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Dispense Printing of Silver Flake Inks on Hydrophilic and Hydrophobic Surfaces

Mohamad Kannan Idris and Gerd Grau*

In printed electronics, achieving precise deposition of conductive materials on challenging substrates like Teflon is critical. This study delves into dispense printing, a technique that offers precision and versatility for creating electronic patterns. The deposition of high-viscosity silver flake inks on both hydrophobic surfaces is investigated, such as Teflon, and hydrophilic ones, highlighting the significant interplay between ink viscosity and substrate wettability. This interaction is key to controlling ink spreading, drying behavior, and, ultimately, printing success. Research explores the relationships between critical parameters such as nozzle height, dispense pressure, and print speed, aiming to enhance the quality and functionality of printed electronics. The printing process is analyzed through its distinct phases: extrusion from the nozzle, spreading on the substrate, and line shrinking during drying. This methodological approach allows one to pinpoint how each parameter specifically influences the printing outcome, particularly on challenging substrates like Teflon. By advancing the understanding of these dynamics, the study offers valuable theoretical insights and practical advancements for fabricating high-quality, flexible electronics across diverse substrates. The findings underscore dispense printing's potential to meet the growing demand for flexible electronics.

1. Introduction

In modern electronics, the demand for advanced, flexible, and cost-effective technologies has prompted an interest in printed electronics. Printed electronics have emerged as a promising technology, with applications ranging from flexible displays and wearable devices to sensors, radio frequency identification tags, and solar cells.[1–5] Central to the realization of these innovations is the precise deposition of conductive materials onto substrates, often necessitating a balance between ink formulation, substrate surface characteristics, and printing parameters.

M. K. Idris, G. Grau
Department of Electrical Engineering and Computer Science
York University
Toronto M3J 2S5, Canada
E-mail: mkidris@yorku.ca

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Among the diverse array of printing techniques, dispense printing stands as a promising contender for the deposition of conductive materials onto various substrates, offering high precision and versatility. It can create intricate patterns with micrometer-scale precision, making it a compelling choice for fabricating functional electronic devices. The successful implementation of dispense printing for printed electronics hinges on the selection of printing parameters and understanding of how these parameters interact with different substrate surfaces and inks.

Dispense printing, also referred to as direct-write printing, is a form of extrusion-based printing. Unlike extrusion methods like fused deposition modeling (FDM), which utilizes melted thermoplastics to create 3D structures, dispense printing deposits high-viscosity liquid inks directly onto substrates, offering versatility in material choice and substrate compatibility such as glass, paper, textiles, and Teflon.[6–17] Dispense printing, with its inherent advantages and challenges, occupies a distinctive niche in printed electronics, especially passive elements. The most common passive elements printed using dispense printing are resistors, capacitors, antennas, and passive sensors.[18–20] Dispense printing has been used to print multiple inks, such as silver, gallium alloy, eutectic gallium indium, etc., to create stretchable and flexible devices.[13,21–23] Compared to other extrusion printing techniques like FDM, dispense printing offers greater precision, allowing for the creation of intricate patterns with micrometer-level accuracy.

Teflon, renowned for its exceptional hydrophobic properties and its role as a high-quality dielectric material, plays an essential role in printed electronics. Its hydrophobicity stems from the material's unique chemical composition, characterized by a low substrate surface energy, which renders it highly resistant to wetting by aqueous solutions. This intrinsic property is beneficial in printed electronics, as it facilitates the creation of moisture-resistant and durable electronic devices. Teflon substrates and packaging are sought after for applications where the prevention of moisture ingress, such as in outdoor sensors and wearable electronics, is of paramount importance. Additionally, Teflon's properties as a dielectric make it ideal for applications where electrical insulation is crucial.[24–26]

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While Teflon's hydrophobicity is invaluable in certain applications, it poses a considerable obstacle when it comes to traditional high-resolution printing techniques like inkjet printing, gravure, and flexography. Hydrophobic surfaces, by their nature, repel aqueous inks commonly used in inkjet printing, making it challenging to achieve reliable adhesion and precise patterning. Surface modification techniques have conventionally been employed to mitigate the challenges posed by low wettability on hydrophobic surfaces. These methods often involve altering the chemical and physical properties of the surface, typically through processes like plasma treatment or the addition/removal of monolayers.[27,28] Other methods include multistep printing processes that involve sequential drying to form lines and patterns.[29,30] In contrast, dispense printing excels with high-viscosity inks on hydrophobic materials, making it the better option in such applications.

While previous research has explored dispense printing parameters and their effects on the quality of printing, an equally significant factor that has not yet been studied is the role of the surface being printed on.[8,9,31,32] Substrate surface characteristics can significantly impact the dispense printing process and final results, a dimension that this article aims to explore comprehensively.

Furthermore, this article shows that despite the advantages of dispense printing and its suitability for hydrophobic substrates, the surface characteristics continue to exert a discernible influence on the printing process, which can be advantageous to some applications.

This article delves into a comprehensive investigation of the dispense printing process, focusing on the influence of printing parameters and surface properties when employing silver flake inks. The study considers a range of surfaces, including glass, Teflon, plasma-treated glass, and plasma-treated Teflon, as well as two distinct silver flake inks characterized by different rheological properties. By exploring the effects of nozzle height, dispense pressure, and print speed on trace dimensions and quality, we aim to provide valuable insights into dispense printing parameters for printed electronics applications. Furthermore, this research studies the interaction of these inks with the selected substrates, revealing the differences between printed lines before and after curing. The study also investigates sample-to-sample variation, highlighting the reproducibility and robustness of the dispense printing process. To augment our understanding, we present an analysis of ink droplet behavior during contact angle measurements and results showcasing the interplay between printing parameters, surface properties, and ink behavior.

In summary, this article seeks to contribute to the field of printed electronics by understanding the effect of dispense printing parameters and their impact on line formation and surface characteristics. The knowledge generated herein has the potential to guide researchers, engineers, and practitioners in printed electronics toward enhanced precision, reliability, and versatility, with a specific focus on silver flake inks. Through a comprehensive exploration of the interplay between ink properties, surface properties, and printing parameters, we provide understanding of dispense printing for the fabrication of next-generation electronic devices.

2. Experimental Section

2.1. Material Preparation

The main ink used in this study was NovaCentrix Metalon HPS-FG77, which is a silver flake ink. According to the technical data sheet, the silver flake diameter was 0.3 μm. The solvent was butyl carbitol, the silver content was 85 wt%, and the ink viscosity was 2500 cP. The second ink used for comparison was Creative Materials 120-07(LPS), which is also a silver flake ink. The silver flakes were larger (3 μm), the solvent was dipropylene glycol monomethyl ether (DGME), the silver content was 88%, and the ink viscosity was 22 000–28 000 cP. Both inks were prepared for printing in 2 mL cartridges (Voltera, Waterloo, Canada). The cartridges were centrifuged at 500 rpm for 10 min to get rid of air bubbles. The Teflon solution was prepared by dissolving Teflon-AF 1600 (Sigma-Aldrich, Oakville, Canada) in Fluorinert FC-40 (Sigma-Aldrich, Oakville, Canada) with 1.6 wt%.

2.2. Measurement Techniques

The rheometric measurements were taken using a Discovery Hybrid Rheometer from TA instruments. The rheometric tests were conducted using a 40 mm Peltier plate. The temperature was fixed at 35 °C. The contact angle images were taken using a Kruss DSA10 contact angle measurement system. Each error bar was calculated using ten data points. The line images (2D) and the height profiles (3D) were taken using a Keyence VHX-970F Digital Microscope.

2.3. Surface Preparation

Experiments were conducted on four surfaces: glass, Teflon, plasma-treated glass (Glass (P)), and plasma-treated Teflon. To create the surfaces, 1×1 inch borosilicate glass slides were used. The glass slides were cleaned by sonication in isopropanol, acetone, and deionized (DI) water in that order for 10 min each and then dried using an air gun. The slides were then used as glass substrates without any other treatments. The Teflon solution was spin coated on the glass slides at 300 rpm for 1 min and then cured at 150 °C for 30 min to create the Teflon substrates. Both glass plasma and Teflon plasma substrates were created by air plasma-treating glass and Teflon substrates for 5 min at 100 W with a MARCH PLASMOD plasma system and a T&C power converter. The plasma-treated substrates were printed on immediately after treatment.

2.4. Dispense Printing

All dispense printing was conducted using NOVA printer (Voltera, Waterloo, Canada) and 100 μm-diameter nozzles (Subrex, Carlsbad, United States). The reference printing parameters are shown in **Table 1**. Nozzle height, dispense pressure, and printing speed were identified as the main parameters that affected the line printing in steady state (i.e., middle of the line). The ink preheating temperature value was selected as the lowest feasible temperature above the temperature rise due to the heat generated by the dispensing tool electronics to obtain a

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Table 1. Reference printing parameters.

Printing parameter	Value
Nozzle Inner Diameter	100 [μm]
Nozzle Height	50 [μm]
Dispense Pressure	600 [a.u.]
Printing Speed	500 [mm min^{-1}]
Relief Pressure	80 [a.u.]
Dispense Threshold	100%
Relief Pressure	0%
Ink Preheat Temperature	35 °C

well-controlled temperature for printing. These parameters, illustrated in **Figure 1**, were swept in a one-factor-at-a-time experiment style. This printer uses dispense pressure instead of force and uses a pressure sensor connected to the nozzle for feedback to maintain that pressure. Unfortunately, the manufacturer of NOVA does not provide a unit for dispense pressure; however, the scale for this parameter is maintained internally; thus, the results in this article are reproducible using another NOVA machine using the same printing parameters. As a result, we used arbitrary unit [a.u.] for dispense pressure. Other parameters, such as relief pressure, dispense threshold, and relief threshold, control when the dispenser applies positive or negative pressure in the cartridge while the nozzle moves. These parameters strictly control the beginning and end of the lines and are used to counteract ink oozing and bulges at the beginning and end of the lines. These parameters provide a basis for an interesting future study; however, they have no effect on the steady-state portion of the lines and are outside of the scope of this article.

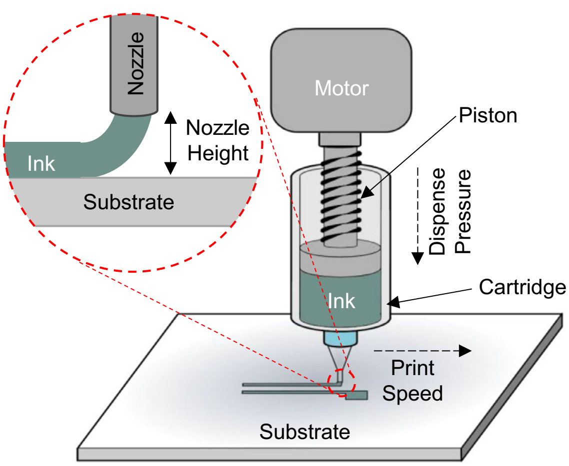

Figure 1. Illustration of the dispense printing technique, indicating the studied parameters: nozzle height, dispense pressure, and print speed. Nozzle height is the distance of the nozzle from the substrate during printing. When the piston moves down, it creates dispense pressure in the cartridge, pushing the ink out of the nozzle. Print speed is the nozzle movement speed during printing.

2.5. Statistical Analysis

Contact angle measurement images were processed using ImageJ. For each printing experiment, five lines were printed and evaluated after curing at 100 °C for 20 min, except when studying the difference between wet and dry lines study, where the lines were evaluated before and after curing. The 2D images and 3D profiles of lines were processed using the built-in functions in MATLAB R2021a. Each 2D image was turned to grayscale and then, using a threshold, turned into a binary image. Edge detection was used to detect each side of the trace, which was used to extract the required parameters. Each printing experiment was evaluated in terms of trace (line) width, trace height, trace height-to-width ratio, trace cross-sectional profile area, and trace edge roughness (R_a). Trace width and edge roughness were extracted from the 2D images. Trace height and cross-sectional profile area were extracted from the 3D profiles, as shown in **Figure 2**a,b. Figure 2c,d,e,f shows the images of traces printed using the NovaCentrix HPS-FG77 ink and reference parameters on the four different surfaces, that is, glass, Teflon, plasma-treated glass, and plasma-treated Teflon. The high brightness of the microscope light makes the silver traces shine and look white in the images, thus making image processing in MATLAB easier.

3. Results

3.1. Ink Characterization

To characterize the flow of the two inks, their viscosity was measured at 35 °C. As shown in **Figure 3**, the measured viscosity of the NovaCentrix HPS-FG77 ink is higher than the viscosity of the Creative Materials 120-07(LPS) ink. This will be used to explain the behavior of the inks during printing in the sections below. Both inks are non-Newtonian liquids which observe shear-thinning when the oscillation frequency increases, thus decreasing their viscosity. This behavior is what allows the inks to flow out of the nozzle when pressure is applied inside the cartridge during printing.

Furthermore, to understand the interaction of the inks with the surfaces of the substrates, contact angle measurements were conducted. The measurements were conducted using DI water, the inks, and their solvents on all four surfaces, that is, glass, Teflon, plasma-treated glass (Glass (P)), and plasma-treated Teflon (Teflon (P)). The average results of the contact angle measurements are plotted in **Figure 4**, showing the interaction of each liquid with the four aforementioned surfaces. As shown from the DI water measurements in Figure 4a, Teflon (hydrophobic) has lower surface energy compared to glass (hydrophilic), resulting in higher advancing and receding contact angles of DI water drops on Teflon than on glass. DI water drops behave as expected on Glass (P) as the plasma treatment adds OH groups to the surface, making it more hydrophilic, thus dropping the contact angles. On the other hand, the plasma affects the Teflon differently, where the advancing contact angle did not change, but the receding contact angle dropped, thus increasing the contact angle hysteresis. These behaviors are also similar for the solvents of the inks shown in Figure 4b,d, except for DGME on Teflon (P),

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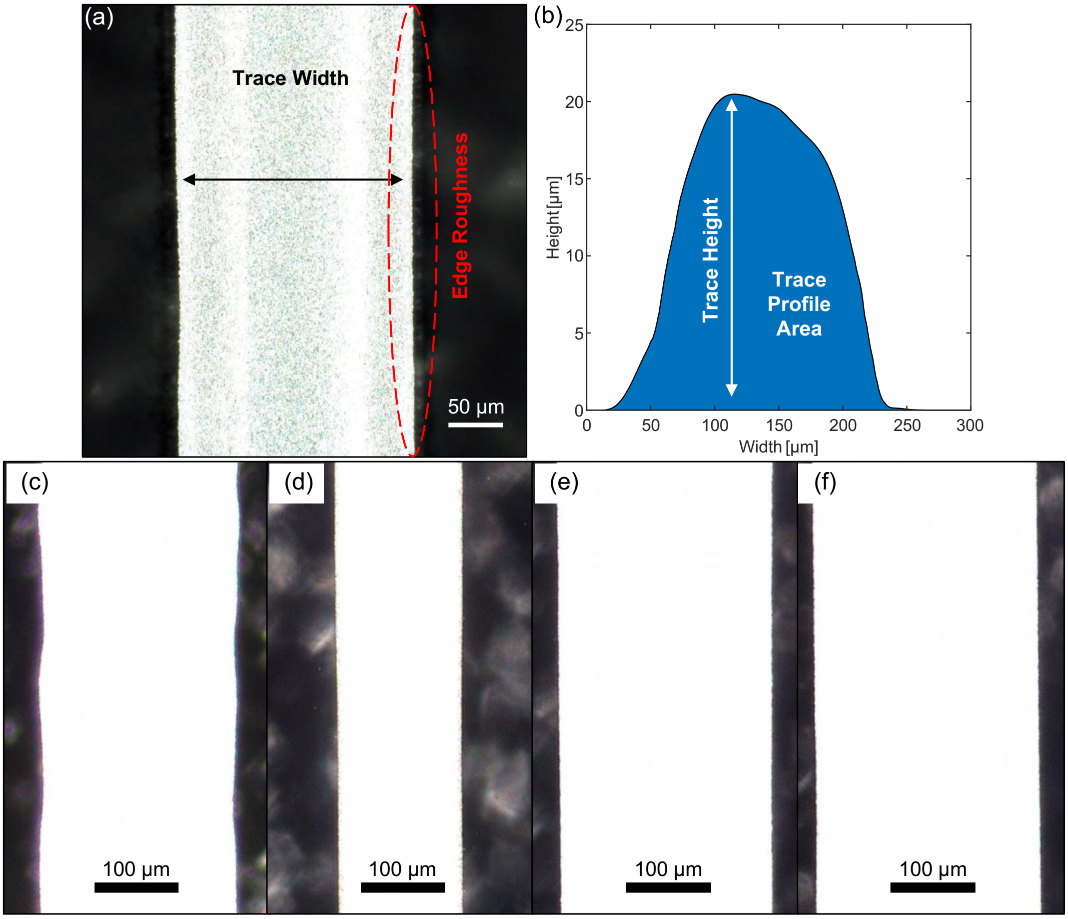

Figure 2. Printed trace parameters extracted from a microscope. a) 2D image of printed trace showing trace width and edge roughness. b) Trace profile extracted from 3D image showing trace height and trace cross-sectional profile area. High-brightness 2D images of lines printed using the NovaCentrix HPS-FG77 ink and the reference parameters on c) glass, d) Teflon, e) plasma-treated Teflon, f) plasma-treated glass. The high brightness of the microscope light is used to improve contrast of the silver traces on the substrate and make the image processing easier to extract the parameters shown in (a).

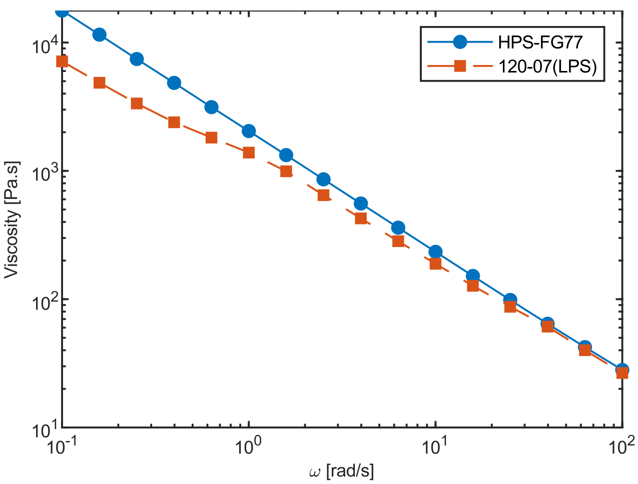

Figure 3. Viscosity change of NovaCentrix HPS-FG77 ink and Creative Materials 120-07(LPS) ink at 35 °C with varying oscillation angular frequency. The measured viscosity of the NovaCentrix HPS-FG77 ink is higher than the viscosity of the Creative Materials 120-07(LPS) ink.

where both the advancing and receding contact angles decrease compared to Teflon, but the hysteresis still increases.

Figure 4c,e shows the behavior of the inks on the four surfaces. As previously mentioned, the advancing contact angles are higher than those of the solvents, and the ink does not recede as the contact line is pinned; thus, the lowest contact angle will be referred to as pinned CA. Interestingly, the contact angles of the inks show no significant difference between the four aforementioned surfaces under these dispensing regimes. Furthermore, the contact angles of the NovaCentrix HPS-FG77 ink are higher than their counterparts of the Creative Materials 120-07(LPS) ink, especially the lowest pinned contact angles. The two inks differ in composition, leading to these variations in contact angle. However, the elevated viscosity of NovaCentrix HPS-FG77 emerges as a primary contributor to its higher contact angle.

The low-viscosity liquids behaved as expected. When the liquids are dispensed from the nozzle, they flow and spread, wetting the surface with an advancing contact angle, and when the liquids are pulled back, the liquids shrink and dewet the surface with a receding contact angle until the liquids are mostly or

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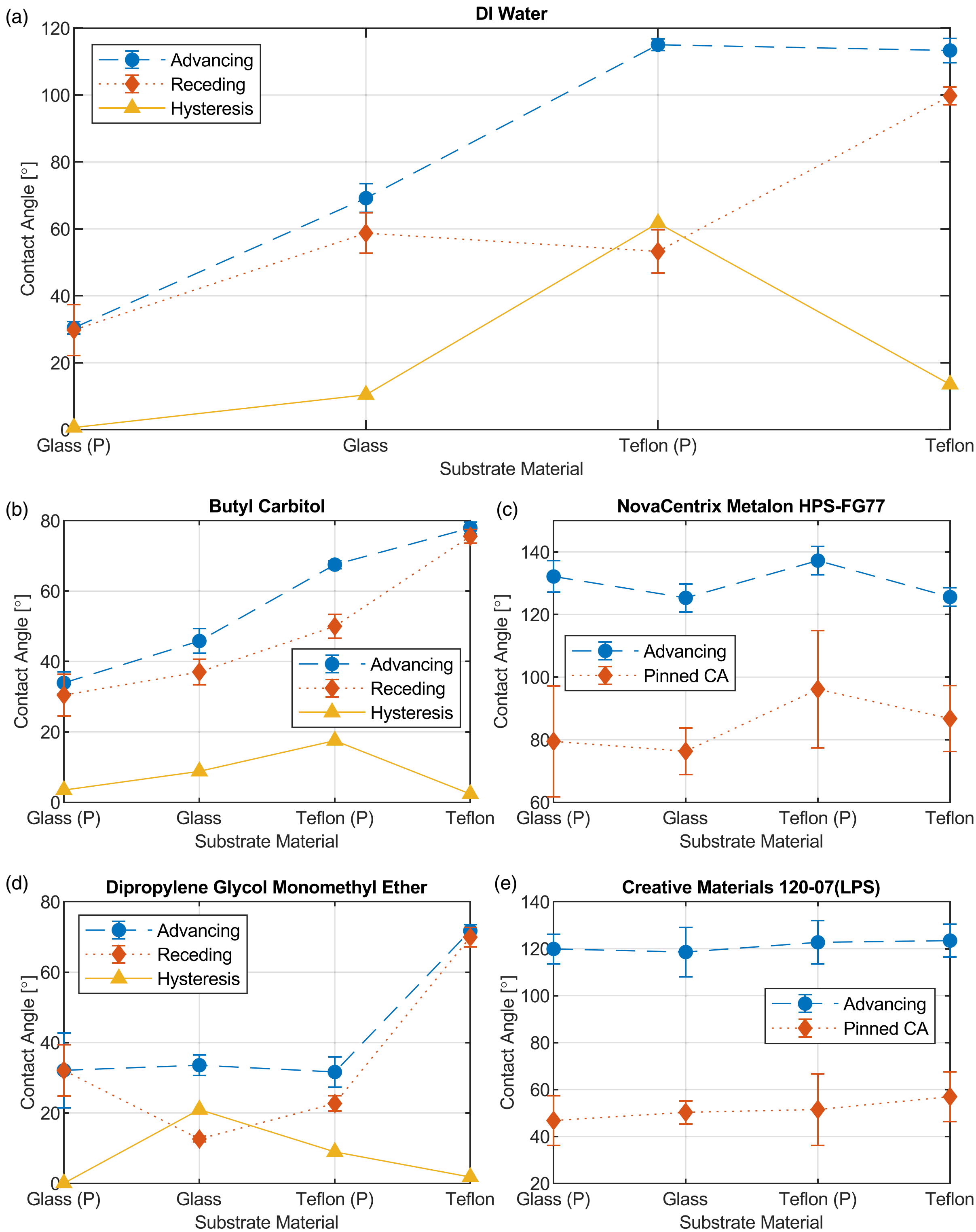

Figure 4. Contact angle measurements on four surfaces: Glass, Teflon, plasma-treated glass (Glass (P)) and plasma-treated Teflon (Teflon (P)), using a) DI water, b) butyl carbitol, c) NovaCentrix Metalon HPS-FG77, d) dipropylene glycol monomethyl ether (DGME), e) Creative Materials 120-07(LPS). Each data point with error bars is the mean and standard deviation of measuring ten drops on each surface. The high-viscosity inks do not recede as the contact line is pinned; thus, the lowest contact angle is referred to as pinned CA.

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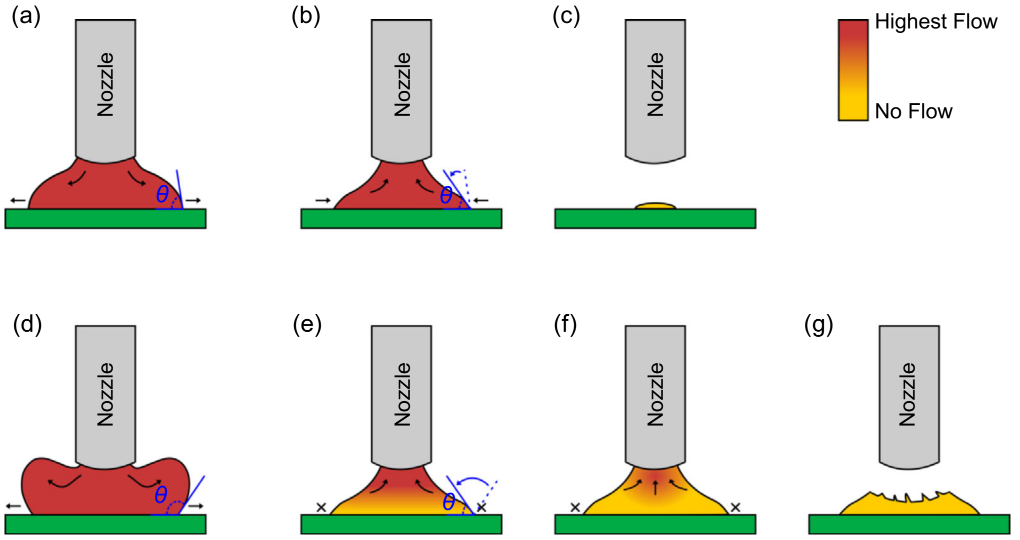

Figure 5. Contact angle behavior comparison between low-viscosity and high-viscosity (non-Newtonian) inks. a) Low-viscosity fluid is pushed out of the nozzle. The ink is dispensed from the nozzle, spreading on the substrate, showing an advancing contact angle. b) The ink is pulled into the nozzle, shrinking on the surface, and the contact angle decreases to a receding contact angle. c) Most or all of the ink is pulled into the nozzle, dewetting the substrate. d) High-viscosity ink is pushed out of the nozzle. The ink is dispensed from the nozzle, spreading on the substrate, showing a higher advancing contact angle. e) The ink is pulled into the nozzle, the contact angle decreases, but the ink does not recede, and the contact line is pinned. f) The force pulling the ink only shear thins part of the non-Newtonian high-viscosity ink while the bottom part is pinned until it separates, leaving most of the ink on the substrate, g) as illustrated.

entirely pulled back into the nozzle. An illustration of the behavior is shown in **Figure 5**a–c.

On the other hand, the high-viscosity, non-Newtonian inks behaved in a more interesting manner. The pressure applied in the nozzle shear thins the inks, dispensing them from the nozzle onto the substrate. The inks flow and spread, wetting the surface with a higher advancing contact angle due to the high viscosity. However, when the inks are being pulled back into the nozzle, the contact angle decreases, but the contact line of the ink drop is pinned and does not recede. This is because the negative pressure pulling the inks back into the nozzle shear thins only the top part of the ink drop. As the negative pressure continues to be applied, the shear-thinned part of the ink separates from the rest of the ink; thus, most of the ink wetting the surface stays on the substrate. An illustration of the behavior is shown in Figure 5d–g. Representative images of droplets for each data point in Figure 5 are shown in Figure S1–S5 (Supporting Information).

These measurements provide an understanding of the behaviors of the inks and their interactions with the substrates, which will explain some of the behaviors in the dispense printing regimes discussed below.

3.2. Dispense Printing Parameters

3.2.1. Nozzle Height

To understand the impact of nozzle height, illustrated in **Figure 6**a, on printing, the parameter was swept from 30 to 140 μm. It is important to note that nozzle heights of 150 μm and above were excluded from the analysis as they failed to produce continuous lines. Reference parameters were maintained for the other printing parameters. The ink used in this study was NovaCentrix HPS-FG77.

Varying the nozzle height does not result in a significant alteration in trace width on the same substrate, as depicted in Figure 6b. However, considering the nozzle diameter is 100 μm, the pressure applied causes the ink to extend beyond the nozzle's dimensions, leading to wider trace widths. Conversely, there is a clear correlation between trace height and nozzle height, as illustrated in Figure 6c. The height-to-width ratio exhibits a similar trend to trace height, as shown in Figure 6d. An increase in trace height does lead to a substantial increase in cross-sectional profile area, indicating that changes in trace height do not significantly affect the amount of dispensed ink per unit length of line because it is mainly set by the dispense pressure. Furthermore, since width also remained constant, this indicates that the line profiles do differ, becoming more triangular with larger nozzle heights. An example of this phenomenon is shown in **Figure 7**. This shows the correlation between nozzle height and line height. When the nozzle is higher up, the ink separates from the nozzle at a higher point, leading to a taller, narrower line. This is similar to what was previously observed in the contact angle measurements. The edge roughness data do not show any significant trends, the data is shown in the Supporting Information in Figure S6.

Comparing trace width, height-to-width ratio, and cross-sectional profile area on different surfaces (Figure 6), it is evident that the quantity of ink dispensed on Teflon surfaces is less than on glass, which is, in turn, less than on plasma-treated glass and plasma-treated Teflon. This can be attributed to surface wettability. The printer maintains a constant pressure in the ink cartridge, and the ink flows more readily on more wettable

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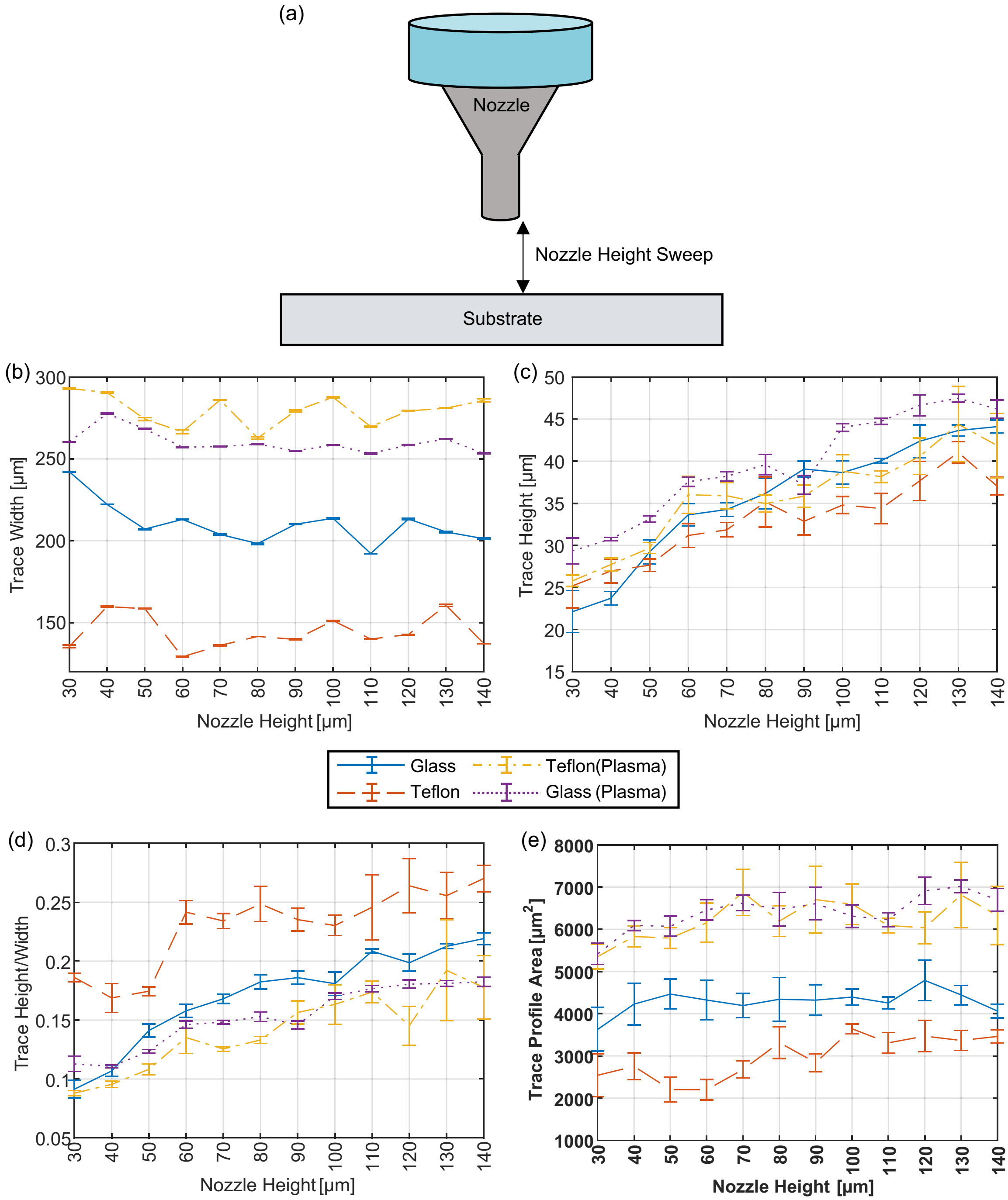

Figure 6. Nozzle height sweep printing on the four surfaces using NovaCentrix Metalon HPS-FG77. a) An illustration showing the nozzle height above the substrate. The effect of nozzle height on b) trace width, c) trace height, d) trace height-to-width ratio, e) trace cross-sectional profile area. Each data point with error bars is the mean and standard deviation of measuring five printed lines on each surface. Trends show consistent width but increased height and triangular profiles at larger nozzle heights.

surfaces. As a result, the printer applies additional displacement of the piston to compensate for the pressure loss, leading to larger amount of ink being dispensed.

Furthermore, the contact angle measurements mentioned previously provide valuable insights into this phenomenon. These measurements indicate that the solvent of the ink exhibits a high contact angle on Teflon, a lower contact angle on glass, and the lowest contact angle recorded is on plasma-treated glass. Notably, in the case of plasma-treated Teflon, the advancing contact angle does not decrease; instead, it exhibits higher hysteresis, further contributing to the intricate dynamics of ink behavior on different surfaces.

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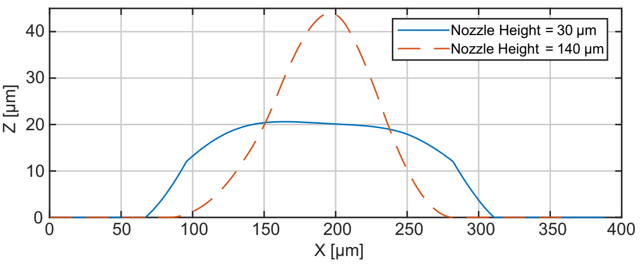

Figure 7. Profiles of traces printed using nozzle heights 30 and 140 µm showing a triangular profile with higher aspect ratio for larger nozzle height even though the cross-sectional profile area remains the same.

3.2.2. Dispense Pressure

To investigate the impact of dispense pressure, illustrated in **Figure 8**a, on the printing process, this parameter was varied within the range of 300–3000 [a.u.] while maintaining all other printing parameters at constant values. It is essential to emphasize that utilizing dispense pressures exceeding 1000 [a.u.] is considered impractical for any application in the field of printed electronics due to the excessive flow of the ink. Data for larger pressure values is shown in Figure S7 (Supporting Information). The ink chosen for this study was again NovaCentrix HPS-FG77.

Increased dispense pressure leads to observable increases in the printing attributes trace width, height, and cross-sectional profile area. Furthermore, a phenomenon emerges within the range of dispense pressure values below 1000 [a.u.], wherein ink was drawn out of the nozzle by hydrophilic substrates, as illustrated in Figure 8. This phenomenon can be attributed to the distinct wetting properties of different substrate surfaces. Specifically, the amount of ink dispensed on Teflon is less compared to glass, which, in turn, exhibits reduced ink deposition when compared to plasma-treated glass and Teflon. These distinctions were evident in the measurements of both trace width and cross-sectional profile area. Conversely, trace height does not show this trend because it is less affected by surface wetting and more by viscosity and the ink separating from the nozzle, as previously mentioned. The edge roughness data did not show any significant trends; the data is shown in the Supporting Information in Figure S8.

3.2.3. Print Speed

Finally, the effect of print speed, illustrated in **Figure 9**a, on the overall printing process has been systematically examined in this study. A range of print speeds, spanning from the lowest operationally viable speed of 100–1200 mm min^{-1}, were investigated. The ink utilized throughout this investigation, namely NovaCentrix HPS-FG77, remained consistent.

One notable finding is that variations in print speed exhibit a profound influence on the key printing outcomes. A consistent trend emerges whereby an increase in print speed leads to a notable reduction in line width, line height, and the overall printed profile area. This is evident in Figure 9b,c. The observed reduction in line width and height implies that faster print speeds contribute to a more concise and compact printing outcome.

Notably, it was also observed that the wettability of the printing substrate plays an essential role in the amount of ink extruded from the nozzle at different print speeds, mirroring the trends seen with nozzle height. The impact of print speed was further magnified when examined in the context of the height-to-width ratio, as depicted in Figure 9d. These findings underscore the importance of considering not only print speed but also the interaction between print speed and surface characteristics to achieve the desired printing outcomes. The edge roughness data did not show any significant trends, the data is shown in the Supporting Information in Figure S9.

In summary, the conducted experiments shed light on several critical aspects of the printing process and its response to variations in dispense pressure, nozzle height, and print speed. These findings contribute to a comprehensive understanding of the intricate dynamics involved in achieving precise and consistent printing outcomes in the realm of printed electronics. Notably, the relationship between dispense pressure and print speed reveals a noteworthy correlation. An increase in dispense pressure necessitates a corresponding increase in print speed to achieve printing results similar to those with lower pressure. This observation underscores the importance of fine-tuning these parameters altogether to optimize the printing process. Conversely, nozzle height, as long as it remains low enough to produce continuous lines, exhibits no significant interaction with dispense pressure and print speed. This can be attributed to this printer's ability to maintain pressure within the ink cartridge using a pressure sensor and closed-loop control rather than relying on open-loop control using piston displacement like other printers.

Furthermore, the role of surface characteristics, specifically wettability, is an essential factor in influencing the amount of ink dispensed and, consequently, the printing outcomes. It is evident that surfaces with higher wettability, such as plasma-treated glass and Teflon, facilitate more efficient ink flow. Consequently, the printer compensated for pressure loss, leading to more ink deposition. On the other hand, less wettable surfaces like Teflon lead to less ink deposition. This surface effect is clearly reflected in measurements of trace width and cross-sectional profile area.

Additionally, the contact angle measurements provide essential insights into this phenomenon. Notably, the solvent of the ink exhibits a high contact angle on Teflon, a lower contact angle on glass, and the lowest contact angle was recorded on plasma-treated glass. In the case of plasma-treated Teflon, the contact angle does not decrease; instead, it exhibits higher hysteresis, further emphasizing the complex dynamics of ink behavior on various surfaces.

3.3. The Effect of Drying

All analyses and evaluations above were conducted after the ink-drying and curing process. This procedure is crucial because curing is an essential step in any application, facilitating solvent evaporation, ensuring high electrical conductivity, and preventing unintended changes in trace patterns. To investigate the impact of the curing process, we conducted evaluations both before and after curing on glass and Teflon substrates, utilizing reference parameters and the NovaCentrix HPS-FG77 ink.

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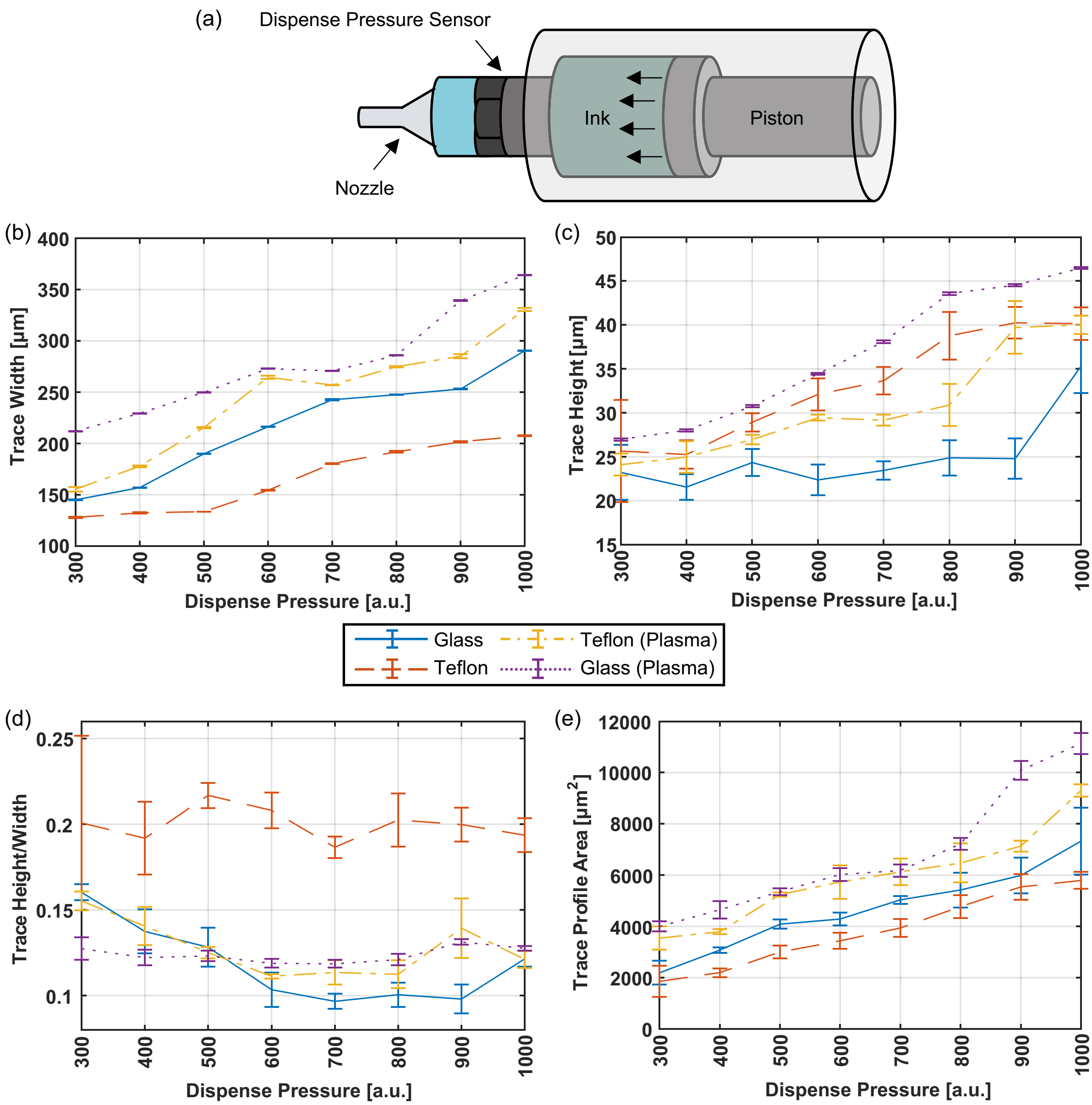

Figure 8. Dispense pressure sweep of printing on four surfaces using NovaCentrix Metalon HPS-FG77. a) An illustration showing the piston that applies pressure on the ink cartridge and the pressure sensor used to measure the dispense pressure. The effect of dispense pressure on b) trace width, c) trace height, d) trace height-to-width ratio, e) trace cross-sectional profile area. Each data point with error bars is the mean and standard deviation of measuring five printed lines on each surface. Trends show increased trace width, height, and cross-sectional profile area, with hydrophilic substrates drawing more ink than hydrophobic ones.

This part of the study was done to distinguish effects during printing and during drying to interpret the dry results above where the two effects cannot be distinguished.

Figure 10a illustrates the difference in trace width on the glass substrate before and after curing. A slight increase in trace width after curing (referred to as "dry lines") is observed, compared to its precuring state (referred to as "wet lines"). Conversely, on the Teflon surface, the trace width decreased after curing. This phenomenon can be attributed to the inherently low wettability of the Teflon surface, causing ink flow and contraction during curing. As a result, the contact edge of the ink line on Teflon was not pinned and could move due to surface tension forces, in contrast to the contact angle study, where the ink droplets' contact edges remained pinned. The ink line experienced forces all around during curing, causing it to contract as the solvent evaporated. In contrast, the contact angle measurement exerted negative pressure only on the ink portion close to the nozzle, and the surface tension forces were insufficient to overcome the wettability of the glass surface, resulting in the absence of ink shrinkage in that context.

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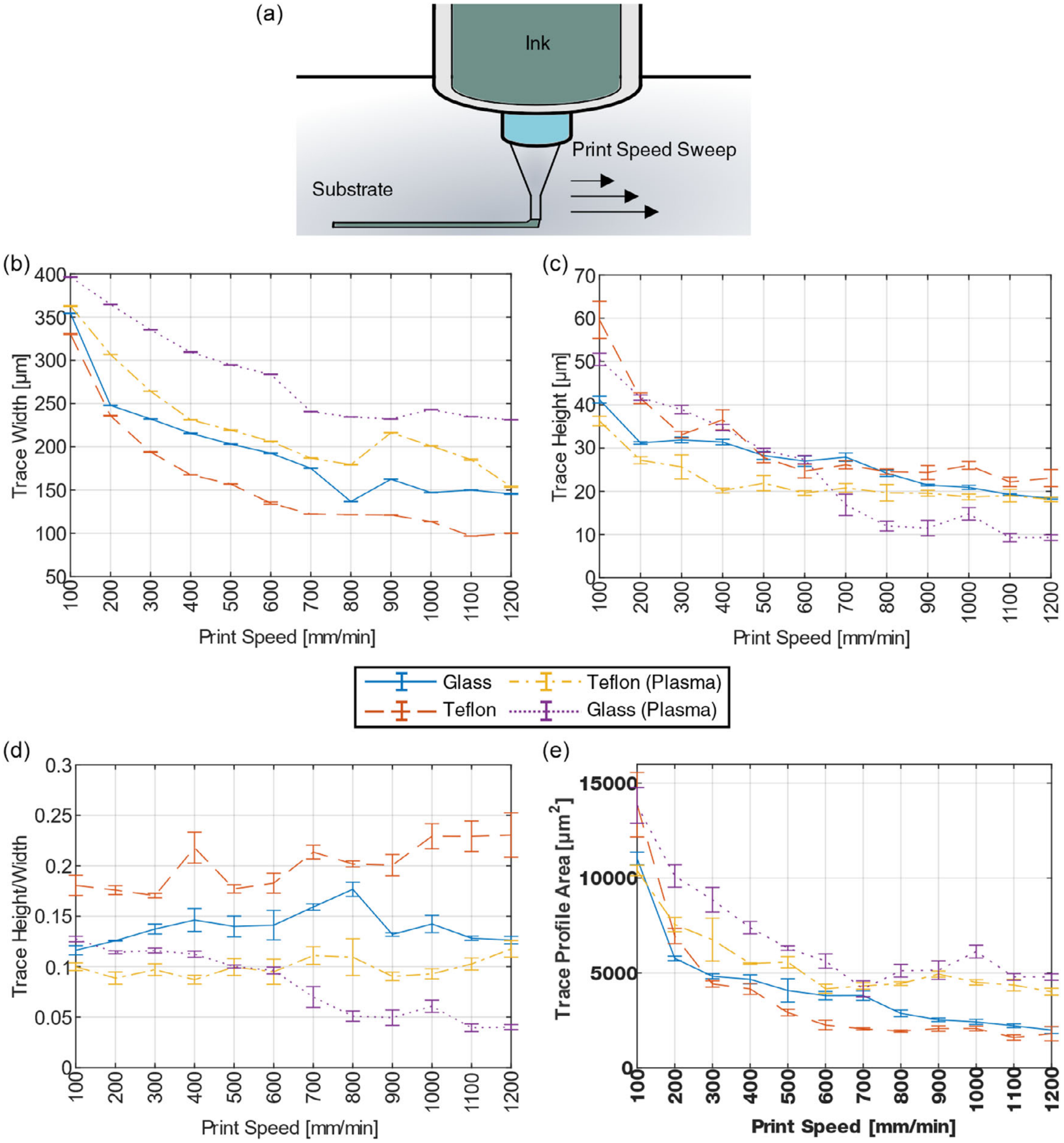

Figure 9. Print speed sweep on the four surfaces using NovaCentrix Metalon HPS-FG77. a) An illustration showing the print speed, which is the nozzle movement speed during printing. The effect of print speed on b) trace width, c) trace height, d) trace height-to-width ratio, e) trace cross-sectional profile area. Each data point with error bars is the mean and standard deviation of measuring five printed lines on each surface. Trends show reduced line width, height, and trace profile area with increased speed.

Both glass and Teflon substrates underwent identical curing conditions. As previously mentioned, the trace widths on Teflon decreased, while those on glass remained unchanged. This suggests that, since ink evaporation amounts for both substrates are equivalent under the same curing conditions, the height of the traces on glass decreases to a greater extent after the curing process, as demonstrated in Figure 10b.

Figure 10c demonstrates the change in the trace height-to-width ratio on glass and Teflon after curing. The change in the ratio on glass is primarily due to the height reduction and the pinned trace width. In contrast, there is no change in the height-to-width ratio on Teflon, indicating that the ink on Teflon uniformly shrank both in height and width due to the surface's low wettability. A similar phenomenon was observed when printing Newtonian low-viscosity silver nanoparticle inks using inkjet printing on Teflon surfaces.[30]

Figure 10d shows that the amount of ink printed, as indicated by the cross-sectional profile area of the line, on Teflon is lower than on glass due to the difference in wettability between the two surfaces. Additionally, due to the trace width shrinking on Teflon, line edge roughness increases after curing, while it decreases on glass, although both remain small, as shown in

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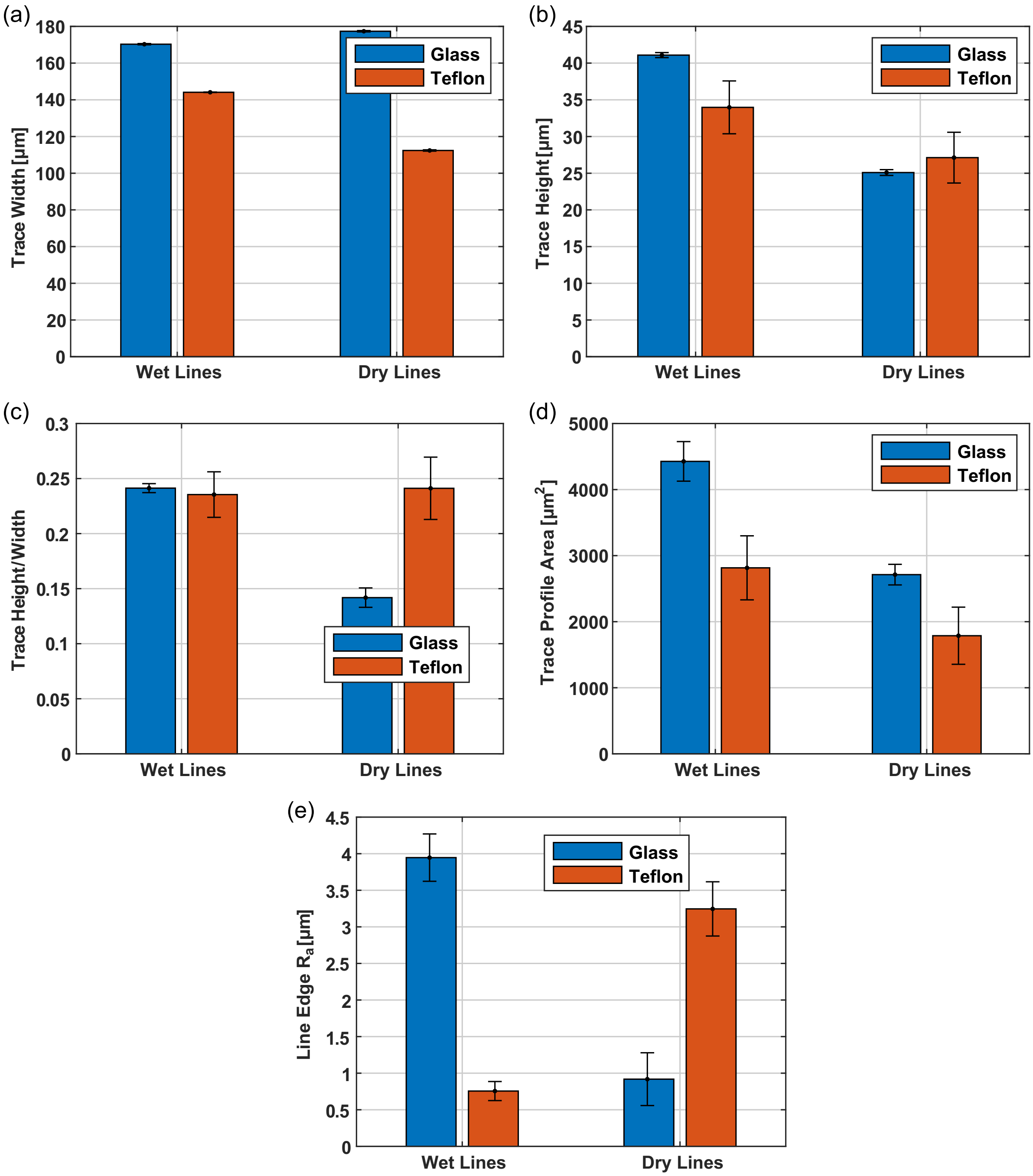

Figure 10. Comparison of NovaCentrix HPS-FG77 printed on glass and Teflon using reference parameters before drying (wet lines) and after drying (dry lines): a) trace width, b) trace height, c) trace height-to-width ratio, d) trace cross-sectional profile area, e) trace edge roughness (Ra). Each data point with error bars is the mean and standard deviation of measuring five printed lines on each surface. Trends show increased trace width on glass and decreased width on Teflon after curing, with height reduction on both surfaces and an increase in line edge roughness on Teflon.

Figure 10e. The profiles of lines before curing (wet lines) and after curing (dry lines) printed on both glass and Teflon are shown in **Figure 11**. Representative images of these lines are shown in Figure S10a–d (Supporting Information).

In summary, this study emphasizes the important role of surface wettability in dispense printing, particularly on Teflon and glass substrates. The observed differences in line dimensions and ink quantity underscore the significant influence of wettability on printing outcomes. On Teflon, the ink lines uniformly contracted due to its low wettability, while on glass, the lines primarily shrank in height. These findings provide valuable insights for optimizing ink printing processes on various

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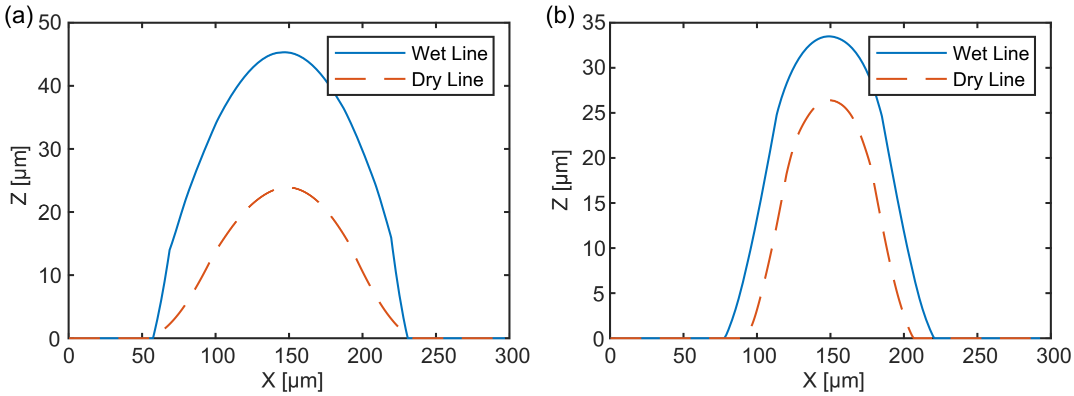

Figure 11. Profiles of lines before curing (wet lines) and after curing (dry lines) printed on different substrates: a) Glass. b) Teflon, showing shrinking on Teflon due to low wettability, while glass lines retain their width but decrease in height after curing.

substrates, highlighting the profound impact of surface wettability in achieving desired results.

3.4. Effect of Ink Parameters on Printing

To understand the effect of the ink on the printing process, two inks were printed using the same reference parameters. The inks were NovaCentrix HPS-FG77 and Creative Materials 120-07(LPS). The first ink has a higher viscosity than the second, as previously mentioned. As a result, when applying the same dispense pressure, the Creative Materials ink flows more (i.e., a larger amount of ink is extruded from the nozzle) than the NovaCentrix ink. However, it should be noted that both inks are in the desirable viscosity range for dispense or screen printing, which is much higher than, for example, inkjet printing. Furthermore, the Creative Materials ink and its solvent have lower contact angles (advancing, receding, and pinned contact angles on all surfaces) compared to the NovaCentrix counterparts, thus spreading on and wetting on the surface of the substrate more. Moreover, Creative Materials 120-07(LPS) has larger silver flakes, and it is flexible after curing as advertised by the manufacturer, while NovaCentrix HPS-FG77 has smaller flakes and is hard and brittle after curing.

The first study conducted was a comparison of the two inks printed on glass before and after curing. This experiment shows how these two inks flow differently. In **Figure 12**a, it is evident that both inks maintain the same trace width on glass before and after curing; however, although both inks were printed using the same parameters, the Creative Materials 120-07(LPS) has more than double the trace width than NovaCentrix HPS-FG77. This is due to the flowing properties of the former ink. This is further evident from the cross-sectional profile area measurements in Figure 12d, where the amount of Creative Materials ink dispensed on the glass substrate is significantly more than the NovaCentrix ink using the same printing setting.

The exact compositions of the inks are undisclosed by the manufacturers. However, the effect of the solvent evaporation rate during curing is negligible. Both inks undergo the same curing process, and by visual observation, they dry up within less than 5 min. This is not enough time for these high-viscosity inks to spread or shrink, that is, they are pinned on glass. Any changes in the measured line width are within the experimental error. After the curing process, in the NovaCentrix HPS-FG77, trace height reduces by ≈40% while in the Creative Materials 120-07(LPS) trace height reduces by ≈60%, thus reducing the cross-sectional profile area of the traces by the same percentages, as illustrated in Figure 12c,d. Representative images of these lines are shown in Figure S10c–f (Supporting Information).

In the following study, we investigated how the two types of inks interacted with four different surfaces by printing them using the reference parameters. After curing, we evaluated the printed lines, with results shown in **Figure 13**.

As previously mentioned, the trace widths of the lines exhibit different behaviors on Teflon compared to the other surfaces. Creative Materials 120-07 (LPS) displays wider trace widths but also a higher degree of width shrinkage than NovaCentrix HPS-FG77. The wider wet traces are due to the lower viscosity, which allows the ink to flow more ink volume out of the nozzle for the same dispense pressure. The higher degree of width shrinkage is due to the lower viscosity and the higher amount of evaporating solvent in the ink. Since both inks dry up quickly (within 5 min), the effect of solvent evaporation rate is negligible. This is evident because the observed trends are the opposite of what would be expected if the solvent evaporation rate was dominant. These phenomena are represented in Figure 13a. In this figure, it can be seen that Creative Materials 120-07 (LPS) also produced wider traces on glass, plasma-treated Teflon (P), and plasma-treated glass (P) as compared to NovaCentrix HPS-FG77. This variation is attributed to the differing wettability of these surfaces. The surfaces' greater wettability than Teflon prevented trace width reduction for both inks, and Creative Materials 120-07 (LPS) displayed better flow and spreading properties under the same printing conditions. On the contrary, the trace width of Creative Materials 120-07 (LPS) on Teflon was narrower than that of NovaCentrix HPS-FG77. This is because of Teflon's low wettability, which allowed both inks to contract without being pinned to the edges of the printed lines, with the former ink experiencing a higher degree of width shrinkage than the latter. Additionally, NovaCentrix HPS-FG77 maintained greater trace heights on all surfaces when compared to Creative Materials 120-07 (LPS), with Teflon showing the highest

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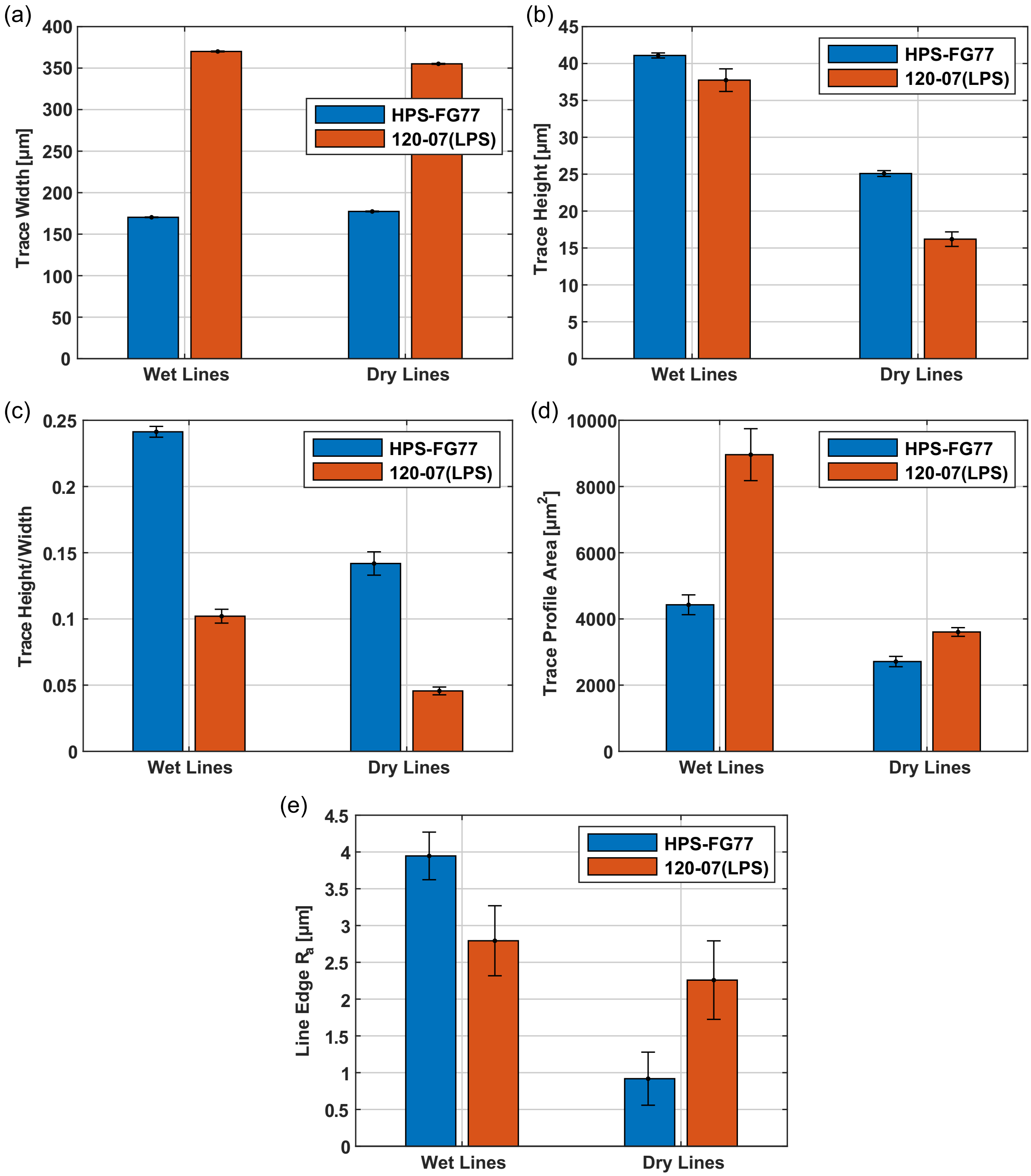

Figure 12. Comparison of two inks, NovaCentrix HPS-FG77 and Creative Materials 120-07(LPS), printed on glass using reference parameters before drying (wet lines) and after drying (dry lines): a) trace width, b) trace height, c) trace height-to-width ratio, d) trace cross-sectional profile area, e) trace edge roughness (Ra). Each data point with error bars is the mean and standard deviation of measuring five printed lines on each surface. Trends show that the Creative Materials ink produces wider traces and a greater cross-sectional profile area due to its lower viscosity, with both inks reducing in height and cross-sectional profile area after curing.

trace heights for both inks, as depicted in Figure 13b,c. The trace heights follow the contact angle trends for each surface where the line height on the less wettable surface (i.e., Teflon) is greater than the rest of the surfaces. At consistent printing parameters, Creative Materials 120-07 (LPS) exhibits a greater volume dispensed on glass, Teflon (P), and glass (P) surfaces, attributed to its lower viscosity and the respective surface wettability. Conversely, NovaCentrix HPS-FG77 demonstrates a higher volume dispensed on Teflon, as depicted in Figure 13d, owing to its higher viscosity. This higher viscosity allows NovaCentrix

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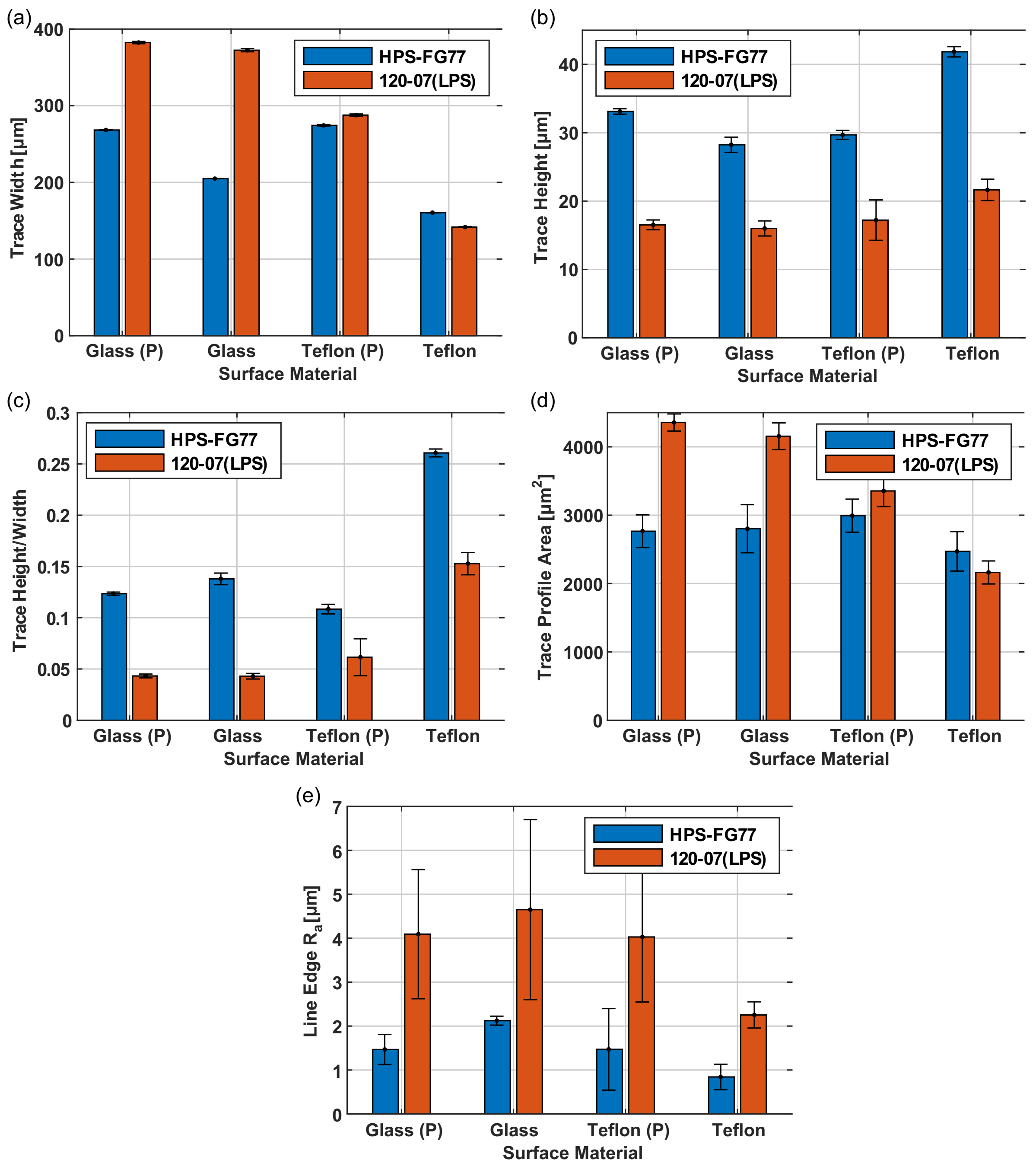

Figure 13. Comparison of two inks, NovaCentrix HPS-FG77 and Creative Materials 120-07(LPS), printed on the four surfaces, glass, Teflon, plasma-treated glass (Glass (P)), and plasma-treated Teflon (Teflon (P)), using reference parameters a) trace width, b) trace height, c) trace height-to-width ratio, d) trace cross-sectional profile area, e) trace edge roughness (Ra). Each data point with error bars is the mean and standard deviation of measuring five printed lines on each surface. Trends show that the Creative Materials ink produces wider traces with greater shrinkage on Teflon due to its lower viscosity, while NovaCentrix maintains higher trace heights on all surfaces, with Creative Materials ink also exhibiting rougher edges after drying.

HPS-FG77 to overcome the low surface wettability, resulting in increased ink extrusion from the nozzle. Finally, as mentioned earlier, Creative Materials 120-07 (LPS) exhibits rougher line edges after drying, a characteristic observed on all four surfaces due to the larger flake size, as evident in Figure 13e. Representative images of the lines printed using Creative Materials 120-07 (LPS) are shown in Figure S11 (Supporting Information).

In conclusion, this comprehensive study delved into the intricate dynamics of two distinct inks, NovaCentrix HPS-FG77 and Creative Materials 120-07(LPS), as they were printed on various surfaces using reference printing parameters and underwent a

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curing process. The results unveiled a contrast in behavior, with Creative Materials 120-07(LPS) demonstrating greater flow and spreading properties, yielding wider trace widths on glass, Teflon (P), and glass (P), but also experiencing more significant width shrinkage during drying, particularly on Teflon due to its low wettability. Conversely, NovaCentrix HPS-FG77 displayed higher trace heights on all substrate surfaces, emphasizing the influence of surface properties on the ink's behavior. Moreover, Creative Materials 120-07(LPS) exhibits rougher line edges post-drying across all substrate surfaces due to the larger flake size. These findings shed light on the critical role that ink composition and substrate surface characteristics play in the final printed outcome.

3.5. Variability Analysis

All of the previously mentioned experiments were conducted in an ambient environment outside of a clean room. Moreover, as previously mentioned, the wettability of the surface, which is affected by dust and particles, has a major effect on the printing. The substrates were cleaned, but they were exposed during printing. Furthermore, other effects causing variations could arise from the printing process, that is, bubbles in the ink cartridges, slightly clogged nozzles, etc. To understand the effect of these variations, five lines each were dispense printed on five separate glass samples using NovaCentrix HPS-FG77 and the reference parameters, and the lines were evaluated. As shown in **Figure 14**, trace widths show a maximum of 3% variation from sample to sample and a maximum of 0.5% variation within the same sample, that is, line to line. Trace height shows a maximum of 4% and 15% sample-to-sample variation and line-to-line variation, respectively. Trace height-to-width ratio shows a maximum of 4% and 11% sample-to-sample variation and line-to-line variation, respectively. Trace cross-sectional profile area shows a maximum of 4% and 10% sample-to-sample variation and line-to-line variation, respectively. Finally, trace edge roughness shows a maximum of 10% and 62% sample-to-sample variation and line-to-line variation, respectively. This is due to the small edge roughness values, which is 0.5% or less of the entire trace width. These results show that the variations are within acceptable ranges and do not compromise the data and the trends presented in this article. Representative images of these lines are shown in Figure S12 (Supporting Information).

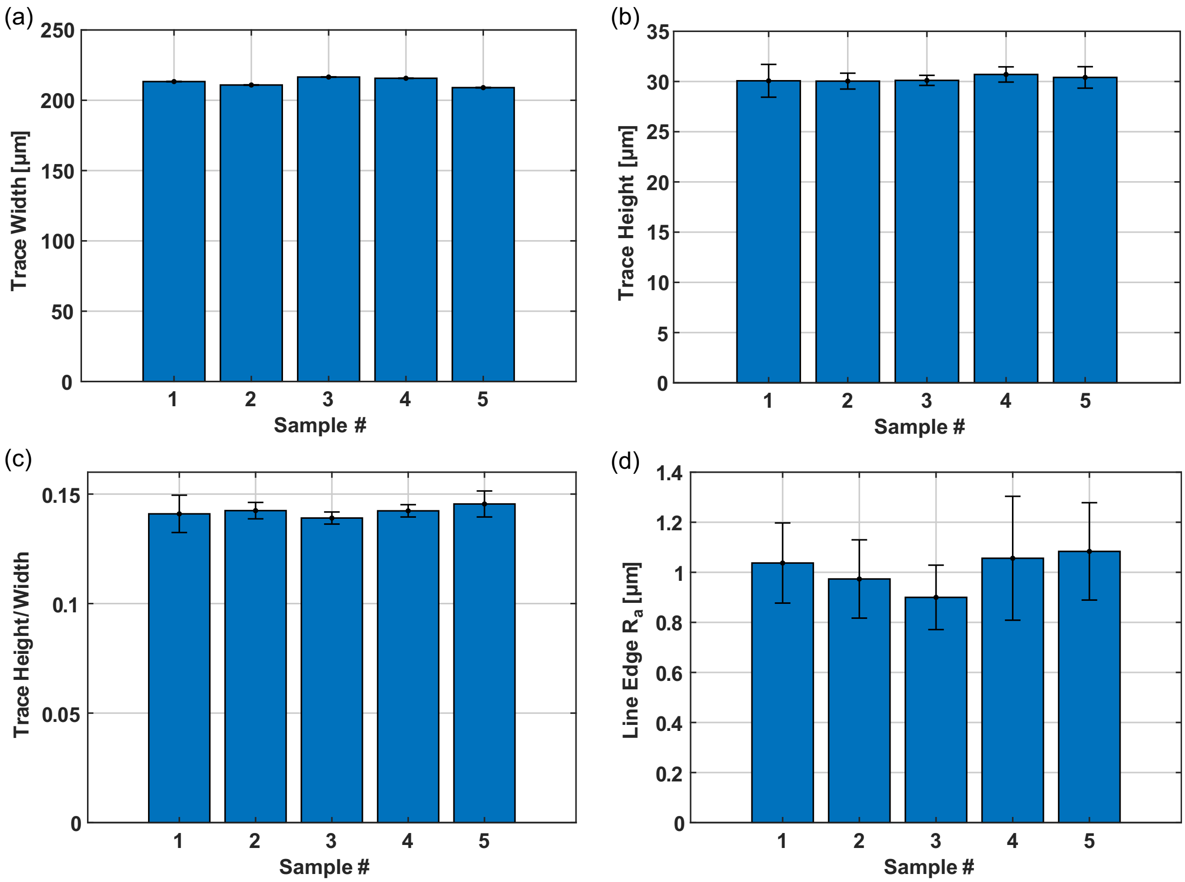

Figure 14. Sample-to-sample variation of NovaCentrix HPS-FG77 printed on glass using reference parameters. Evaluation in terms of a) trace width, b) trace height, c) trace height-to-width ratio, and d) trace edge roughness (Ra). Each data point with error bars is the mean and standard deviation of measuring five printed lines on each surface. Trace width, height, and cross-sectional profile area show variations of up to 4% sample to sample and 15% line to line, confirming that the variations do not affect the overall data integrity.

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4. Discussion

Our investigation into dispense printing of silver flake inks delineates a comprehensive understanding of the process, which can be separated into three critical phases: extrusion from the nozzle, spreading of ink on the substrate, and line morphology alteration during drying. This segmented approach allows for a detailed exploration of the influence that various parameters exert across the dispense printing process, providing actionable insights for optimizing printing strategies on diverse substrates.

4.1. Phase 1: Extrusion from the Nozzle

Extrusion efficiency is governed by the interplay between dispense pressure, nozzle height, and ink viscosity. To achieve a steady and controlled extrusion of ink, it is crucial to adjust the dispense pressure according to the ink's viscosity. A higher viscosity necessitates increased pressure to overcome the resistance of the ink to flow, ensuring it can be pushed through the nozzle effectively. The optimal nozzle height is determined by the trace shape required for the application while also avoiding contact with the substrate. The nozzle height affects the aspect ratio of the printed electrode. Substrate wettability affects the amount of ink dispensed while using the same printing parameters. More ink is drawn from the nozzle and dispensed on hydrophilic compared to the hydrophobic surfaces due to the larger attractive force between the ink and the substrate surface. This phase is closely linked with Phase 2, as the initial extrusion conditions set the stage for how the ink interacts with the substrate surface.

4.2. Phase 2: Ink Spreading on the Substrate during Extrusion

The spreading of ink upon contact with the substrate is influenced by dispense pressure, printing speed, nozzle height, substrate wettability, and ink viscosity. Higher dispense pressures and slower printing speeds allow more ink to flow per unit length of the line and spread, increasing line width. Furthermore, substrate wettability significantly affects ink spreading, with hydrophilic surfaces facilitating wider lines and more uniform ink distribution compared to hydrophobic surfaces. The interaction between ink viscosity and substrate wettability determines the final morphology of the printed lines, emphasizing the need for precise control over these parameters.

4.3. Phase 3: Line Shrinking on the Substrate during Drying

The final phase involves the drying and curing of the ink, during which line shrinking occurs. This process is primarily affected by substrate wettability and ink viscosity. On hydrophobic substrates, high-viscosity inks tend to shrink more uniformly, maintaining the integrity of the printed patterns. Conversely, on hydrophilic substrates, the ink's adhesion to the surface is stronger, leading to less shrinkage but potentially increasing edge roughness if not properly managed.

This work contributes to the field of printed electronics in two main aspects: the comprehensive analysis of the dispense printing process and the investigation into the effect of substrate wettability on high-viscosity dispense printing. We present a detailed examination of how printing parameters and substrate properties interact across different phases of dispense printing, offering insights that significantly advance the understanding of this complex process. Furthermore, our study on the impact of substrate wettability, particularly on the extrusion and spreading phases of high-viscosity inks, unveils critical factors that influence the efficacy and reliability of dispense printing on various substrates. This contributes to the broader body of knowledge by highlighting strategies to overcome the challenges associated with printing on hydrophobic substrates, thus expanding the applicability of dispense printing in the fabrication of printed electronics.

5. Conclusion

In concluding our detailed exploration of the dispense printing process for silver flake inks, this study has systematically addressed the complexities involved in printing on hydrophilic and hydrophobic substrates. Through focused analysis of two silver flake inks, we have illuminated the critical parameters—nozzle height, dispense pressure, and print speed—that significantly impact the efficiency and quality of printed electronic components.

Our research presents a nuanced understanding of how these parameters influence the deposition and behavior of silver flake inks during the printing process. The adjustment of nozzle height, for instance, was found to directly affect the height, aspect ratio, and profile of the printed lines, which is crucial for achieving optimal print quality. Similarly, variations in dispense pressure and print speed were shown to play essential roles in modulating the inks' spreading on and wetting of different substrates.

A key insight from our investigation is the intricate interplay between ink viscosity, substrate wettability, and printing parameters. We have demonstrated that the wettability of the substrate surfaces, whether hydrophilic or hydrophobic, significantly affects the extrusion from the nozzle as well as spreading and drying behaviors of high-viscosity inks, such as those studied. This understanding is critical for selecting appropriate printing strategies that can accommodate the wide range of substrate materials used in printed electronics.

Moreover, our investigation provides further evidence of the robustness of dispense printing technology, particularly emphasizing the process's adaptability to challenging substrates like Teflon. The ability to print effectively on Teflon not only showcases the versatility of dispense printing but also opens new avenues for the application of printed electronics in environments where moisture resistance and durability are paramount.

In essence, this study contributes to a comprehensive framework for optimizing the dispense printing of silver flake and other high-viscosity inks, offering practical guidelines for enhancing the production of printed electronic devices. By dissecting the effects of key printing parameters and substrate properties, we provide valuable insights for researchers and practitioners aiming to advance the capabilities and applications of printed electronics.

Several avenues for future research emerge from the findings of this study, which could further refine and optimize the dispense printing process for printed electronics. A standardized ink with controllable properties, such as varying viscosities, silver flake and nanoparticle concentrations, and solvent evaporation rates, could be used for a more detailed investigation into

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how each of these factors influences the overall printing process and the final performance of printed components.

Another critical area for further exploration is substrate surface modification. Techniques like substrate heating during printing and chemical modifications could enhance ink adhesion and performance, particularly on hydrophobic surfaces such as Teflon. Investigating these surface treatments will help to expand the range of materials suitable for dispense printing, facilitating the process's use in more diverse applications.

Additionally, future work could focus on optimizing the dispense printing process for emerging substrates, including flexible and stretchable materials. Expanding the applicability of dispense printing to such substrates would enable its use in next-generation electronic devices, particularly in wearable and flexible electronics.

Finally, further studies could further explore the effects of postprinting treatments, such as curing and environmental factors like temperature and humidity, on the long-term stability and electrical performance of printed components. These investigations would provide valuable insights into the durability and reliability of printed electronics in real-world applications.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

dispense printing, hydrophilic surfaces, hydrophobic surfaces, printed electronics, silver flake inks surface wettabilities, teflons

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