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CHARACTERIZATION OF THE DIRECT WRITE INKJET PRINTING PROCESS FOR AUTOMATED FABRICATION OF PEDOT: PSS THIN FILMS

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ABSTRACT

Direct write Inkjet Printing is a versatile additive manufacturing technology that allows for the fabrication of multiscale structures with dimensions spanning from nano to cm scale. This is made possible due to the development of novel dispensing tools, enabling controlled and precise deposition of fluid with a wide range of viscosities (1 – 50 000 mPas) in nano-liter volumes. As a result, Inkjet printing has been recognized as a potential low-cost alternative for several established manufacturing methods, including cleanroom fabrication. In this paper, we present a characterization study of PEDOT: PSS polymer ink deposition printing process realized with the help of an automated, custom Direct Write Inkjet system. PEDOT: PSS is a highly conductive ink that possesses good film forming capabilities. Applications thus include printing thin films on flexible substrates for tactile (touch) sensors. We applied the Taguchi Design of Experiment (DOE) method to produce the optimal set of PEDOT:PSS ink dispensing parameters, to study their influence on the resulting ink droplet diameter. We experimentally determined that the desired outcome of a printed thin film with minimum thickness is directly related to 1) the minimum volume of dispensed fluid and 2) the presence of a preprocessing step, namely air plasma treatment of the Kapton substrate. Results show that an ink deposit with a minimum diameter of 482 μm, and a thin film with approximately 300 nm thickness were produced with good repeatability.

Keywords: additive manufacturing, direct write Inkjet printing, design of experiment (DOE), PEDOT:PSS, polymer thin film fabrication.

1. INTRODUCTION

In recent years direct write inkjet printing has become a popular technique applied in the development and manufacturing of wearables, solar cells, flexible electronics, OLED displays, sensors, and in the assembly of Micro-Electro-Mechanical Systems (MEMS) [1-7]. It was recognized as a potential standard tool in research applications, for example in material science [3,5,6].

A diverse number of applications illustrate the versatility of inkjet printing as a fabrication technique, due to its precise dispensing of pico and nanoliter volumes of fluid on various substrates [3,4], and deposition of thin films with thicknesses below 100 nm [6]. Furthermore, inkjet printing allows deposition of fluids of a wide range of viscosity in the range 1–50 000 mPas, and type: 1) polymer solutions, including poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), and 2) inks with nanoscale structures such as metal nano/microparticles and carbon nanotubes [1-4]. However previous studies reveal some limitations of inkjet printing, specifically concerning the size of the deposited features – usually above 100 μm for piezo jet dispensing, and low control of the deposition morphology [1,4]. Advantages of inkjet printing include relatively low cost of manufacturing, high flexibility, and very quick turn-around, making it a viable alternative to cleanroom fabrication for specific applications [4,5], and enabling automated additive manufacturing [8-10].

Our previous studies showed that cleanroom techniques can be employed to fabricate tactile sensors, serving as artificial robotic skin for human-robot interaction control, where the sensing component of the device is based on the piezoresistive material PEDOT:PSS or *Poly (3,4-ethylenedioxythiophene) –*

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poly (styrene sulfonate) [4-6]. Touch sensors with various geometries of the MEMS structures were produced and tested. For all the sensor designs, during the fabrication process in a cleanroom, a spin coating was used to form PEDOT: PSS thin film on a Kapton surface over the area of approximately 45 mm x 29 mm [6]. Results revealed that the morphology of the PEDOT: PSS film, thickness, and polymer composite uniformity, was critical factors in the optimization of the sensor's performance. As studies also showed, control of the PEDOT's thin film morphology in the case of spin coating over a relatively large area (>1 cm^2) can be a challenging task [6].

In this paper, we present a method for fabrication of the PEDOT: PSS thin films, utilizing Direct Write Inkjet printing as a potential alternative to the spin coating process currently realized in the cleanroom. The proposed Inkjet printing method allows control of the film's morphology at nano/microscale and enables future automation of the skin sensor fabrication process outside the cleanroom [8]. Printing of the PEDOT: PSS ink is conducted with the help of a custom automated system composed of Nordson EFD Pico Pulse® Inkjet Piezo jet dispenser, XY motorized stages, and National Instruments (NI) LabVIEW® User Interface (UI). Firstly, we have identified the main dispensing parameters: stroke, pressure, and deposition height; affecting selected single response – droplet diameter on the substrate. We applied the Taguchi Design of Experiment (DOE) method to determine the optimal set of dispensing parameters needed for the reduction of the droplet diameter. Secondly, we realized thin film fabrication with help of our printing system. Characterization of the printed structures: individual droplets, lines, and films; were conducted with the help of optical microscopy, and profilometry.

The paper is organized in the following way: in Section 2, we describe our experimental setup and experimental methods: deposition, printing processes, and characterization of the samples. Section 3 presents experimental results and details the application of the Taguchi DOE method. We also discuss our results and optimization of the deposition process and printing process. Finally, in Section 4, we conclude the paper and discuss future work.

2. MATERIALS AND METHODS

2.1 Experimental setup

The Nordson EFD PICO Pulse® Inkjet printer was used to conduct PEDOT: PSS deposition experiments. The experimental setup is shown in Figure 1, depicting the following major system components:

- Pico Pulse® print head with the piezoelectric actuator, fluid syringe, and valve assembly with 50 µm nozzle
- Nordson EFD Pico Pulse® controller
- Velmex® motor controller (not pictured)
- Stage 1 and 2: two motorized stages for x and y directional movement
- Stage 3: manual vertical displacement stage to control sample deposition height
- Air pressure gauge (not pictured)

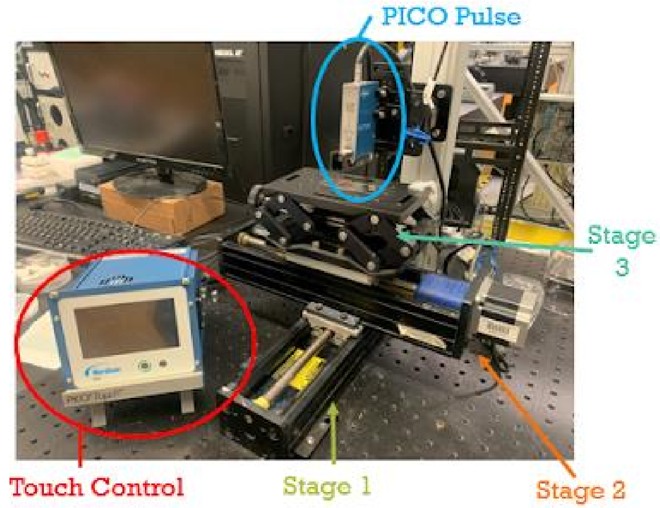


FIGURE 1: EXPERIMENTAL SET UP OF THE PICO PULSE®

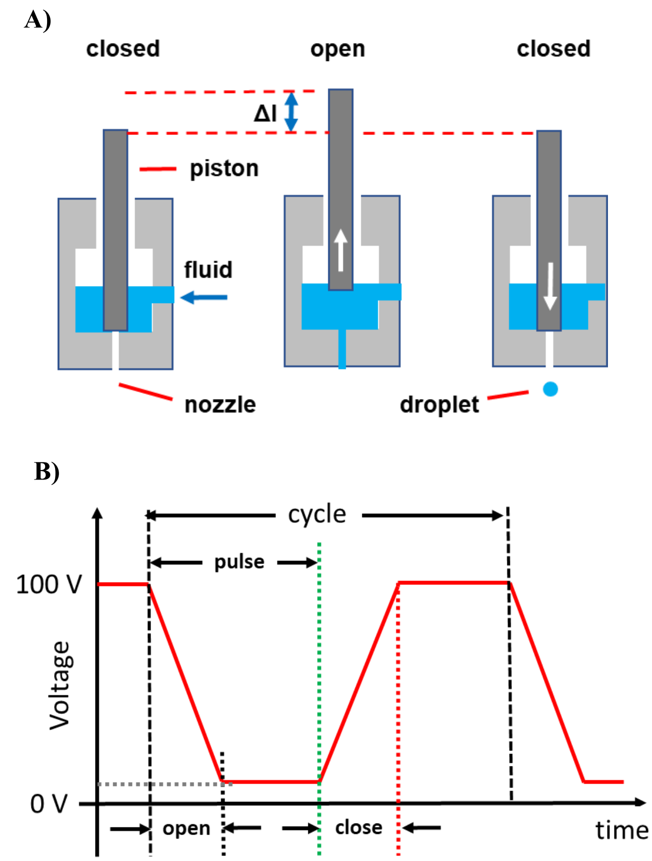


FIGURE 2: A) CROSS-SECTIONAL VIEW OF THE CARTRIDGE (FLUID CHAMBER WITH NOZZLE) DURING DISPENSING PROCESS. B) THE DISPENSING CYCLE (WAVEFORM) OF THE PICO PULSE®

The Pico Pulse® printing head is composed of a piezoelectric actuator and a valve assembly. The valve assembly's main components include a fluid body seat, fluid inlet fitting, and cartridge. A detailed description of the valve assembly is presented elsewhere [7] in this study the most essential is the cartridge consisting of the fluid chamber, piston (tappet), and nozzle (Figure 2A).

Based on the information provided by the Nordson EFD, the fluid dispensing process is realized in 3 basic steps (Figure 2A):

1) Closed mode - the piezoelectric actuator is initially engaged, keeping the piston tip in the "closed" position and preventing fluid from entering the nozzle opening.
2) Open mode - the piezoelectric actuator is disengaged - the piston tip is lifted by a specific distance Δl from the nozzle opening - an "open" position. The value of Δl depends on the voltage V applied to the actuator (Figure 2A, middle illustration). The lifted piston enables a portion of the fluid to enter the fluid body seat and nozzle opening.
3) Finally, the actuator is engaged again which results in the piston's tip forcing fluid out of the chamber through the nozzle opening, sealing it off from the fluid reservoir, and releasing a droplet ("jetting").

The following process parameters control the fluid dispensing process [7]:

- Pulse Time (0.27ms – 0.52ms): time duration of the valve's open mode. (Figure 2B)
- Open time (0.25ms - 0.50ms): Time is taken to lift the piston to the specified stroke position. (Figure 2B)
- Close time (0.20ms – 0.40ms): duration of the 3rd step in dispensing process. The amount of time it takes the piston to return to the "closed" position. (Figure 2B)
- Air Pressure, p_A (20psi - 100psi): Pressurized air forces the fluid through the chambers of the valve assembly.
- Voltage, ΔV (Change in voltage ≤ 90V): Difference between voltage values in "open" and "closed" modes (Figure 2B) [7].
- Stroke (50% - 90% of 100V): Percentage change between open and closed voltage ΔV. This determines how far the piston is lifted from the nozzle opening (Δl). 90% will correspond to a larger Δl and allow for the release of a larger volume of fluid, e.g., Stroke = 90% would correspond to the value of voltage 10 V being applied to the piezoelectric actuator (Figure 2B). At this value, the piston would be retracted the farthest distance from the nozzle opening.
- Deposition Height, h (1 mm - 5 mm): Distance from the printer head's nozzle to the surface of the substrate.
- Temperature (30 °C - 75 °C): Temperature of the heater body and fluid - in this study kept at a room level (20°C)

In this study, the instrument's stroke, pressure (p_A), and deposition height (h) were chosen as the parameters with significant impact on the droplet diameter d_d [7].

2.2 Taguchi design of experiment

The Taguchi DOE is a robust statistical method for designing a set of experiments that has a negligible sensitivity to variations of uncontrollable experimental factors (noise) and focuses on estimation of the main effect for control parameters (signal) utilizing acceptable signal-to-noise ratios S/N. In the Taguchi method, the influence of each experimental factor is investigated by variating ''response'' choosing an adequate signal-to-noise (S/N) ratio. The S/N is defined as the ratio of signal power (the mean) to noise power corrupting the signal (the standard deviation) and can be described as an output response of a selected system and a measure for the robustness of the system [14, 16, 17].

Since the primary goal of this study was the optimization of the Inkjet printing process to reduce the size of the deposited droplet. To achieve this goal, we used the smaller-the-better S/N ratio described by the following equation [7, 14, 16]:

$$S/N = -10\log\left(\frac{1}{N}\sum_{i=1}^{N} y_i^2\right) \quad (1)$$

where, y_i is an i^{th} observation and N is a total number of observations in the experiment. In this case, y_i corresponds to the measured diameter of the deposited droplet.

For this study, a Taguchi Design of Experiment (DOE) with three parameters and three-level sets for deposition of PEDOT: PSS was applied to investigate which parameters have a statistically significant impact on droplet diameter reduction. Taguchi DOE statistical analysis was performed with the help of Origin.

2.3 Experimental procedures – sample preparation and characterization

Three structures were fabricated on the Kapton substrates using PEDOT: PSS ink: individual ink droplets, lines, and films. Before printing, substrates were cleaned to remove any impurities or particles from the surface. Kapton sheets were sonicated in DI water for 10 minutes and then dried before plasma treatment. Next, Kapton sheets were treated with air plasma (Harrick Plasma Cleaner) for 30 seconds. This step was introduced to enhance the wettability effect to improve adherence of the PEDOT: PSS ink to the Kapton's surface and reduce the height of the deposited droplet on the substrate. PEDOT: PSS ink (CleviosTM®) from Heraeus was used for deposition trials. During printing, PEDOT: PSS ink was kept at room temperature (~20°C).

A Nikon microscope was used for visual inspection and PEDOT droplet diameter measurements. Profilometry measurements of the PEDOT:PSS thin films were conducted with the help of Dektak® instrument.

Our experimental study was divided into two parts. Firstly, after analyzing multiple trial numbers and identifying the behavior of the PEDOT:PSS ink on the substrate during deposition, Taguchi DOE was applied to determine a new set of parameters towards droplet diameter reduction. Based on the last set of DOEs, the data collected enabled the determination of parameters that have the strongest effect on droplet size. In the second part of our study, we implemented a discovered set of parameters for reduced droplet size, to print PEDOT: PSS thin films on the Kapton substrate (Figure 6).

2.4 Synchronization of fluid dispensing and motion control.

Studies show that the formation of the continuous lines or films with a single nozzle inkjet printer requires control of the droplet overlap on the substrate with an adequate resolution [3]. It is especially critical in the case of the various conducting materials, such as nano/micro particle inks, and conducting polymer composites including PEDOT: PSS ink used in this study. Droplet overlap in a single printed line and line spacing for a film are the key parameters in the inkjet printing process that determine the properties of the fabricated planar structure - uniformity of the printed film – constant thickness across the whole area of the film.

To assure uniformity of the printed PEDOT: PSS films with Pico Pulse, we have adopted the method proposed by Gengenbach et al and Duineveld P et al [9 and 15]. This approach enables synchronization between the dispensing process of the printhead and motorized stage motion, expressed by the following formula,

$$V_s(t) = f_D(t)d_{dot} \quad (2)$$

where $V_S(t)$ is a motorized stage velocity, PhD is a deposition frequency, and d_{dot} is a spacing constant, a measure of the droplet overlap. Here low values of d_{dot} would result in a high overlap of the droplets, and large values would produce the opposite situation.

2.5 PEDOT: PSS thin film fabrication – printing automation

To conduct deposition and film printing experiments with adequate control, we have developed a custom NI LabVIEW® UI (Figure 3A) enabling synchronization of the Pico Pulse® and motorized stages. Labview UI includes (Figure 3A):

Input terminals:

- "Time for print" – duration of the dispensing procedure needed to print a single line of a specific length (Figure 4, Task 2) corresponding to the deposition frequency (f_D).
- "Times of repeat" - # of iterations (loops) desired for producing a film (Figure 4, Task 3).
- "File (use dialog)" – file path for document with text-based commands for Velmex® stages controller: speed of motorized stages (V_S), step size (min) – 7 µm). Commands written to produce a single line of a specific length.

Output terminals:

- "Output string" – indicates which command (from Velmex® code) is currently executed
- "Motor 1, 2 Position" – indicates coordinates for the motorized stages.

A simplified diagram depicting the integration scheme of the Pico Pulse® and Velmex controller is shown in Figure 3B. The LabVIEW program inputs included:

- Control of the motorized stages speed, Vs(t) and displacement
- Remote initiation of the dispensing using Pico Pulse®
- Programming specific motion path (printed pattern) for the stages with the help of text-based code for Velmex® stages controller

Once the PEDOT:PSS droplet diameter was known for a specific set of parameters, then with the help of eq. (2) we were able to determine the required separation distance between each droplet to form a continuous line, and a film consequently based. Droplets were combined to form a line, and lines were

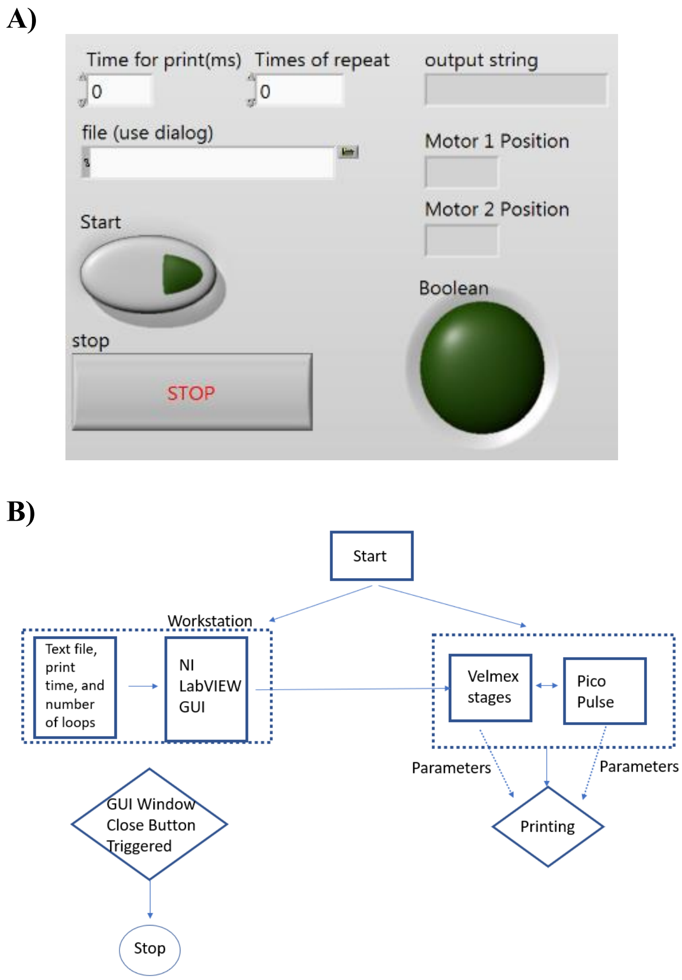


FIGURE 3: A) LABVIEW USER INTERFACE; B) FLOWCHART FOR THE LABVIEW PROGRAM FOR THE PRINTING PROCESS CONTROL WITH TWO STAGES AND THE PICO PULSE®

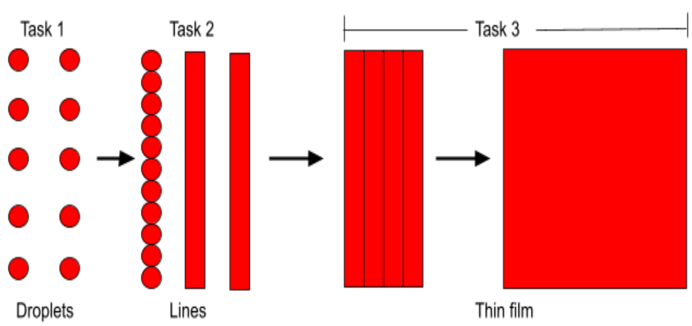


FIGURE 4: THE PROCESS THAT WAS FOLLOWED TO FORM THE FILMS OF PEDOT: PSS

combined to form a film – as described in a diagram (Figure 4). This allowed us to program our system for PEDOT: PSS thin film printing with the help of our NI LabVIEW® UI (Figure 3A).

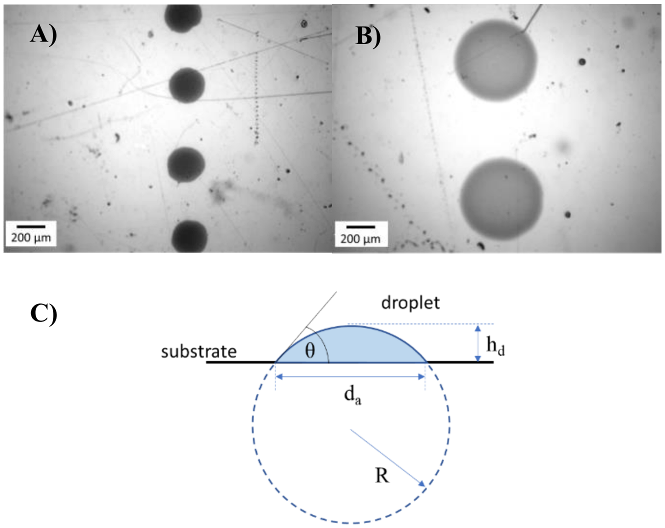


FIGURE 5: PEDOT:PSS DEPOSITS ON A KAPTON'S SURFACE: A) UNTREATED; B) PLASMA TREATED. DEPOSITION CONDITIONS: STROKE=55%, P_A=20 PSI, H=1MM. C) DROPLET FORMATION ON THE SUBSTRATE.

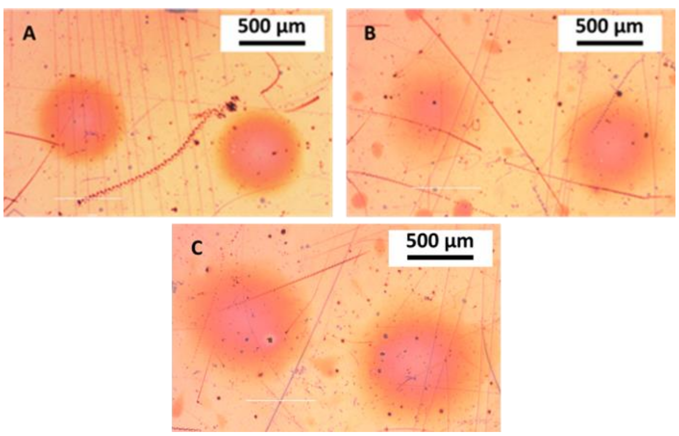


FIGURE 6: A: 55% STROKE B: 65% STROKE C: 75% STROKE D: 85% STROKE. EVERY OTHER PARAMETER WAS HELD CONSTANT - P_A=40 PSI, H=1MM.

3. RESULTS AND DISCUSSION

We first deposited droplets on both untreated and plasma treated Kapton to see how the plasma treatment affected droplet diameter. Microscopic images of the droplets are shown (Figure 5). The average diameter for droplets deposited with the parameters in Figure 5A was about 185 microns while the average diameter for Figure 5B was about 602 microns. The diameter for the plasma treated Kapton was much larger than that for the untreated Kapton. By using the same parameters, we know that the volume of fluid deposited was the same for both substrates. Therefore, the fluid is much more spread out on the plasma-treated Kapton and thus the height of the droplet is likely much smaller for the plasma-treated Kapton, as we wanted. We then proceeded to deposit droplets for the different levels of the DOE on plasma treated Kapton.

After the collection of the characterization data, droplet diameters d_d for each combination of parameters, we performed

TABLE 1: TAGUCHI DOE TESTING PARAMETERS AND LEVELS

Level	Stroke (%)	Pressure, p_A (psi)	Deposition height, h (mm)
1	55	20	1
2	65	40	3
3	75	60	5

TABLE 2: TAGUCHI DOE DATA FOR PEDOT:PSS ON PLASMA-TREATED KAPTON SUBSTRATE

Stroke [%]	p_A [psi]	h [mm]	Mean Diameter, d_d [µm]
55	20	1	603
55	40	3	612
55	60	5	799
65	60	1	800
65	20	3	491
65	40	5	732
75	40	1	1051
75	60	3	883
75	20	5	599

Taguchi DOE analysis with three testing parameters and three control levels as presented in Table 1. The mean values of the diameter for each set of parameters for the Taguchi DOE are shown in Table 2. In Figure 6, we present microscope images of the deposited PEDOT: PSS droplets on the plasma treated Kapton substrate. In Figure 10, we show an example of a film fabricated with the Pico Pulse®.

The purpose behind the Taguchi DOE was to find the parameters that would result in the smallest diameter of the droplets. The minimum diameter would correspond to the dispensing of the minimum amount of fluid. This is critical for the fabrication of thin films. As the fluid tends to spread out more on the plasma-treated substrate, reduction in the volume of dispensed ink will result in a smaller height of each droplet [3, 5, 18]. This behavior is described through relation between droplet height h_d and droplet fluid volume V which is expressed by the following formula (3) (Figure 5 C) [18]:

$$R(1-cos\theta) = h_d, \quad V = \frac{2\pi R^3}{3}\left(1-\frac{3}{2}cos\theta+\frac{1}{2}cos^3\theta\right)$$

$$V = h_d^3\,\frac{2\pi}{3}\,\frac{\left(1-\frac{3}{2}cos\theta+\frac{1}{2}cos^3\theta\right)}{(1-cos\theta)^3} \qquad (3)$$

where V – droplet volume (dispensed fluid volume), h_d – droplet height, d_a - droplet contact diameter, R – sphere radius (Figure 5 C), θ – droplet contact angle (Figure 5C).

By merging the individual droplet of a given height one can produce the line and the film of the respective thickness.

Reduction of the droplet height would result in the printed line and film with smaller thickness.

The parameters' effects for signal-to-noise (S/N) ratios were calculated using Eq. (1) and logged in Table 3. The values from Table 3 are plotted in Figure 7 as the blue dotted lines. The S/N is reciprocal to the mean diameter plotted as the black line, concerning the x-axis. This reciprocal trend indicates that there is no significant noise from the other parameters at any given moment.

A good signal-to-noise ratio indicates a good quality in data and gives further assurance in the behavior of the mean diameters plotted. Table 3 is the response table for the signal-to-noise ratios. In Table 3, ΔS/N = (ΔS/N, Max – ΔS/N, Min) represents a change in S/N. This value shows how each parameter ranks in the effect on S/N. The ratio was most affected by the air pressure parameter, which has the greatest ΔS/N value. Results show that pressure and stroke have a larger impact on S/N than deposition height.

Results of the statistical analysis and ranking for effects on the droplet diameter are collected in Table 4. $\Delta d_{mean} = (\Delta d_{mean, Max} - \Delta d_{mean, Min})$ represents mean change. This value shows how each parameter ranks in the effect on droplet diameter. This table shows a similar trend in the ranking of the parameters as Table 3– air pressure and the stroke has the most impact on droplet size while deposition height has the least impact on droplet size.

TABLE 3: RESPONSE TABLE FOR SIGNAL TO NOISE RATIOS S/N FROM TAGUCHI DOE

Level	Stroke	Pressure	h
1	-56.62	-55.07	-58.47
2	-56.74	-58.27	-56.68
3	-58.74	-58.36	-57.09
ΔS/N	2.12	**3.29**	1.79
Rank	2	1	3

TABLE 4: RESPONSE TABLE FOR MEAN VALUES OF DROPLET DIAMETER IN MICRONS FROM TAGUCHI DOE

Level	Stroke	Pressure	h
1	671	565	818
2	674	799	662
3	845	828	710
Δd_{mean}	173	**262**	155
Rank	2	1	3

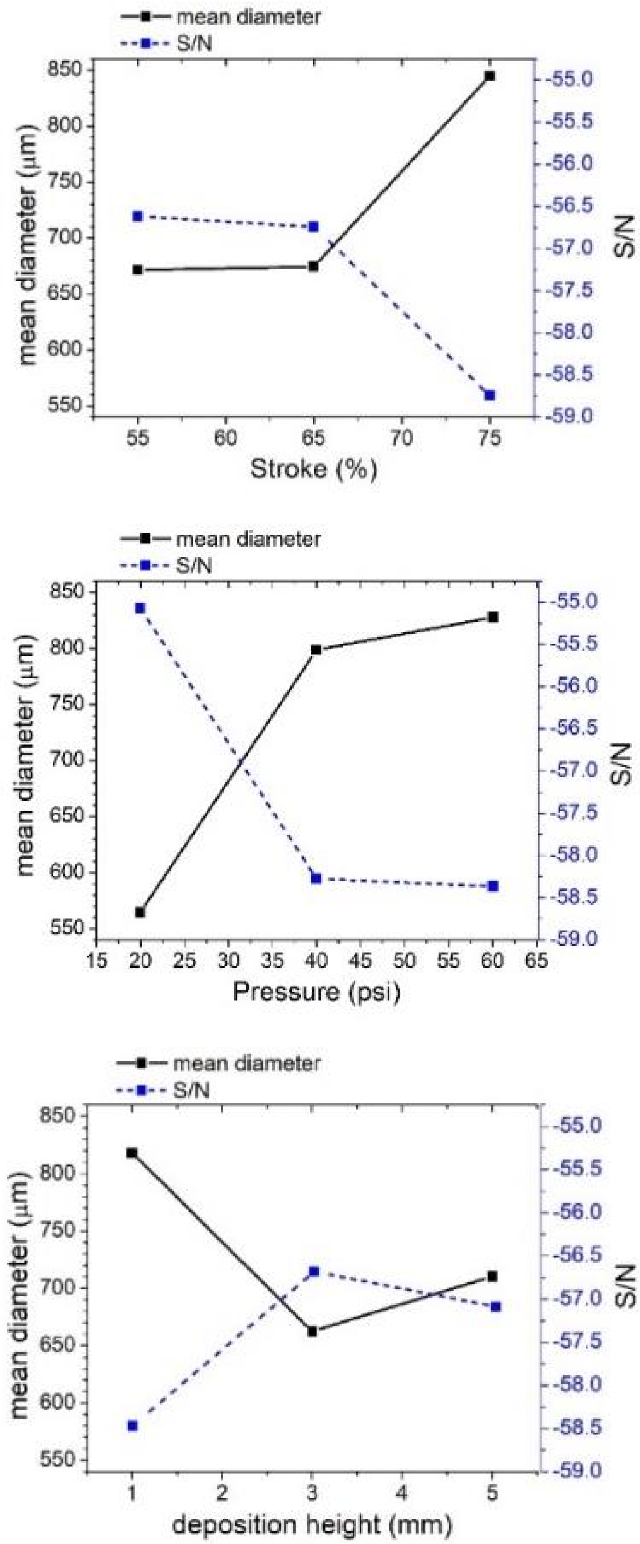


FIGURE 7: PARAMETERS EFFECT PLOTS FOR DROPLET DIAMETER MEANS FROM TAGUCHI DOE WITH THE SIGNAL TO NOISE RATIOS IN BLUE

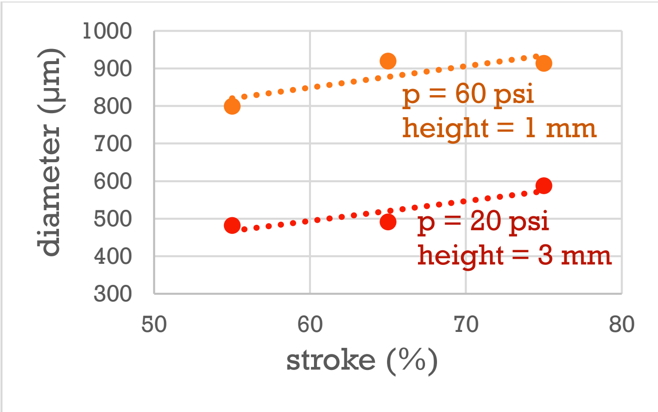
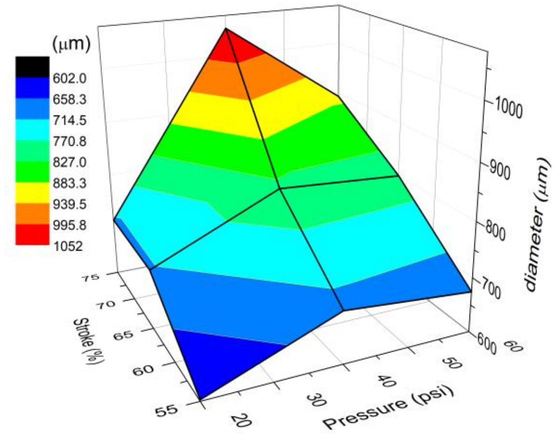
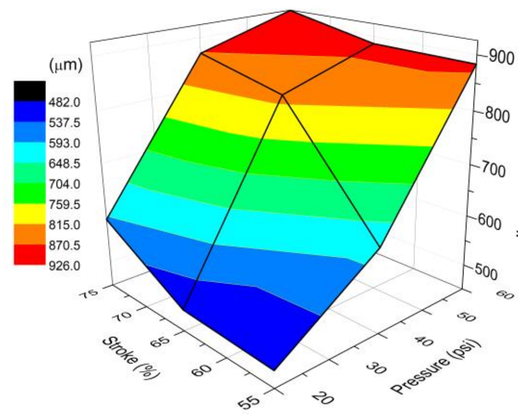


FIGURE 8: TRENDS OF EXPECTED MINIMUM AND MAXIMUM PARAMETERS BASED ON THE TAGUCHI DOE ANALYSIS

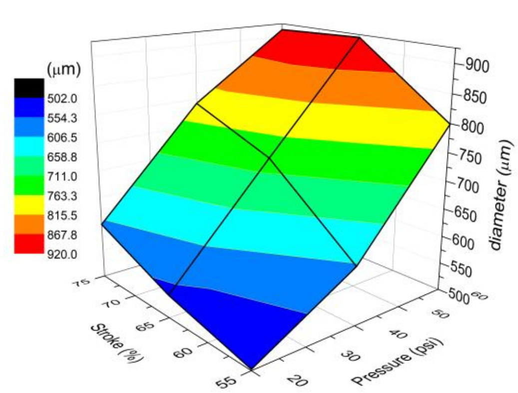
Figure 8 depicts the expected trend for the selected parameter, stroke, from the Taguchi DOE. The parameters shown are the two sets expected to result in the minimum and maximum diameters for a given case. However, after running all the experiments a small difference was found in the parameters for the maximum diameter. The set of parameters for the maximum diameter (~1050 µm) was found to be: Pressure – 40 psi, Stroke – 75%, Deposition height – 1 mm. The lowest diameters of the droplets/deposits are observed at lower values of pressure (20 psi) and stroke (55%). The minimum diameter of ~480 µm was observed for the following set of parameters: Pressure – 20 psi, Stroke – 55%, Deposition height – 3 mm (Figure 8 and 9). Based on the response tables (Table 3, 4) we have indicated that deposition height has the least impact on droplet diameter. Therefore, to illustrate the dependence of droplet diameter on both stroke and pressure, we have conducted additional series of experiments and expanded sets of the parameter data for each of the height values to extract additional information - response results are plotted in Figure 9. For a deposition height of 3 mm and 5 mm, increasing pressure results in the greatest increase of droplet diameter. Stroke follows this trend as well to a lesser extent. Which is an expected result according to response tables ranking (Table 3 and 4). However, for 1 mm deposition height, this trend is not observed (Figure 9). The significant impact of the pressure on the droplet diameter and its direct proportional relation could be contributed to fluid dynamics within the chambers of the printing head's cartridge. Droplet diameter is dependent on the released volume of the fluid – a large amount of the fluid would result in a larger diameter of the droplet on the substrate. On the other hand, volume of the dispensed fluid is affected by its flow rate through the nozzle and cartridge chamber, and consequently the pressure. Lastly, the presented plots in Figure 9 serve another important purpose as a way of mapping the dispensing process parameters enabling their tuning to produce a droplet of the desired size for a given type of fluid. This feature allows better command of the printing process of the structures with various geometries: single lines, thin films, more complex patterns, and a result enables better control of the structure's morphology.



Deposition Height: 1 mm



Deposition Height: 3 mm



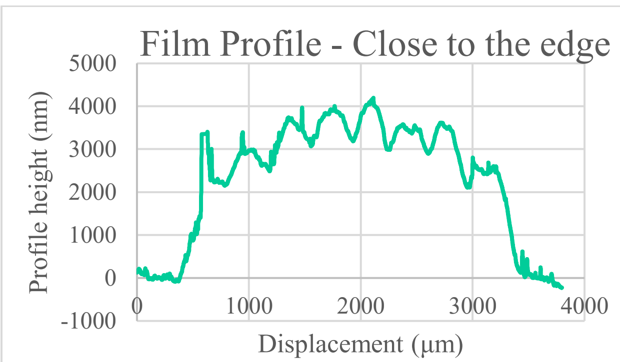
Deposition Height: 5 mm

FIGURE 9: 3D PLOTS COMPARING THE EFFECT OF STROKE AND PRESSURE ON DIAMETER SIZE OF PEDOT: PSS DROPLETS.

To conduct profilometry measurements we have fabricated a PEDOT:PSS film composed of 10 single layers on top of each other. Initial results from a single layer PEDOT:PSS thin film were distorted by noise affecting the reliability of measurement. We found that 10 layers worked best for the Dektak® profilometer (Figure 10). The results indicate a film thickness of around 3 microns, with a range from 2 to 4 microns. This gives us a thickness of 200 to 400 nm per individual layer. This is comparable to the films fabricated in the cleanroom using the spin coating.

Figure 10 shows the side profile of a film made up of 8 merged lines. Each line's profile can be seen in the plot, which shows that the film itself is not uniform in thickness. This could be an accumulated effect since every single layer of the thin film is not uniform.

A



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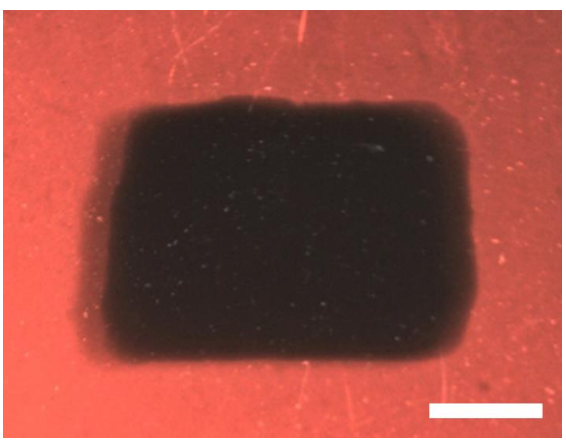

FIGURE 10: A: PROFILOMETRY RESULTS FOR A FILM PRINTED ON KAPTON ON A SILICON WAFER WITH THE FOLLOWING PARAMETERS: PRESSURE – 20 PSI, DEPOSITION HEIGHT – 3MM, STROKE – 55%. RESULTS ARE FROM THE FILM COMPOSED OF 10 SINGLE LAYERS; B: IMAGE OF A FILM COMPOSED OF 8 LINES (PER SINGLE LAYER) AND 5 LAYERS. 60 PSI – 55% STROKE – 1MM DEPOSITION HEIGHT. SCALEBAR = 1MM.

Nevertheless, we have demonstrated the ability to produce the PEDOT:PSS film with a thickness in the range of a few hundred nm using the Inkjet printing technique. Optimization of the printing process would allow for the fabrication of the uniform thin films enabling potentially better control over the morphology of printed structures. For example, enabling tuning of the film properties, not only thickness but also resistivity in case of conducting materials, by adding additional layers on top of each other [19].

4. CONCLUSION

In this paper, we demonstrated applications of Inkjet printing as the method for fabrication of thin films of PEDOT: PSS. Dispensing of the PEDOT: PSS was realized using the Nordson EFD® Pico Pulse system, which is controlled by many different parameters. We applied the Taguchi Design of Experiments (DOE) method to identify the optimal set of parameters for minimizing droplet diameter on plasma treated Kapton substrate. We conducted characterization of the printed features with the help of optical microscopy and the Dektak Profilometer. Experimental characterization data reveals that PEDOT: PSS droplets deposited on plasma Kapton have a minimum diameter of around 482 microns. The parameters that resulted in the minimum diameter gave a film thickness of around 300 nm. Thus, plasma treatment allows for successful printing of the films that have the morphology comparable to the films that were fabricated in the cleanroom.

In the future, we plan to optimize the printing process concerning thickness uniformity of the PEDOT:PSS thin films and introduce conductivity testing of the fabricated structures.

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REFERENCES

[1] Chang JS , Facchetti AF , Reuss R . "A circuits and systems perspective of organic/printed electronics: review, challenges, and contemporary and emerging design approaches. IEEE Journal on emerging and selected topics in circuits and systems", 7(1), 7–26, 2017.

[2] Saengchairat N , Tran T , Chua CK . "A review: additive manufacturing for active electronic components." Virtual Phys Prototyp, 12(1), 31–46, 2017

[3] B.Derby, "Inkjet Printing of Functional and Structural Materials: Fluid Property Requirements, Feature Stability, and Resolution", Ann. Rev. Mater. Res., 40:395–414, 2010.

[4] Kye-Si Kwon, Md Khalilur Rahman, Thanh Huy Phung1, Stephen D Hoath, Sunho Jeong and Jang Sub KimFlex. "Review of digital printing technologies for electronic materials", Print. Electron. 5, 043003, 2020.

[5] Jorge Alamán, Raquel Alicante, Jose Ignacio Peña and Carlos Sánchez-Somolinos, "Inkjet Printing of Functional

Materials for Optical and Photonic Applications", Materials, 9, 910, 2016.
[6] H. Minemawari et al, "Inkjet printing of single-crystal films", Nature, 475, 364, 2011.
[7] A. Sherehiy et al, "Adhesive deposition process characterization for microstructure assembly" (2021). Proceedings of the ASME 2021 16th International Manufacturing Science and Engineering Conference MSEC2021 June 21-25, 2020.
[8] Wei, D et al, "Precision evaluation of Nexus, a custom multi-robot system for microsystem integration", Proceedings of the ASME 2021 16th International Manufacturing Science and Engineering Conference MSEC2021 June 21-25, 2020.
[9] Ulrich Gengenbach, Martin Ungerer, Liane Koker, Klaus-Martin Reichert, Peter Stiller, Stephan Allgeier, Bernd Köhler, Xiaoqi Zhu, Chengyuan Huang, Veit Hagenmeyer, "Automated fabrication of hybrid printed electronic circuit", Mechatronics 70 102403, 2020.
[10] A.H. Ghahremani et al, "Automated Fabrication of Perovskite Photovoltaics Using Inkjet Printing and Intense Pulse Light Annealing", Energy Technol. 9, 2100452, 2021.
[11] M. N. Saadatzi and D. O. P. Joshua R. Baptist Zhong Yang, "Modeling and fabrication of scalable Tactile Sensor," *IEEE SENSORS JOURNAL,* vol. 19, no. 17, pp. 1558-1748, 2019.
[12] J. R. Baptist. M. Saadatzi, I. Wijayasinghe, Dan O. Popa, "Characterization of Large-area Pressure Sensitive Robot Skin," in SPIE Commercial + Scientific Sensing and Imaging, 2017.
[13] Olowo, O et al, "Organic Piezoresistive Robotic Skin Sensor Fabrication, Integration and Characterization" (2021) Proceedings of the ASME 2021 16th International Manufacturing Science and Engineering Conference MSEC2021 June 21-25, 2020.
[14] Roy, R. K., A, "Primer on the Taguchi Method", Van Nostrand Reinhold, New York, 1990.
[15] Duineveld P. The Stability of Ink-Jet Printed Lines of Liquid with Zero Receding Contact Angle on a Homogeneous Substrate. J Fluid Mech; 477:175–200, 2003 .
[16] Soltman, Dan and Subramanian, Vivek, "Inkjet-Printed Line Morphologies and Temperature Control of the Coffee Ring Effect", Langmuir, 24, 2224-2231, 2008.
[17] Shih, Hsueh, Ramachandran, Chen, Kumar, Vasant, Glowacki, Bartlomiej A., "Study on chemical-solution-deposited lanthanum zirconium oxide film based on the Taguchi method", J Sol-Gel Sci Technol, 51:102–111, 2009.
[18] Lambert, Pierre, "Capillary Forces in Microassembly: Modeling, Simulation, Experiments, and Case Study", pp 147-148, Springer, 2011.
[19] Yoo-Yong Lee et al, "Growth Mechanism of Strain Dependent Morphological Change in PEDOT: PSS Films", Scientific Reports, 6, 25332, 2016