International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 8, August - 2014

Contribution of Flexo Process Variables to Fine Line Ag Electrode Performance

Michael Joyce*, Sai G. R. Avuthu**,
Sepehr Emamian**, Ali Eshkeiti**, Dr. Massood Atashbar**, Dr. Paul D. Fleming III*,
Tony Donato***
*Western Michigan University
Department of Chemical and Paper Engineering
Kalamazoo, MI, United States
**Western Michigan University
Department of Electrical and Computer Engineering
Kalamazoo, MI, United States
***Harper Corporation of America
Charlotte, NC, United States

***Abstract*-In the last decade, there have been significant efforts toward developing and adapting functional materials to use with printing processes to produce low cost flexible electronic devices. Interest has been growing in the roll-to-roll (R to R) printing processes. As the knowledge and supply of printed electronic materials continues to grow, the desire to print highly conductive continuous fine features has become of great interest. Recent advancements in flexo plate materials and platemaking technology have brought flexography to the forefront of printing technologies for the printing of fine lines and miniaturized devices. However, there are many process and material variables that must be considered before the successful printing of fine lines can be achieved. This study examined the contribution of process and material properties on line resolution and electrical performance. Print trails were performed using a sliver flake and nano silver ink on two different substrates; a machine glazed paper and PET film. The photopolymer flexible plates were imaged with our simulated circuit and trace line pattern at 2400 and 4000 dpi (dots per inch). The process variables altered were the hardness of the mounting tape (commonly called sticky back) used to mount the flexible imaged plate to the plate cylinder and the line screen ("cpi" cells per inch) and volume of the anilox rolls (the ink carrying roll).**

It was found that the large particles of the flake ink flooded the narrowest lines on the 2400 dpi plate due to the ink flakes being larger than the opening of the anilox roll needed to be run with the high resolution plates. As a result, fine lines (sub 100 micron) could not be printed.

For the nano silver ink, the narrowest lines printed on both substrates were obtained using an 800 cpi/3.3 BCM anilox (cpi=cells per inch/ BCM= billion cubic microns per square inch). Under these print conditions, 29.1 µm lines on paper and 20.7 µm lines on PET were printed in the MD direction (Machine Direction). The 440 cpi/5.0 BCM anilox over inked the plate causing smearing of the lines. Comparison of the conductivity and line widths of the 800 cpi/3.3 BCM and 440/5.0 BCM fine lines show the delicate balance between providing enough ink for functionality without loosing the fidelity of the fine lines. The absorptivity of the paper helped to control line gain, but reduced functional performance. The proofing press used enabled sufficient trials to indicate the plate and anilox specifications needed to allow only ink to be deposited by the anilox roll to the top of the plate dots, which is required for printing fine lines, because when the ink is allowed to contact the stems of the plate dots, the line widths grow uncontrollably.

Keywords—Flexography, Printed Electronics, Anilox roll, Line-Screen, Dots-per-Inch, Image-Analysis, Conductivity.

I. INTRODUCTION

In the last decade, there have been significant efforts toward developing and adapting functional materials for printing to produce low cost flexible electronic devices. From these efforts, researchers have been able to demonstrate the ability to fabricate RFID, photovoltaics, OLED, batteries and biosensors through the total or partial printing of stacked functional layers of a device[1-7].

The advantage of using graphic printing processes over traditional photolithography[8] as a fabrication process is its potential for low-waste and high throughput, which reduces the overall costs of device fabrication. Unlike photolithography, printing is an additive process, allowing for patterned deposition, hence eliminating the need for etching, washing and disposal steps in-between the deposition of each layer. The most commonly used printing processes for the development of printed electronic devices are screen, rotogravure, inkjet and flexography. The printing process needed for a particular project depends largely on the interaction of the fluid dynamics (viscosity and surface tension) and electrical properties (conductivity) of the ink with the substrate in achieving a three-dimensional dried deposited layer (ink film thickness). The carrier solvent used in the ink is also very important, not only because it impacts the surface tension, leveling and drying properties of the ink, but because it can impact the longevity and cleaning of materials used on press, e.g., flexographic plates and press rolls.

The ability to control the print resolution and ink film thickness intrinsically impacts the performance and costs of each printed layer. Ink films that are too thin can cause shorting between layers and premature failure, while ink films that are too thick will increase the amount of ink needed to achieve proper step coverage when the next printed ink layer is deposited. Ink spreading, reduces print resolution, which will reduce the cross-sectional area of conductive traces and increase the sheet resistivity. Spreading will also narrow the spacing between features making the registration between layers more difficult. Thus, the ability to control print resolution and ink film thickness is extremely important, especially in the case where it is desired to print micro-devices.

The desire to miniaturize devices requires the ability to print highly conductive continuous fine lines. While the conductivity of the lines depends on the thickness and continuity of the deposited ink film, the size of the printed lines depends on the resolution of the image carrier and amount of ink spreading. For the gravure process, the shape and volume (width to depth ratio) of the engraved cells impacts the volume of ink delivered to the substrate and optimal print resolution. For the screen-printing process, the open area of the screen and wire diameter determines the amount of ink delivered and optimal resolution of the printed image. In inkjet printing, the size of the nozzle opening determines the smallest drop that can be ejected, hence the volume of ink delivered and optimal print resolution.

Recent advancements in flexo plate materials and platemaking technology have greatly increased the resolutions at which plates can be imaged. Newer, thinner photopolymer plates are available that require less processing time because less image depth has to be etched, cured and uncured, and washed away. The shorter processing time results in less loss of detail. As a result, the new plates can hold finer image detail and can be imaged at much higher resolutions. Digital plates can now be imaged at resolutions up to 10,000 dpi[9], which enables ultra fine features to be printed. At this resolution, lines that are one pixel wide on the plate could ideally print (if no spreading) a line under 1 micron wide (at 10,000 dpi, one pixel = 2.54 microns). But, because the failure of one dot (pixel) to transfer from plate to substrate would result in a disconnected circuit, it is less risky to print lines with a minimal width of at least two pixels. Even working within this minimal recommended design rule, the ability to print sub 10-micron lines puts flexo in the forefront of printing ultra fine line electrodes for printed electronics applications. Another advantage of flexo printing over screen and rotogravure printing is that the amount of ink delivered to the substrate is not mainly dependent on the image carrier (open area of the screen or size of the gravure cells), but rather can be altered based on the anilox roll selected. As shown in Figure 1, the resolution of the plates must be matched to the resolution of the anilox roll in order to avoid the dot on the plate being smaller than the opening of the cell. If this occurs, the dot will enter the anilox cell, picking up excess ink resulting in poor printed line quality (ragged lines, ink smearing, etc.) Thus, the relationship between the resolution of the printing plate and the line screen of the anilox roll directly affects print quality and functional performance of the printed lines. When using a high line screen printing plate (a plate imaged at a high resolution, dpi) an anilox of a higher line screen (cells per inch, cpi) should be used. Typically for high definition flexographic printing a ratio of 6 to 10 anilox cells are required for each plate halftone dot. For example, a plate screen of 150 lpi requires the anilox be a minimum of 6 times or 900 cpi.

Though the line screen will dictate the opening of each cell, the depth of the cell can be varied. However, there are limitations in how deep a cell can be engraved without adversely impacting ink release. The width and depth of the cells determine the cell volume, hence volume of ink available to ink the plate. A depth to opening ratio of 28 to 33% has been established for graphic printing but ratios for functional inks have yet to be established and most likely a different ratio will be needed for each functional ink type, since performance is related to ink film thickness (something graphic printers do not have to contend with).

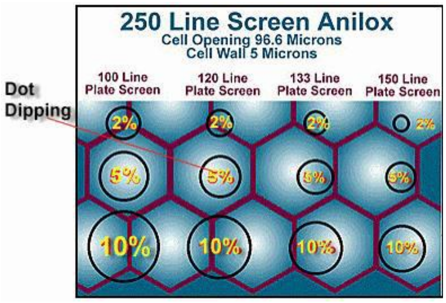


Fig. 1. Dot dipping caused by poor match between anilox and plate resolutions[7]

So in comparison to screen and rotogravure printing, flexo printing enables more control of the ink film delivered to the substrate, and in comparison to inkjet printing, flexo enables higher solids and a broader range of inks (viscosity and surface tension) to be printed. The ability to manipulate more process variables to control ink film thickness could be a major advantage over the gravure process for the printing of fine lines. Previous work has shown the difficulty in printing functional fine lines by the gravure process due to the inability to engrave cells deep enough, to carry enough ink for the fine lines to be functional.[10] Another advantage is that it is a higher throughput process in comparison to the screen and inkjet printing processes.

For all printing processes, the properties of the ink are important to maintaining good print quality. Besides the flow and leveling properties needing to be matched to the process, the size of the ink particles must also be of proper size to prevent nozzle clogging, screen binding or cell plugging. So as the cell count (line screen) of an anilox roll increases to accommodate the use of a higher resolution plate, the size of the particles in the ink must also be adjusted to enable them to readily flow in and out of the engraved cells. The higher the anilox line screen used, the smaller the ink particles should be to assure good ink filling, metering, and transfer from the anilox to the substrate.

One of the most underestimated factors in flexographic printing is the combined contribution of the flexographic printing plate and the sticky back tape hardness on print quality. The sticky back tape is used to mount the flexo plate to the plate cylinder. Different print results can be achieved depending on how the properties of each are combined. Soft plates will conform to rougher surfaces. Harder plates compress less reducing dot gain, but have a tendency to produce more pinholes. The hardness of the sticky back will also influence dot gain and ink transfer. Therefore, it too can greatly impact line fidelity, image quality, and functional performance. The ability to print ultra fine conductive lines is important to the miniaturization and manufacture of low cost printed electronic circuits.

In this work, the influence of plate resolution, anilox line screen, hardness of sticky back and substrate on printed line width and electrical resistivity of the lines is reported. Two inks; a silver flake, and nano silver were printed on both a PET film and machine glazed paper. The widths of the lines were measured with an ImageXpert image analyzer[11]. The resistances of the lines were measured with a Keithley handheld multimeter. From these measurements, the importance of process set-up variables on print quality and electrical performance were observed. The importance of matching the anilox to plate for the printing of ultra fine lines is evident in this work.

II. EXPERIMENTAL

The image in Figure 2 was designed to evaluate the print resolution at various line widths, print directions and anilox cell volumes. The overall dimensions of the printed circuit board layout were 11cm by 8cm. The nominal line widths (microns) and line lengths (mm) for the lines in the highlighted area are shown.

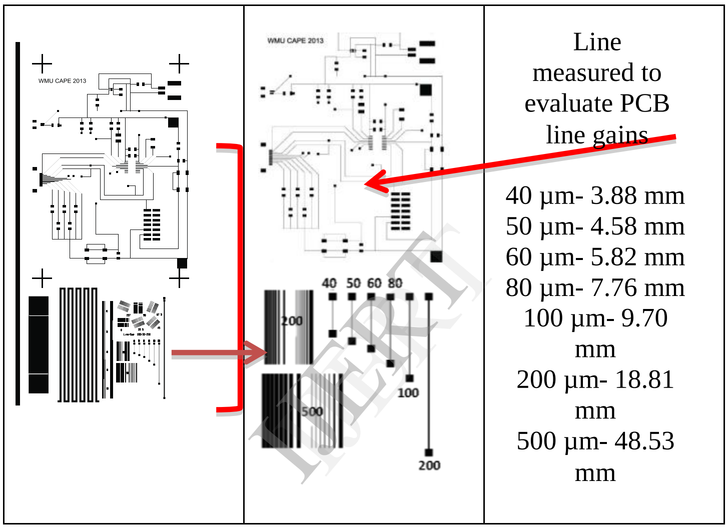


Fig. 2. Flexo plate design

The characteristics of the two substrates are shown in Table 1. The paper was supplied by Dunn Paper Co., Port Huron MI, and the PET film was supplied by DuPont Teijin Films, Chester, VA. The surface energy of the substrates were measured using a First Ten Angstroms FTA 200 dynamic contact method and performing Owens-Wendt[12] calculations from the equilibrium contact angle measurements measured for water and methylene iodide. Caliper was measured with a Technidyne digital thickness gauge and compressibility was calculated from the difference in the roughness values measured on a Parker Print Surf Tester at clamping pressures of 500 and 1000 kPa. The ink used was a water-based silver flake ink.

TABLE I. SUBSTRATE PROPERTIES

Substrate:	Surface Energy (dynes/cm)	Roughness (nanometers)	Caliper (microns)	Compressibility (%)
Duncote Paper	49.3	830	64.5	.267
Melinex ST506 PET	49.1	1.53	127.0	.136

The plate for these print trials was imaged at a resolution of 2400 dpi, with a line screen of 150lpi. The hardness of the plate was 45 DPR (shore hardness of 61). The plate was mounted to a plate cylinder with a medium hardness sticky back tape. Trials were performed on a 3 station web-fed Comco Commander flexographic press. The press conditions for these trials are shown in Table 2. A 440 cpi anilox was selected based on the particle size of the silver flakes in the ink. The ink was applied at the first print station using an enclosed doctor blade inking system to minimize ink evaporation (drying) and minimize the initial amount of ink needed to wet the anilox. The inks were applied on the first station and dried by the three drying station units operating at temperatures of 200°F, 300°F, and 300°F, respectively. Samples were then cut from the web and placed in a drying oven at 266°F for an additional 5 minutes, which were the conditions determined to be the point where the sheet resistances leveled off.

TABLE II. COMCO PRESS RUN CONDITIONS

Melinex ST506 and DunCote				
Anilox (cpi)	**Cell Volume (BCM)**	**Ink**	**Plate Resolution (dpi)**	**Nominal line width of PCB lines (microns)**
440	5.0	Flake Ag	2400	32

The dimensions of the printed lines were measured using an ImageXpert[11] image analyzer. For each line, 5 sections were measured on five different samples, so a total of 25 measurements were taken per line. From the averages of these measurements, the amount of ink spreading that occurred during printing was determined. The resistivity of each dimensionally measured line was measured using a Keithley 2400 mulitmeter. In order to assure an accurate reading of the electrical properties, the measurements were repeated three times by varying the location of the probes on each sample measured. Five samples per condition were measured, so a total of 15 measurements per line were measured for each print condition.

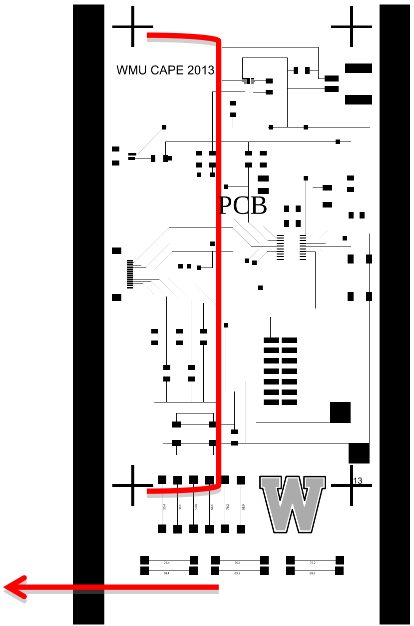
In addition to the above print trials, print trials were performed with a water-based nano silver ink, on a Harper flexo proofing press (Figure 3). The press conditions for these trial runs are shown in Table 3.

Fig. 3. Flexo Proofing Press

TABLE III. PRINT CONDITIONS

Anilox		Speed	Plate	PCB Design	Sticky
CPI	BCM	(ft/min)	Type	Nominal Line Width	Back
440	5.0	28	Plate A	13 micron	Medium
800	3.3	28	Plate A	13 micron	Medium
800	3.3	28	Plate A	13 micron	Hard
1200	3.1	28	Plate A	13 micron	Hard
800	3.3	28	Plate B	32 micron	Medium
800	3.3	28	Plate B	32 micron	Hard
1200	3.1	28	Plate B	32 micron	Hard
800	3.3	28	Plate A	32 micron	Hard
800	3.3	28	Plate A	32 micron	Medium
1200	3.1	28	Plate A	32 micron	Hard

The plate design used for these print trials is shown in Figure 4. Two different plate chemistries were used in this study: Plate B and Plate A. Plate A plates were imaged at a resolution of 4000 dpi, at 4000 lpi while Plate B plates were imaged at a resolution of 2400 dpi, at 150 lpi (the same resolution at which the Comco press trial plates were imaged). The shore hardnesses of Plate A and Plate B were 61 and 65, respectively.



MD and CD lines of
25.4, 38.3, 50.8, 63.5,
76.2 and 88.9 µm
nominal widths

Fig. 4. Flexo Harper Proofer Plate Design

The results from the first and second print trial were compared to determine the minimal line widths and sheet resistances that could be obtained for each ink type for the substrate and anilox/plate combination used.

III. Results and Discussion

The % gain, difference between the plate line widths (nominal line width) and printed line widths (measured line width after printing), and resistances of the silver flake printed lines on PET and paper substrates are shown in Figure 5. For both substrates, the line widths are substantially wider than the nominal line widths on the plate for the sub 500 µm lines. The differences in ink spreading between the two substrates decreased as the nominal line width of the plates increased. The large % gains found are due to the large size of the flake ink particles (7-10 µm). The large ink particles flood the low-resolution lines on the plate with ink, causing the high gain. Although, the gains are slightly lower for paper, due to its absorptive properties, it is clear that fine line printing is not possible with this ink and print conditions. The ability to use a higher line screen anilox is not viable due to the large size of the flake ink particles. The general rule of thumb is to use an anilox with a cell opening at least 3 times the size of the largest ink particle. Based on this general practice, an anilox with a cell opening of no less than 21-30 µm should be used. The diameter of 440 cpi anilox cells used was above this limit at about 53 µm. The resistances of the line printed on the PET substrate are higher in comparison to paper due to the greater amount of ink spreading.

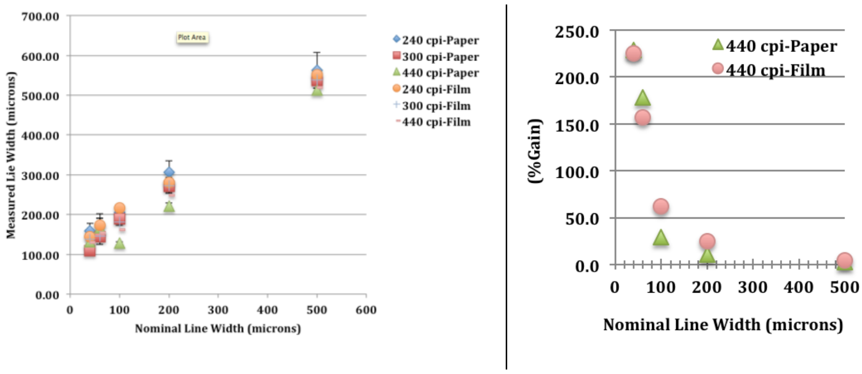
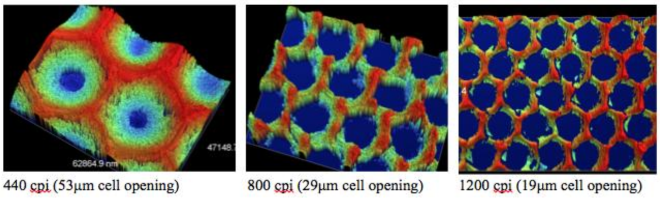


Fig. 5. Print Quality and Electrical Performance of MD Printed Lines

Like the MD lines, the line gains for 32 µm nominal PCB lines printed were also large (around 100 µm on both paper and film). As shown in Figure 5, the measured line was printed in the MD direction. It is well known that line gain is always less in the MD direction due to less ink drag. This is why an MD line was selected for measurement.

Line (width) gain is one of the intrinsic disadvantages of flexographic printing. It occurs due to the compression of the plate during ink transfer from the flexible plate to the substrate and is influenced by the type of sticky back tape used and the impression pressure set by the operator between the plate and the substrate. Due to the high lines on film, some of the lines failed to conduct. Though the sticky back used was not varied on press, it was varied on the flexo proofer trials.

Due to the much smaller size of the nano silver particles (approximately 30 nm), a much higher line screen anilox could be used for the Harper (QD) Proofer print runs. Applying the same general rule of practice, a minimum cell opening of 90 nm would be suitable for use with this ink. Images of the anilox cell diameters (cell openings) for each of the anilox rolls used are provided in Figure 6.

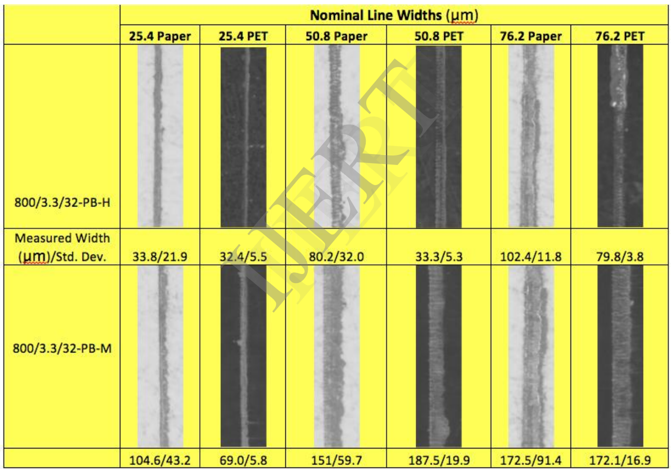


440 cpi (53µm cell opening) 800 cpi (29µm cell opening) 1200 cpi (19µm cell opening)

Fig. 6. Comparison of anilox roll cell openings

The influence of sticky back on print quality is clear from a comparison of the nominal and measured line widths shown in Table 4. From the pictures and measured values, it is clear that the use of the softer sticky back resulted in higher line gain. For functional inks, this finding is critical because higher gains can result in shorting if gaps are not maintained. The increased spreading will also reduce the thickness and conductivity of the printed line.

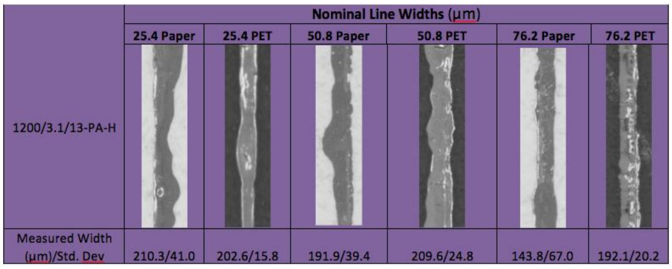
TABLE IV. PICTURES OF CD PRINTED NANO AG LINES



	Nominal Line Widths (µm)					
	25.4 Paper	25.4 PET	50.8 Paper	50.8 PET	76.2 Paper	76.2 PET
800/3.3/32-PB-H						
Measured Width (µm)/Std. Dev.	33.8/21.9	32.4/5.5	80.2/32.0	33.3/5.3	102.4/11.8	79.8/3.8
800/3.3/32-PB-M						
	104.6/43.2	69.0/5.8	151/59.7	187.5/19.9	172.5/91.4	172.1/16.9

It is also apparent from these pictures that the ink smearing occurs due to the CD orientation of the substrate as it passes through the nip on press. To avoid this problem, lines should be printed at an angle of 30 degrees or more to the CD direction. The poorest line quality resulted from the 1200 cpi anilox as a result of the dot on the plate being smaller than the opening of the cell. This resulted in the dot entering the anilox cell, picking up and transferring excess ink, Table 5. The lowest line gains for both substrates were obtained with the 800 cpi anilox, which enabled lines close to 32 microns in width to be printed in both the MD and CD directions.

TABLE V. PICTURES OF CD PRINTED NANO AG LINES



	Nominal Line Widths (µm)					
	25.4 Paper	25.4 PET	50.8 Paper	50.8 PET	76.2 Paper	76.2 PET
1200/3.1/13-PA-H						
Measured Width (µm)/Std. Dev	210.3/41.0	202.6/15.8	191.9/39.4	209.6/24.8	143.8/67.0	192.1/20.2

Figures 7 and 8 show the results of the ink spreading measurements for the paper and film CD printed samples. As for the Comco 440 cpi anilox printed samples, the gains are significantly higher at the lower nominal line widths. Due to the absorptive properties of the paper, the line gains were lower for the paper printed samples.

Pictures of the 800 cpi MD printed lines, which printed closest to the desired nominal line widths on both paper and film are compared in Table 6. The finest printed line obtained on paper was 29.1 µm and 20.7 µm for PET (less than the 25.4 µm nominal line width). Unfortunately, the resistance of the 29.1 µm line on paper was high (75 ohms), and the 20.7 µm on PET was over the measureable limit or non-conductive. The high resistances of these lines is attributed to insufficient ink volume being transferred, resulting in a low ink thickness. The absorptivity of the paper most likely limited the amount of ink spreading, but reduced the thickness of the ink film on the surface. Hence, the absorptivity and uneven surface of the paper helped to limit these line gains, but increased the resistances of the printed lines. The hardness of the sticky back influenced the amount of ink spreading on film and ink absorption and spreading on paper. The gains were higher for the samples printed with the more compressible sticky back tape. The average line width values for the PCB lines are provided in Table 7.

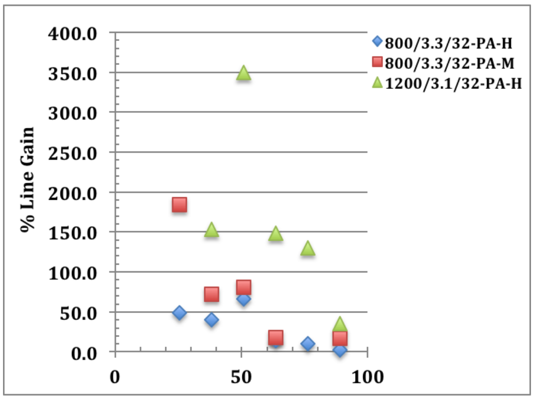


Fig. 7. % Gain of CD Lines on Paper

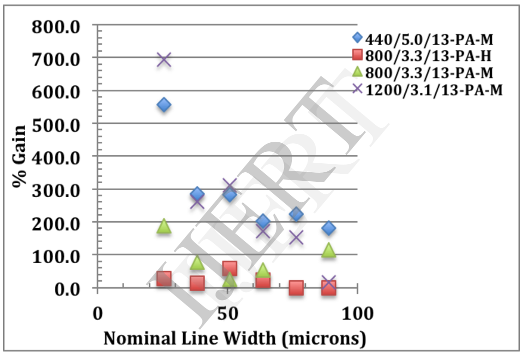
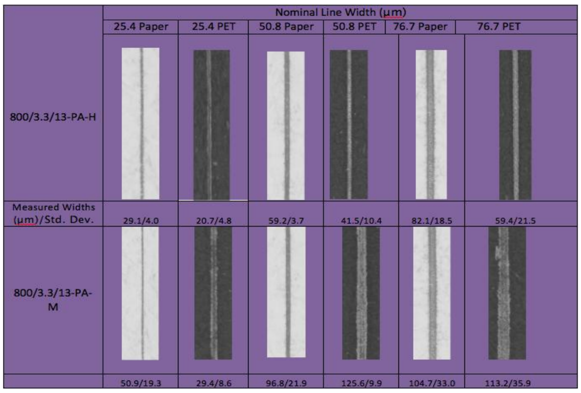


Fig. 8. % Gain of CD Lines on Film

TABLE VI. PICTURES OF MD PRINTED LINES



	Nominal Line Width (µm)					
	25.4 Paper	25.4 PET	50.8 Paper	50.8 PET	76.7 Paper	76.7 PET
800/3.3/13-PA-H						
Measured Widths (µm)/Std. Dev.	29.1/4.0	20.7/4.8	59.2/3.7	41.5/10.4	82.1/18.5	59.4/21.5
800/3.3/13-PA-M						
	50.9/19.3	29.4/8.6	96.8/21.9	125.6/9.9	104.7/33.0	113.2/35.9

Even though the line gains are high for some of the print conditions, they are not large enough to prevent the overlap of the lines in the portion of the PCB design shown below. For overlap to occur between the pads in Figure 9, a gain greater than 120% would be required. Therefore, even though these lines are large, they are acceptable.

TABLE VII. MEASURED LINE WIDTHS FOR 13 MICRON AND 32 MICRON NOMINAL PCB LINES.

	Paper Line Width (microns)	Std. Dev.	Film Line Width (microns)	Standard Dev.
440/5.0/13-PA-M	27.4	10	87.1	8.6
800/3.3/13-PA-H	36.2	9.4	ICP/20.3	2.4
800/3.3/13-PA-M	ICP/24.5	5.7	64.1	17
1200/3.1/13-PA-M	76.5	28.3	52.4	4.9
800/3.3/32-PB-H	104.2	2.5	41.3	17.9
800/3.3/32-PB-M	63.8	10.5	105.7	32.4
1200/3.1/32-PB-H	42.5	18.9	79.9	23.4
800/3.3/32-PA-H	94.1	21.8	93.5	10.8
800/3.3/32-PA-M	45.7	6.7	114.7	30.4
1200/3.1/32-PA-H	32.1	12.1	73.2	3.6

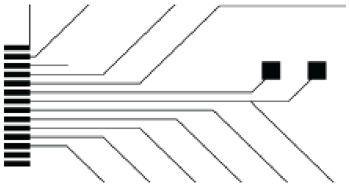


Fig. 9. Expanded view of the microcontroller portion of the PCB design

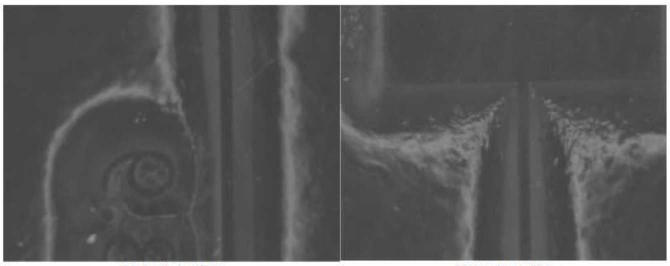
The resistances of the printed lines on paper, which were conductive, are shown in Table 8. None of the MD printed lines on film were conductive. The failure of the lines to conduct could be due to an insufficient ink volume for the amount of ink spreading that occurred, or for the case of paper, the amount of ink absorption that occurred. It could also be due to poor ink release from the higher line screen anilox rolls which must be engraved deeper to obtain the desired cell volume, while still maintaining the higher line screens. The results demonstrate the complexity of matching the anilox to the plate for the printing of fine lines. The cell volumes of higher line screen anilox rolls are limited by the depth at which they can be engraved and still provide good ink release.

The higher volume, lower line screen anilox provided a sufficiently thick ink film for the lines to be conductive on the more porous paper substrate, but the ink spreads too much when on the PET substrate, causing discontinuities in the lines, and resulted in them failing to show conductivity. The hardness of the sticky back influenced the amount of ink spreading, and hence, influenced the resistance of the printed lines.

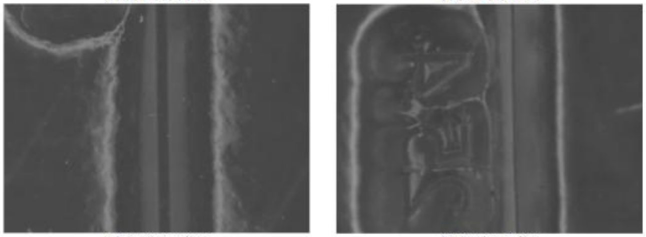
TABLE VIII. RESISTANCES OF MD PRINTED NANO AG LINES

Condition	PAPER Average Resistance (ohms)					
	25.4	**38.1**	**50.8**	**63.5**	**76.2**	**88.9**
440/5/13-PA-M	4.7	9.2	2.0	3.6	5.1	4.3
800/3.3/13-PA-H	75	52.7	76.9	38.5	17.1	16.6
800/3.3/13-PA-M	open	open	open	open	open	open
1200/3.1/32-PA-H	6.2	5.8	5.9	2.5	4.5	9.4
800/3.3/32-PA-H	open	open	open	open	open	open
800/3.3/32-PA-M	open	open	open	78.5	209.5	101.1
1200/3.1/32-PA-H	open	open	open	20.3	9.3	18.2

Images of the 32 micron Plate A are shown in Figure 10. Two of the images show the photochemically etched areas around the 88.9 MD lines' width label and one image shows the area of the line leading into the block (pad) attached to the line for measurement purposes. There is also an image of the 25.4 micron line alongside its width label. These images clearly show the issues pertaining to the printed lines and the apparent line gains. The darker straight trench area shown in all the images is that of the nominal line width, while the surrounding area supporting the line may be seen directly adjacent to it. Inspection of these images indicates that some of the lines gains may have been caused by ink transfer or smearing from these supporting areas. Similar plate issues are observed around the area where the line merges with the pads connected to the lines. The reason the plates are imaged this way is to provide support to the fine lines at low impression pressures, these surfaces of the plate, should not contact either the anilox roll or substrate. However, from the results, it would appear that over compression of the plate, due to high impression, might have occurred.



88.9 micron line 88.9 micron line



88.9 micron line 88.9 micron line

Fig. 10. Plate A 32 micron plate ImageXpert Images of MD lines

Below 3D topographical images of Plate B (32 micron) and Plate A (32 micron), are shown in Figures 11 and 12 respectively. Differences between Plate B and Plate A plate can be observed. In the image of the Plate B plate it may be seen that the lines are consistently level throughout, having no change in thickness. The image of the Plate A plate (Figure 12) shows a variance in the thickness of the plate from the edges to the center of the plate. It may be seen that the edges of this plate are slightly higher than the center of the plate giving a convex (trench like) shape to the plate.

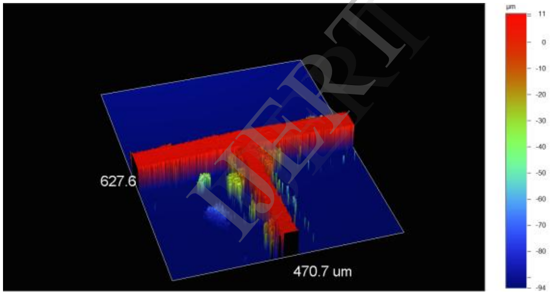


Fig. 11. Plate B (32 micron) 3D image (Provided by Bruker)

In Figures 13 and 14, 3D and 2D images of the printed pads (silver pads) on the paper substrate are shown. In these Figures, it may be seen that the printed pad is recessed within the substrate itself. This is most likely due to the high impression forces occurring during the printing process, and subsequent absorption of the ink into the paper. The change in ink film thickness at the edges of the pad corresponds with the amount of ink spreading (gain) that was measured.

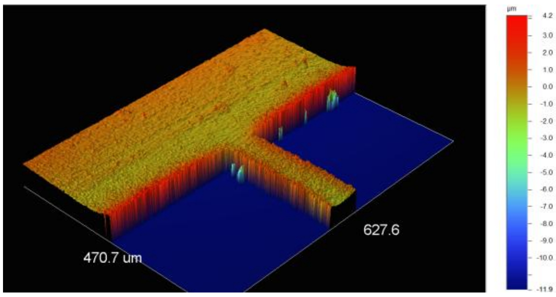


Fig. 12. Plate A (32 micron) 3D image (Provided by Bruker)

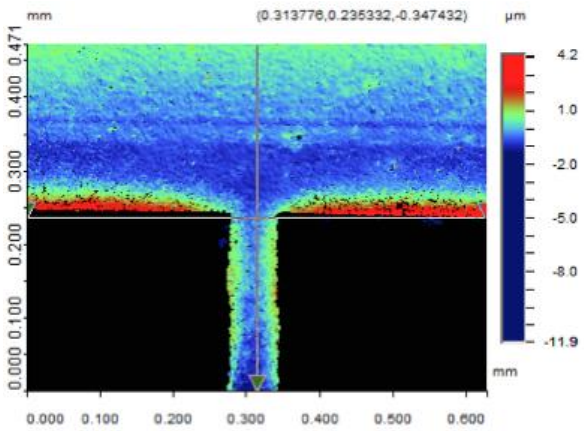
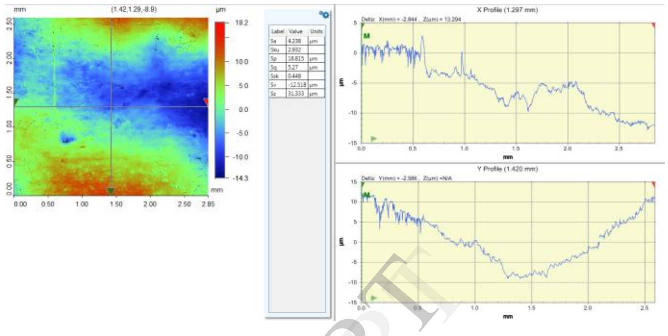


Fig. 13. Plate A 32um plate image (Provided by Bruker)



Label	Value	Units
Sa	4.238	µm
Sku	2.932	
Sp	18.815	µm
Sq	5.27	µm
Ssk	0.448	
Sv	-12.518	µm
Sz	31.333	µm

Fig. 14. Printed pad on paper substrate (Provided by Bruker)

From the analysis of all the above results, it was determined that the poor line quality for the 440 cpi trial conditions was contributed by the line on the plate being smaller than the opening of the anilox cell. This resulted in the line entering the anilox cell, picking up and transferring excess ink. To maintain image quality, inks should only be deposited by the anilox roll to the top of the plate features, because when the ink is allowed to contact the stems of the plate dots the line widths grow uncontrollably, as observed. An illustration of this is shown in Figure 15.

For the 800 and 1200 cpi print conditions, it is believed that image quality suffered as a result of too much impression pressure being applied, which was difficult to fine tune since (on this proofing press), impression is controlled by the spring used. The results also highlight a prevalent problem not yet addressed by the printed electronics industry, which still relies on imaging software used by the graphic printing industry to image its flexographic plates, and gravure cylinders. Even though new flexo plate and anilox engraving technologies have increased the resolution at which the plates can be imaged and anilox rolls engraved, the software used to rasterize the image used to create the plate has not kept pace. Current software used by the graphic printing industry does not allow the plate maker to define the point of origin on a bitmap grid. Instead, the software analyzes the image and sets the point of origin for the plate maker. Without the ability to control the origin of the grid, it is possible to have unintended print results, which, could result in the failure of a line to be conductive. While the failure to print one pixel in a graphic image can be tolerated, the same cannot be said for the printing of functional inks. New software that addresses this problem is needed for the printing of functional inks.

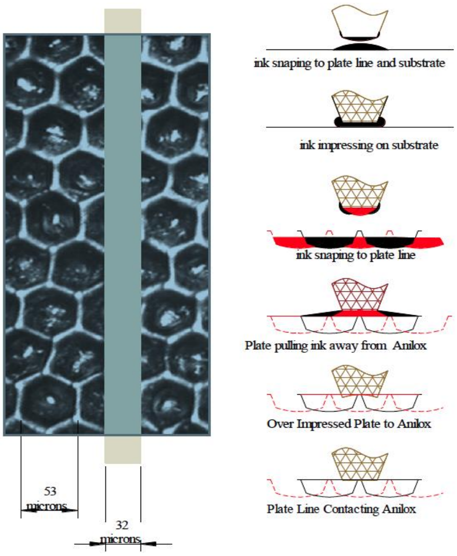


Fig. 15. Visualization of Theoretical ink Transfer from Anilox to Plate Substrate (Image Provided by Harper Corporation of America)

IV. CONCLUSIONS

The large particles of the flake ink flooded the low-resolution lines on the 2400 dpi plate, causing high gains. Although the printed line gains (%) were slightly lower for the absorptive paper, in comparison to the PET film, it is clear that the silver flake ink used was not suitable for fine line printing. This is because the higher line screen anilox rolls needed to be run with the high-resolution plates to print the fine lines. The ratio of cell opening to particle size should be approximately 3:1 for metallic inks, and the particle size of the flake ink used exceeded this ratio for the anilox cell openings. Hence, even though a high-resolution 2400 dpi plate containing 40 µm lines was used, lines less than 100 µm could not be printed.

For the nano silver ink, the finest resolution lines for both substrates were obtained using the 800 cpi/3.3 BCM anilox. Under these print conditions, 29.1 µm lines on paper and 20.7 µm lines on PET were printed in the MD direction. Unfortunately, the resistance of the 29.1 µm line on paper was high (75 ohms), and the 20.7 µm line was over the measureable limit or non-conductive. Similar to the flake ink, at the lower line screens and higher cell volume print condition, 440 cpi/5.0 BCM anilox, the CD and MD line gains were very high and line quality very poor due to smearing. The poor line quality was caused by the line width on the plate being smaller than the opening of the cell. This resulted in the line entering the anilox cell, picking up and transferring excess ink.

Due to the technology used to create the plates, the impression pressure applied must be closely controlled in order to prevent the over compression of the fine features. Since higher impression pressures are usually required to assure complete ink transfer on rougher substrates, the ability to hold print tolerances might not be possible beyond a certain roughness value. The results suggest that a highly smooth, slightly absorptive paper would have accomplished better prints with the printing equipment used. Even with better controllable press conditions, we believe the trends revealed would remain the same even if the specific measurements would change.

Use of the flexo proofing press provides sufficient information to indicate the initial process conditions that should be used for a larger scale print study. It is expected that future results will improve due to having a clearer understanding of the plate and anilox combination requirements, as well as knowing that the impression pressure can be more finely tuned on a commercially used press. It is reasonable to expect that the inks would also set faster on a commercially used press, which would also further improve image quality by reducing line gain. By reducing ink spreading, the conductivities of the lines should increase with ink film thickness.

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