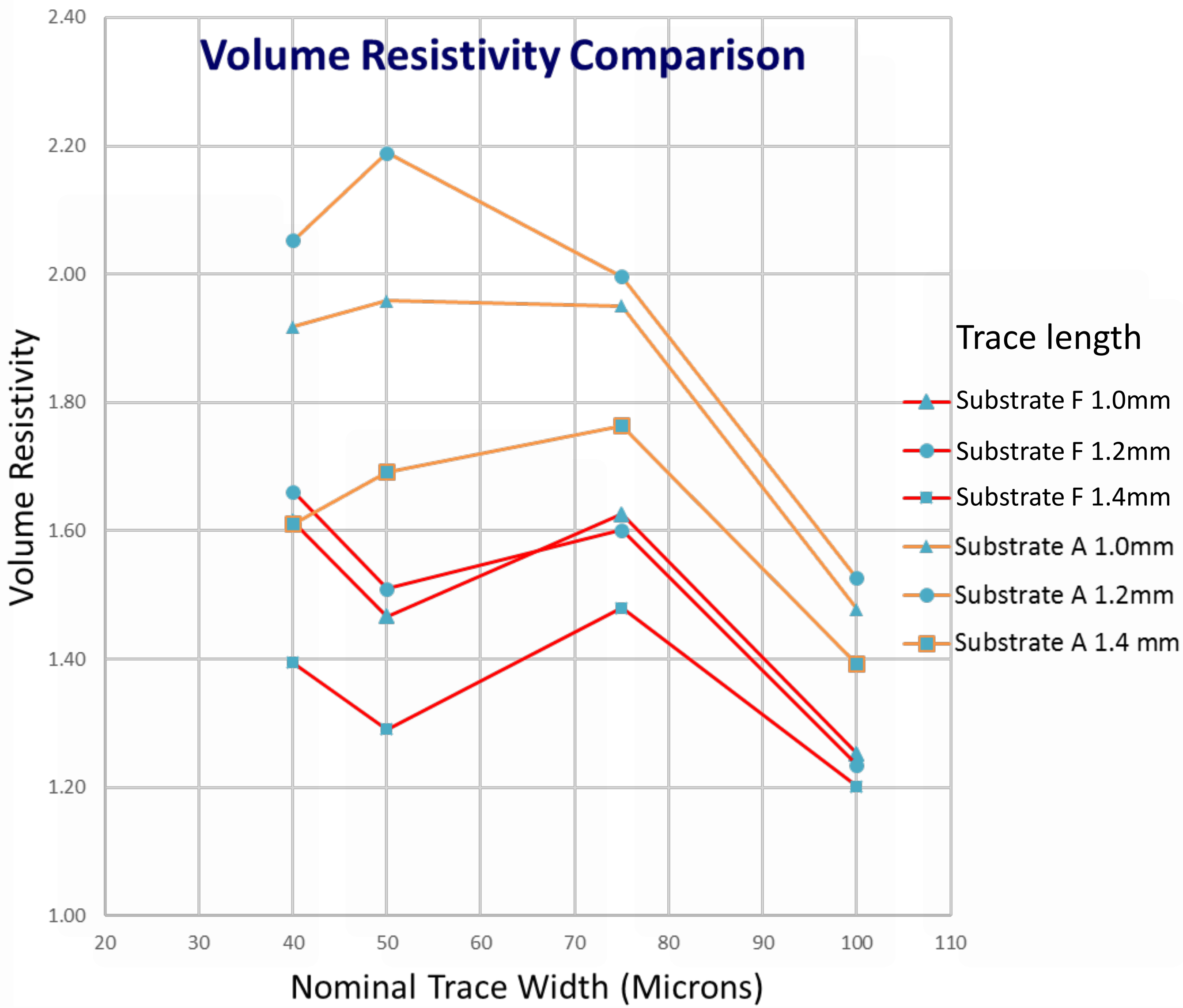
- Volume resistivity is higher for Substrate A
- Volume resistivity delta remains relatively constant with decreasing resistivity as trace width increases.
- Substrate A has volume resistivity increase of 14% to 45% over Substrate F



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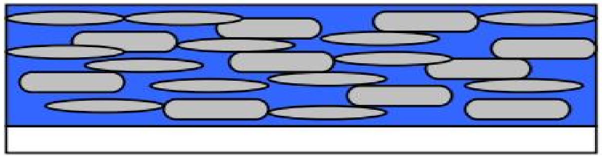
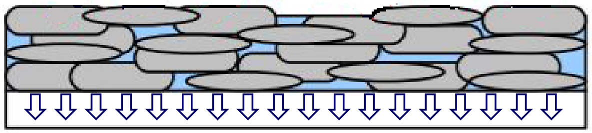
Lower Resistance Values





The migration of the vehicle and solvents in the printed paste into the coated substrate inhibits the paste from spreading laterally. The printed paste then retains position and the draw down of the ink's fluids into the substrate causes a more "confined packing" of the conductive particles resulting in higher conductivity.

Summary

The goal was to improve print accuracy and print definition, and in turn increase resolution and reduce line resistance on flexible printed electronic circuits. The combination of advanced screen stencil materials capable of reproducing printed image features with high accuracy, and a new flexible substrate solution that is capable of inhibiting ink spread, reproduce image sizes to an exceptional degree of accuracy.

Results of both field and in-house testing of the advanced screen stencil materials and coated PET substrate suggest these goals have been realized. Greatly increased printed image accuracy provides the opportunity for sub-100 micron feature sizes. Print results very similar to those reported here were regularly achieved while using 10 different commercial Ag conductive ink formulations.

Test measurements identified a significant reduction in line resistance when printed on Substrate F. This is due to the improved 3-dimensional profile of the traces when printed on Substrate F, resulting in improved packing of the paste as it is drawn into the substrate coating.

Acknowledgements

We would like to thank the following companies who were kind enough to provide sample materials for various print tests:

Conductive Paste:
DuPont
EMS
Heraeus
Insulectro
PPG
ESL
AGFA

Special thanks to those customers, industry allies, & company personnel who assisted with time, materials, and equipment during various stages of print testing.

[1] Slide 45 Figure: Courtesy of Intrinsiq Materials

Advanced Flexible Substrate Technology for Improved Accuracy, Definition, and Conductivity of Screen Printed Ag Conductors

Thank you for your kind attention!

Can I answer any Questions?

Art Dobie
Chromaline Screen Print Products