

INTEGRATING ORGANIC ELECTROCHEMICAL TRANSISTORS WITH 3D-PRINTED OBJECTS

MOHAMAD KANNAN IDRIS

A DISSERTATION SUBMITTED TO THE FACULTY OF GRADUATE STUDIES IN PARTIAL
FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

GRADUATE PROGRAM IN ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

YORK UNIVERSITY

TORONTO, ONTARIO

MAY 2025

© Mohamad Kannan Idris, 2025

ABSTRACT

Printed electronics provide an additive manufacturing approach for fabricating electronic devices by depositing functional materials such as conductive, semiconductive, and dielectric inks onto various substrates. Unlike traditional subtractive methods, printing techniques reduce material waste and simplify the fabrication process. However, achieving high-performance printed devices remains challenging, particularly in terms of conductivity and resolution. This challenge is amplified when integrating printed electronics with three-dimensional (3D) printed objects, where surface roughness and material compatibility affect device functionality. This dissertation studies the integration of organic electrochemical transistors (OECTs) with 3D-printed objects, focusing on three key aspects: improving the surface quality of fused deposition modeling (FDM) substrates, dispense printing of silver electrodes on both hydrophilic and hydrophobic substrates, and the fabrication and characterization of fully printed high-performance OECTs. Surface ironing is studied as a method to reduce the roughness of FDM-printed substrates, demonstrating a reduction of more than 90% in absolute surface roughness. The study of dispense-printed silver electrodes on hydrophobic and hydrophilic surfaces highlights the impact of substrate properties on printing consistency and electrode formation. Fully printed OECTs are fabricated using dispense-printed silver electrodes and inkjet-printed PEDOT:PSS semiconducting layers. Electrical characterization shows that these transistors achieve a peak transconductance (g_m) of 98.2 mS, the highest reported for a fully printed OECT. This high g_m is attributed to the low-resistance, thick electrodes enabled by dispense printing, ensuring enhanced charge injection and reduced contact resistance. The devices also exhibit stable operation over multiple measurement cycles, demonstrating repeatability and robustness. The primary goal of this work is the embedding of high-performance OECTs within 3D-printed objects, enabling the direct integration of electronics into complex geometries. By demonstrating the feasibility of fully printed OECTs on smoothed 3D-printed surfaces, this research establishes a foundation for advancing printed electronic systems. The findings open possibilities for bioelectronics, wearable sensors, flexible circuits, and integrated functional devices, where seamless integration of electronics with non-planar structures is critical for next-generation applications.

DEDICATION

To my father, Dr. Khaldoun Idris, whose guidance, wisdom, and unwavering support shaped the person I am today. Though you are no longer here, your love and encouragement continue to inspire me every day.

This work is dedicated to your memory.

فمات المؤمل قبل الأمل	يؤمل دنيا لتبقى له
فعاش الفسيل ومات الرجل	حنيثا يروي أصول الفسيل

ACKNOWLEDGMENTS

I would like to express my deepest gratitude to my supervisor, Dr. Gerd Grau, for his unwavering support, guidance, and mentorship throughout my PhD. His insights, patience, and encouragement were instrumental in shaping this research, and I am truly grateful for the opportunity to learn under his supervision. I also extend my sincere appreciation to my dissertation committee members, Dr. Simone Pisana and Dr. Reza Rizvi, whose valuable feedback and thoughtful discussions greatly enriched this work. Their expertise and guidance played a significant role in refining my research and pushing me toward higher standards of academic excellence. Additionally, I would like to thank my examining committee members, Dr. Aleksander Czekanski and Dr. Nathan Lazarus, for taking the time to review my dissertation and provide their insights. Their feedback and evaluation are deeply appreciated.

I would like to extend my sincere gratitude to Benno Neuhaus, whose contributions to this work were invaluable. His dedication, insights, and efforts played a significant role in shaping aspects of this research, and I am deeply appreciative of his collaboration. I am also grateful to my lab mates, Saumik Shovan, Milad Ghalamboran, Mohammad Nazeri, and Yoland El-Hajj, for their support, discussions, and assistance throughout my PhD. Their camaraderie made the research journey more enriching and enjoyable. Additionally, I thank the Electronics Additive Manufacturing Lab and all its members, past and present, for fostering a collaborative and stimulating research environment. The exchange of ideas and technical support within the lab have contributed immensely to this work.

I am profoundly grateful to my wife, Baraa, whose unwavering support and encouragement sustained me on a daily basis. Her patience, understanding, and belief in me made this journey more manageable, and I could not have done it without her by my side. I owe a deep debt of gratitude to my mother, Shaden, who sacrificed the most to ensure that I could continue and complete my PhD. Her endless support, resilience, and unwavering faith in my success have been a constant source of strength. I would also like to thank my sister, Layla, for her encouragement and for always standing by me. Finally, I am forever indebted to my father, Khaldoun, whose every decision in life shaped my path and ensured that I had everything I needed to reach this achievement. His influence and guidance continue to inspire me every day.

TABLE OF CONTENTS

Abstract.....	ii
Dedication.....	iii
Acknowledgments	iv
Table of Contents	v
List of Tables	ix
List of Figures.....	x
Chapter 1. Introduction.....	1
1.1. Printed Electronics.....	1
1.2. Traditional Microfabrication Techniques vs Printing	3
1.3. Functional Inks	4
1.4. Substrates.....	6
1.5. Printing and Coating Techniques.....	7
1.5.1. Dispense Printing.....	9
1.5.2. Inkjet Printing	11
1.6. 3D Printing.....	13
1.6.1. Fused Deposition Modeling (FDM)	13
1.6.2. 3D Printing Materials	15
1.6.3. Surface Ironing	16
1.7. Organic Electrochemical Transistors (OECTs).....	19
1.7.1. Organic Semiconductors for OECTs	19
1.7.2. OECT Electrodes	20
1.8. 3D Printed Electronics.....	22
1.9. Dissertation Organisation	24

Chapter 2. FDM Printing and Ironing.....	26
2.1. Introduction.....	26
2.2. 3D printing of the test samples	27
2.3. Sample design for optimization	28
2.4. Path generation	29
2.5. Surface Characterization.....	31
2.6. Parameter study: General flow without ironing.....	33
2.7. Parameter study: Ironing flow	34
2.8. Parameter study: Ironing speed	37
2.9. Parameter study: Ironing line spacing	40
2.10. Parameter study: Ironing Temperature	41
2.11. Parameter study: Sample size	42
2.12. Microscale characterization with SEM.....	45
2.13. Comparison with other smoothing methods and substrates	46
2.14. Final assessment of surface roughness improvement by ironing	48
2.15. Conclusion	50
Chapter 3. Dispense Printing of Conductive Silver Inks.....	51
3.1. Introduction.....	51
3.2. Materials and Methods	52
3.2.1. Material Preparation	52
3.2.2. Measurement Techniques	52
3.2.3. Surface Preparation.....	52
3.2.4. Dispense Printing.....	53
3.2.5. Statistical Analysis.....	54

3.3. Ink Characterization.....	55
3.4. Dispense Printing Parameters	62
3.4.1. Nozzle Height	62
3.4.2. Dispense Pressure	65
3.4.3. Print Speed.....	67
3.5. The effect of drying	69
3.6. Effect of Ink Parameters on Printing	73
3.7. Variability Analysis.....	78
3.8. Discussion.....	80
3.8.1. Phase 1: Extrusion from the Nozzle	80
3.8.2. Phase 2: Ink Spreading on the Substrate During Extrusion.....	80
3.8.3. Phase 3: Line Shrinking on the Substrate During Drying	80
3.9. Conclusion	81
Chapter 4. Printed Organic Electrochemical Transistors (OECTs)	82
4.1. Introduction.....	82
4.2. Materials	84
4.3. Device Fabrication.....	84
4.4. Characterization	86
4.5. Results and Discussion	86
4.6. Conclusion	100
Chapter 5. 3D Objects with Embedded Transistors.....	102
5.1. Introduction.....	102
5.2. Materials and Methods	104
5.2.1. Materials	104

5.2.2. Device Fabrication.....	104
5.2.3. Characterization.....	108
5.3. Results and Discussion	108
5.4. Comparison of Transistor Performance on Glass and Embedded in 3D Printed Object.....	118
5.5. Conclusion	118
Chapter 6. Conclusion and Future Work	120
6.1. Conclusions.....	120
6.2. Future Work	123
References.....	127
Appendices	150

LIST OF TABLES

Table 1-1. Attributes of several printing and coating methods. Ref. [10,31,72,121,124,130,131].....	9
Table 2-1. List of 3D printing materials used in this study.....	27
Table 2-2. Lowest roughness values found in the studies for the samples with and without ironing. The last column shows the reduction that can be achieved by ironing for the absolute, high-frequency, and low-frequency roughness.	49
Table 3-1. Reference printing parameters.....	53
Table 4-1. Dispense printing parameters	85
Table 4-2 (Part 1). OECTs in the literature using pristine PEDOT:PSS and the transistors that are presented in this work with five different channel lengths.	96
Table 5-1. FDM printing parameters	105
Table A-1. Print settings of the samples analyzed under the scanning electron microscope.	183

LIST OF FIGURES

Figure 1-1. Examples of applications of printed electronics including a) flexible displays (www.news.cnrs.fr); b) wearable sensors (www.vttresearch.com); c) RFID tags (www.kymc.com).	2
Figure 1-2. Comparison of the steps involved in subtractive manufacturing versus additive manufacturing of electronics.....	4
Figure 1-3. Contact angle measurement of water droplets on (a) more wettable (hydrophilic) glass substrate. (b) hydrophobic Teflon substrate.	6
Figure 1-4. 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.[95]	10
Figure 1-5. Inkjet printing. Illustration of the inkjet printing technique, indicating the nozzle, ink reservoir, signal generator, and piezoelectric actuator. The piezoelectric actuator generates pressure waves that force a droplet to jet through the nozzle.	12
Figure 1-8. Illustration of fused deposition modeling (FDM)	15
Figure 1-9. Cross-section of the general ironing process to achieve a smooth FDM printed surface to reliably print electronics on top. In this process, the hot nozzle goes over the printed top surface in a back-and-forth path with fine line spacing while adding and remelting material.	18
Figure 1-10. Structure of organic electrochemical transistors (OECTs). Silver electrodes create the source, drain, and gate electrodes. The organic semiconductor is printed in the channel. Finally, electrolyte liquid connects the gate and the channel.....	19
Figure 2-1. a) Sample design used to sweep the overall printing flow from left to right with 16 different settings. All layers have the same printing orientation to amplify the buildup of the material over all layers. Each of the sixteen rectangles is scanned on five different spots in the middle as shown on the right. b) Sample design used to sweep each of the ironing parameters from top to bottom. To prevent artifacts from the edges of the model and the lower layers, the ironing is performed in the middle of one uniformly printed surface. To get this base layer as evenly as possible, the printing direction of the layers beneath is alternated. Each rectangle represents the areas that are ironed perpendicular to the top layer orientation. Additionally,	

the width of the ironed area is varied in 15 mm steps to study whether the length of each ironing path line has an effect.29

Figure 2-2. Cross-section of an extruder hot end affected by heat creep. The combination of slow extrusion speed, constant pressure, and heat creeping upwards in the filament causes the filament to expand in colder areas which causes higher friction inside the feeding channel or even total clogging of the hot end. In that case, the molten polymer can leak irregularly from the nozzle due to gravity.30

Figure 2-3. Overview of the image processing algorithm. a) Flow chart of the main processing steps for two selected samples from our study. b) Frequency response from values returned by the algorithm with ideal sine waves of different wavelengths as input. c) Resulting roughness values for the two printed samples. The two samples show high roughness values for different frequencies: Sample 1 is mostly flat but contains ripples with a shorter wavelength. Meanwhile, sample 2 has a smooth surface but is wavy with a much bigger wavelength. Depending on the application, one or the other roughness could be more important..32

Figure 2-4. Effect of the general flow on surface roughness without ironing. a) Roughness data that was calculated with our algorithm for PLA, PETG, and ABS. Selected scans are shown for every second flow value below the graphs. The results for the three high-temperature materials PSU, PEI, and PEEK, and the other sample sizes are presented in Appendix A. b) Larger cross-section of the PLA surfaces with varying flow values. As the flow is increased, lines start overlapping and material spills over and accumulates. c) Schematic general trend of roughness for the general flow with some reference points from the scans in b). The peak of this general trend is found at around 112% for PLA, 115% for PETG, and 104% for ABS...34

Figure 2-5. Effect of the ironing flow on surface roughness. a) Roughness data that was calculated from profilometry scans with our algorithm for PLA, PETG, and ABS. Selected scans are shown for every second flow value below the graphs. The results for the three high-temperature materials PSU, PEI, and PEEK, and the other sample sizes are presented in the supplementary material. b) Schematic cross-section of material build-up during ironing. Proportions are not to scale. The height of the ironed layer can be regulated by adjusting the ironing flow, even though the position of the nozzle in the z-axis always remains the same as the last layer. The results indicate that increasing the ironing flow has only a small impact on the surface roughness compared to the general flow, as the primary effect is only a shift of the surface profile in the z-direction.36

Figure 2-6. Effect of the ironing print speed on surface roughness. a) Roughness data that was calculated from profilometry scans with our algorithm for PLA, PETG, and ABS. Selected scans are shown for every

second ironing speed value below the graphs. The results for the three high-temperature materials PSU, PEI, and PEEK, and the other sample sizes are presented in the supplementary material. b) Schematic top view of heat gradient for different ironing speeds with selected sample scans of PLA. Low speeds allow the heat to disperse deeper and wider into the material causing almost complete remelting of the surface. A slight increase in speed can result in a longer heat gradient, but the overlapping lines will still be cooled down by the time the toolhead moves to the adjacent line. High speeds will cause sufficiently larger areas of material to still be hot by the time the nozzle returns to the same area on the adjacent line, which allows better fusion between the last line and the newly printed line. c) General trend of roughness found for the ironing flow resulting from this.39

Figure 2-7. Effect of the ironing line spacing on surface roughness. The graphs show the roughness data that was calculated with our algorithm for PLA, PETG, and ABS. Selected scans are shown for every second line spacing value below the graphs. The results for the other two high-temperature materials PSU and PEEK and all other sample sizes are presented in the supplementary material. While a large line spacing is preferable for ABS, in the case of PEI a very smooth surface can be created by choosing the smallest line spacing.41

Figure 2-8. Effect of the ironing temperature on surface roughness. The graphs show the roughness data that was calculated with our algorithm for PLA, PETG, and ABS. Selected scans are shown for every second temperature value below the graphs. The results for the other two high-temperature materials PEI and PEEK and the other sample sizes are presented in the supplementary material. For the PETG and PSU samples, a transition from ripples to straight lines can be observed in the surface plots with increasing temperature.42

Figure 2-9. Boxplot of the roughness values grouped by sample size and averaged for each parameter experiment. The whiskers and quartiles reflect how much variation in roughness was achieved by varying the parameter of that study. For PLA and PSU, the average roughness decreases slightly with smaller samples while for the other materials roughness increases with smaller samples. The sample size directly translates to the path length in the ironing process and therefore is an important factor to consider when designing the geometry of the ironing path. Box plots are also shown for the unironed samples averaged over the general flow study. Note the scales of the y-axes are different in different graphs to improve readability.44

Figure 2-10. SEM images of ironed and unironed surfaces. While PETG and PSU show a more roughened-up surface on the micrometer scale compared to the unironed version, PLA, ABS, and PEI remain mostly

the same after the ironing step but with less waviness. In the case of PEEK, the large profile of the wide lines is replaced with finer lines but with an inferior high-frequency roughness.....45

Figure 2-11. Comparison of different methods to improve surface quality. The histograms and surface plots share the same scale in the first two rows and a different scale bar is shared for the third to fifth row. The ironed samples exhibit similar roughness as traditional PCBs and sanded 3D printed surfaces, but higher roughness than flexible PET substrates.47

Figure 3-1. 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)55

Figure 3-2. 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.56

Figure 3-3. 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.58

Figure 3-4. 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, de-wetting 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, as illustrated in (g).59

Figure 3-5. Advancing and receding contact angle images of DI water droplets on multiple surfaces. a) Advancing on plasma-treated glass; b) Receding on plasma-treated glass; c) Advancing on glass; d) Receding on glass; e) Advancing on plasma-treated Teflon; f) Receding on plasma-treated Teflon; g) Advancing on Teflon; h) Receding on Teflon;	60
Figure 3-6. Advancing and receding contact angle images of butyl carbitol droplets on multiple surfaces. a) Advancing on plasma-treated glass; b) Receding on plasma-treated glass; c) Advancing on glass; d) Receding on glass; e) Advancing on plasma-treated Teflon; f) Receding on plasma-treated Teflon; g) Advancing on Teflon; h) Receding on Teflon;	60
Figure 3-7. Advancing and receding contact angle images of NovaCentrix Metalon HPS-FG77 droplets on multiple surfaces. a) Advancing on plasma-treated glass; b) Receding on plasma-treated glass; c) Advancing on glass; d) Receding on glass; e) Advancing on plasma-treated Teflon; f) Receding on plasma-treated Teflon; g) Advancing on Teflon; h) Receding on Teflon;	61
Figure 3-8. Advancing and receding contact angle images of dipropylene glycol monomethyl ether (DGME) droplets on multiple surfaces. a) Advancing on plasma-treated glass; b) Receding on plasma-treated glass; c) Advancing on glass; d) Receding on glass; e) Advancing on plasma-treated Teflon; f) Receding on plasma-treated Teflon; g) Advancing on Teflon; h) Receding on Teflon;	61
Figure 3-9. Advancing and receding contact angle images of Creative Materials 120-07(LPS) droplets on multiple surfaces. a) Advancing on plasma-treated glass; b) Receding on plasma-treated glass; c) Advancing on glass; d) Receding on glass; e) Advancing on plasma-treated Teflon; f) Receding on plasma-treated Teflon; g) Advancing on Teflon; h) Receding on Teflon;	62
Figure 3-10. 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.	64
Figure 3-11. Profiles of traces printed using nozzle heights 30 μm 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.	65
Figure 3-12. 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.66

Figure 3-13. 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.68

Figure 3-14. 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.71

Figure 3-15. 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.72

Figure 3-16. High-brightness optical micrographs of wet and dry traces printed using the reference parameters. a) NovaCentrix HPS-FG77 on glass before curing (wet), b) NovaCentrix HPS-FG77 on glass after curing (dry), c) NovaCentrix HPS-FG77 on Teflon before curing (wet), d) NovaCentrix HPS-FG77 on Teflon after curing (dry), e) Creative Materials 120-07 (LPS) on glass before curing (wet), f) Creative Materials 120-07 (LPS) on glass after curing (dry).72

Figure 3-17. 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 greater cross-

sectional profile area due to its lower viscosity, with both inks reducing in height and cross-sectional profile area after curing.74

Figure 3-18. 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.77

Figure 3-19. High-brightness optical micrographs of cured traces printed using Creative Materials 120-07 (LPS) and the reference parameters on a) glass, b) Teflon, c) plasma-treated Teflon, d) plasma-treated glass.78

Figure 3-20. 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, 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 variations do not affect data integrity.79

Figure 3-21. High-brightness optical micrographs of traces printed using NovaCentrix HPS-FG77 and the reference parameters on five different glass samples. a) Sample #1, b) sample #2, c) sample #3, d) sample #4, e) sample #5.79

Figure 4-1. The structure of the OEET. a) top view, showing the printed design and channel dimensions. b) The layers of the printed OEET are glass for the substrate, dispense printed electrodes, inkjet printed OSC, and drop-casted electrolyte liquid.86

Figure 4-2. Profiles of a) the dispense printed electrodes showing the thickness and width of the electrodes; b) the inkjet printed organic semiconductor along the width of the OEET channel87

Figure 4-3. Electrical characterization of printed organic electrochemical transistor with smallest channel length (113 μm). (a) Transfer characteristics showing the drain current as a function of gate voltage. The drain voltage (V_D) is -1 V. (b) Transconductance (g_m) and drain current on a linear scale versus gate voltage, highlighting a peak transconductance of 103 mS and a threshold voltage (V_{th}) of 0.39 V. The drain voltage

(V_D) is -1 V. (c) Output characteristics illustrating the drain current response to varying drain voltage at different gate voltages.....89

Figure 4-4. Electrical characterization of printed organic electrochemical transistors with varying channel lengths. a) Transfer characteristics (I_D - V_G) for a device with channel length $L=205\ \mu\text{m}$. b) Output characteristics (I_D - V_D) for $L=205\ \mu\text{m}$. c) Transfer characteristics (I_D - V_G) for a device with channel length $L=309\ \mu\text{m}$. d) Output characteristics (I_D - V_D) for $L=309\ \mu\text{m}$. e) Transfer characteristics (I_D - V_G) for a device with channel length $L=437\ \mu\text{m}$. f) Output characteristics (I_D - V_D) for $L=437\ \mu\text{m}$. g) Transfer characteristics (I_D - V_G) for a device with channel length $L=526\ \mu\text{m}$. h) Output characteristics (I_D - V_D) for $L=526\ \mu\text{m}$91

Figure 4-5. Analysis of the influence of channel length on the performance of printed organic electrochemical transistors. (a) Absolute transconductance (g_m) values for OECTs with varying channel lengths, showing a decrease in g_m with increasing channel length. (b) Transconductance normalized by channel dimensions W/L , indicating an increasing trend with longer channel lengths. (c) ON/OFF current ratio (I_{ON}/I_{OFF}) across different channel lengths, with shorter channels exhibiting higher ratios. Red stars denote mean values, highlighting the trend and variability in device performance.92

Figure 4-6. Resistance characteristics of printed organic electrochemical transistors using TLM. Total device resistance plotted against channel length for different gate voltages ($V_G=0, -0.5, -1\ \text{V}$), showing an increase in resistance with longer channel lengths. Linear fits indicate the trend for each gate voltage. Each data point is the average total resistance for 10 devices of the same channel length.94

Figure 4-7. Comparative analysis of transconductance (g_m) and I_{ON}/I_{OFF} of printed organic electrochemical transistors against other reported devices. [82,89,90,158,160–162,172,175,176] (a) Transconductance (g_m) versus sheet resistance (R_s) demonstrating superior g_m for our devices due to low sheet resistance. (b) Normalized transconductance (g_m) by width-to-length ratio (W/L), indicating our device's high performance relative to its dimensions. (c) Normalized transconductance (g_m) by channel thickness (t), showing optimal balance and high performance of our device. (d) Transconductance (g_m) as a function of channel thickness, where our device achieves the highest g_m compared to others with similar channel thicknesses, highlighting the effectiveness of our fabrication process. Performance comparison of the on/off ratio (I_{ON}/I_{OFF}) for printed organic electrochemical transistors against other reported devices. (a) On/off current ratio versus sheet resistance, showing our device achieves a significantly high I_{ON}/I_{OFF} due to low sheet resistance. 100

Figure 5-1. Fabrication steps for the OECT embedded into a 3D-printed substrate. (a) The initial substrate design, including an alignment notch, printed using PLA on a Voxelab Aquila C2 FDM printer. (b) In-situ

surface ironing of the top layer to reduce roughness, enhancing compatibility with subsequent printing steps. (c) Dispense printing of silver electrodes using the NOVA printer, followed by curing at 100°C for 30 minutes. (d) Inkjet printing of the PEDOT:PSS semiconductor channel in a rectangular pattern using a custom drop-on-demand printer, with subsequent curing at 100°C for 20 minutes. (e) Correction of substrate warping by placing a 550 g glass weight during the final minutes of semiconductor curing. (f) Alignment frame printed to position the device for printing the microfluidic channel with a thickness of 1 mm. (g, h) The final printed OECT integrated with a microfluidic channel, featuring Luer taper inlet and outlet for syringe connection, designed for liquid electrolyte deposition and concentration studies..... 107

Figure 5-2. Contact angle measurements of advancing and receding droplets of DI water and PEDOT:PSS on both glass and ironed PLA substrates 109

Figure 5-3. Advancing and receding contact angle images of DI water droplets on multiple surfaces. a) Advancing on glass; b) Receding on glass; c) Advancing on non-ironed PLA surface; d) Receding on non-ironed PLA surface; e) Advancing on ironed PLA surface; f) Receding on ironed PLA surface..... 110

Figure 5-4. Advancing and receding contact angle images of PEDOT:PSS droplets on multiple surfaces. a) Advancing on glass; b) Receding on glass; c) Advancing on non-ironed PLA surface; d) Receding on non-ironed PLA surface; e) Advancing on ironed PLA surface; f) Receding on ironed PLA surface..... 110

Figure 5-5. Fabrication and dimensional analysis of printed electrodes for organic electrochemical transistors. (a) Electrode design created in EAGLE with a channel length of 300 μm and a channel width of 5000 μm . (b) Optical image of the printed electrodes on ironed PLA substrates, highlighting dimensional deviations post-fabrication. The final channel dimensions measured were $250 \pm 21 \mu\text{m}$ in length and $5050 \pm 15 \mu\text{m}$ in width. (c) Profilometric analysis of the printed electrodes and PEDOT:PSS semiconductor layer, showing electrode thickness of $36 \pm 2 \mu\text{m}$, electrode width of $251 \pm 17 \mu\text{m}$, and PEDOT:PSS thickness of $2 \pm 0.7 \mu\text{m}$. (d) Image of the final OECT device with PEDOT:PSS and microfluidic channel printed onto the electrodes. 112

Figure 5-6. Electrical characterization of printed organic electrochemical transistor with channel length 250 μm . (a) Transfer characteristics showing the drain current as a function of gate voltage and the transconductance (g_m), highlighting a peak transconductance of 77.7 mS. The drain voltage (V_D) is -1 V. (b) Output characteristics illustrating the drain current response to varying drain voltage at different gate voltages. 114

Figure 5-7. The electrical characteristics of the organic electrochemical transistors for multiple measurements (runs). During each run, a new volume of electrolyte liquid with the same concentration (100 mM) is pushed through the fluidic channel. a) The change of transconductance (g_m) during each run for each transistor. b) The change of ON/OFF current ratio (I_{ON}/I_{OFF}) during each run.	115
Figure 5-8. Transfer characteristics of the same organic electrochemical transistor for multiple measurements (runs) showing the drain current as a function of gate voltage. During each run, a new volume of electrolyte liquid with the same concentration (100 mM) is pushed through the fluidic channel.	116
Figure 5-9. The drain current versus time for $V_G = -1V$ and $V_G = 0.6V$, representing the role of ions in the OECT when it transitions from the saturation to the cut-off regimes.	117
Figure 5-10. The effect of the concentration of electrolytes (NaCl) on the transistor's drain on-current (I_{ON}).	117
Figure A-1. Printed PSU sample to analyze the effect of ironing speed on surface roughness.	150
Figure A-2. Effect of the overall flow without ironing on roughness for PLA.	151
Figure A-3. Effect of the ironing flow on roughness for PLA.....	152
Figure A-4. Effect of the ironing speed on roughness for PLA.....	153
Figure A-5. Effect of the ironing line spacing on roughness for PLA.....	154
Figure A-6. Effect of the ironing temperature on roughness for PLA.....	155
Figure A-7. Effect of the overall flow without ironing on roughness for PETG.....	156
Figure A-8. Effect of the ironing flow on roughness for PETG.....	157
Figure A-9. Effect of the ironing speed on roughness for PETG.	158
Figure A-10. Effect of the ironing line spacing on roughness for PETG.	159
Figure A-11. Effect of the ironing temperature on roughness for PETG.	160
Figure A-12. Effect of the overall flow without ironing on roughness for ABS.	161
Figure A-13. Effect of the ironing flow on roughness for ABS.	162
Figure A-14. Effect of the ironing speed on roughness for ABS.....	163
Figure A-15. Effect of the ironing line spacing on roughness for ABS.....	164

Figure A-16. Effect of the ironing temperature on roughness for ABS.....	165
Figure A-17. Effect of the overall flow without ironing on roughness for PSU.	166
Figure A-18. Effect of the ironing flow on roughness for PSU.....	167
Figure A-19. Effect of the ironing speed on roughness for PSU.....	168
Figure A-20. Effect of the ironing line spacing on roughness for PSU.....	169
Figure A-21. Effect of the ironing temperature on roughness for PSU.....	170
Figure A-22. Effect of the overall flow without ironing on roughness for PEI.....	171
Figure A-23. Effect of the ironing flow on roughness for PEI.	172
Figure A-24. Effect of the ironing speed on roughness for PEI.	173
Figure A-25. Effect of the ironing line spacing on roughness for PEI.	174
Figure A-26. Effect of the ironing temperature on roughness for PEI.	175
Figure A-27. Effect of the overall flow without ironing on roughness for PEEK.....	176
Figure A-28. Effect of the ironing flow on roughness for PEEK.	177
Figure A-29. Effect of the ironing speed on roughness for PEEK.	178
Figure A-30. Effect of the ironing line spacing on roughness for PEEK.	179
Figure A-31. Effect of the ironing temperature on roughness for PEEK.	180
Figure A-32. Effect of the ironing flow on the sample thickness for PLA.....	181
Figure A-33. Effect of the line spacing of the layer before the ironing step.	181
Figure A-34. Material properties and ironing roughness.....	182
Figure A-35. Nozzle temperature fluctuations of the two different printheads.....	183
Figure B-1. Nozzle height sweep of printing on the four surfaces using NovaCentrix Metalon HPS-FG77. The effect of nozzle height on edge roughness (R_a) is negligible.	184
Figure B-2. Dispense pressure sweep for large pressures of printing on four surfaces using NovaCentrix Metalon HPS-FG77. The effect of dispense pressure on a) trace width, b) trace height, c) trace height-to-width ratio, d) trace cross-sectional profile area, (e) line edge roughness (R_a).	185

Figure B-3. Dispense pressure sweep of printing on four surfaces using NovaCentrix Metalon HPS-FG77. The effect of dispense pressure on edge roughness (R_a) is negligible.....186

Figure B-4. Print speed sweep of printing on the four surfaces using NovaCentrix Metalon HPS-FG77. The effect of print speed on edge roughness (R_a) is negligible.186

Chapter 1. Introduction

1.1. Printed Electronics

Printed electronics represent a transformative approach to manufacturing electronic components and devices. This technology utilizes advanced techniques to deposit functional materials, such as conductive, semiconductive, and insulating inks, onto various substrates. Unlike traditional subtractive fabrication methods, which rely on removing material to define structures, printed electronics are inherently additive. This not only minimizes material waste but also simplifies the production process, making it more environmentally sustainable and cost-effective.[1]

The flexibility of printed electronics is among its most defining features. By enabling the deposition of materials on both rigid substrates, such as glass or silicon, and flexible ones, such as polymer films, paper, or textiles, this technology opens new possibilities for creating devices that can bend, stretch, or conform to complex shapes.[2–4] Such adaptability is critical for applications in emerging fields, including wearable technology, flexible displays, environmental sensors, and bio-compatible systems. For example, flexible printed electronics are already employed in lightweight, foldable displays and skin-like sensors that monitor physiological parameters, showcasing their versatility.[5–11]

A critical distinction in printed electronics lies between passive and active devices. Passive devices, such as resistors, capacitors, and antennas, are simpler to fabricate because they do not require many layers. These elements are typically used for basic electrical functions like resistance, capacitance, or signal transmission.[12–14] On the other hand, active devices, such as printed organic transistors, introduce additional complexity as they require intricate materials and architectures to enable switching and amplification functionalities. The ability to integrate both passive and active devices on the same substrate has allowed for the development of entire systems, such as sensors with integrated processing or communication capabilities.[15–31]

Printed electronics offer numerous advantages, particularly in terms of scalability and cost-efficiency. Techniques such as roll-to-roll printing are well-suited for high-volume manufacturing, enabling the production of devices on large sheets or continuous rolls of material.[32,33] This contrasts with sheet-to-sheet methods, which are better suited for prototyping and small-batch production. [34–36] Both approaches highlight the versatility of printed electronics in addressing diverse manufacturing needs. From an environmental perspective, printed electronics are inherently more sustainable than traditional methods.

Many printing processes operate at lower temperatures, allowing compatibility with a broader range of substrates, including those sensitive to heat, such as plastics. Furthermore, by directly depositing materials where needed, the process avoids the chemical waste and inefficiencies associated with subtractive techniques.[37–41]

However, there are notable challenges that limit the widespread adoption of printed electronics. While the resolution and performance of printed conductive traces have improved, they often fall short of the precision and conductivity achieved through traditional methods. Ensuring long-term stability, especially for devices exposed to environmental stresses like humidity and temperature changes, is another ongoing hurdle. Additionally, printed electronics are currently limited in their ability to produce the complex, high-performance circuits that are easily achievable using silicon-based technologies.[37,40,42–44]

Printing techniques in printed electronics can broadly be categorized into several clusters, each offering unique advantages depending on the application. Sheet-to-sheet printing provides high precision for small-batch or prototype production. Roll-to-roll printing, by contrast, is designed for high-throughput production, enabling the continuous fabrication of electronic components on flexible substrates. The choice of printing technique often depends on the desired application and the materials being used. For example, roll-to-roll printing is ideal for producing large-scale flexible sensors, while sheet-to-sheet techniques are better suited for high-resolution patterns in biosensors or display components.[2,3,32,33,45–51] Figure 1-1 demonstrates the versatility of printed electronics by illustrating various applications, such as flexible displays, wearable sensors, and RFID tags. This figure highlights how printed electronics can be integrated into a wide array of innovative technologies.

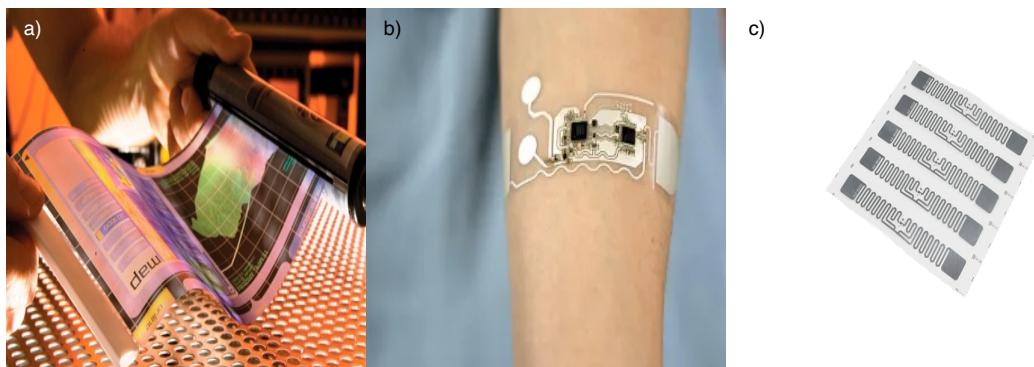


Figure 1-1. Examples of applications of printed electronics including a) flexible displays (www.news.cnrs.fr); b) wearable sensors (www.vttresearch.com); c) RFID tags (www.kymc.com).

1.2. Traditional Microfabrication Techniques vs Printing

Traditional techniques for fabricating electronic devices, such as photolithography, chemical vapor deposition, and etching, have long been the standard in electronics manufacturing. These methods, however, come with significant limitations that make them less favorable in modern applications demanding flexibility, sustainability, and cost efficiency. The subtractive nature of these techniques requires removing material to create patterns, leading to considerable waste and high material usage. Additionally, they rely on cleanroom environments and involve multiple complex steps, including deposition, masking, etching, and cleaning, which increase processing time and costs. The reliance on rigid substrates, such as silicon wafers, further limits their applicability to flexible or unconventional materials.[52–56]

In contrast, printing techniques offer an additive manufacturing approach that deposits material only where it is needed, greatly reducing waste and simplifying the production process. With fewer steps involved, as shown in Figure 1-2, printing eliminates many of the redundancies inherent in subtractive manufacturing, reducing time and cost while also lowering the environmental footprint. Printing methods are inherently versatile, enabling fabrication on a wide range of substrates, including flexible polymers, textiles, and paper. This adaptability makes printing the ideal choice for applications such as wearables, foldable displays, and large-area sensors.[57–62]

One of the most compelling advantages of printing techniques is their scalability and accessibility. Many printing methods, such as inkjet and dispense printing, can be employed on small, low-cost tabletop setups, making them ideal for prototyping and research environments. At the same time, these methods can be adapted for roll-to-roll manufacturing, enabling large-scale production at a fraction of the cost of traditional approaches. This dual capability allows printing techniques to address both small-batch customization and high-volume production with equal ease.[3,7,33,47,63,64]

Furthermore, printing methods enable compatibility with a diverse range of materials, from conductive and semiconducting inks to insulating and dielectric layers. Unlike traditional methods, which are often constrained by the thermal and mechanical limitations of the materials they process, printing operates at lower temperatures, preserving the integrity of heat-sensitive substrates. This feature expands the range of possible applications and opens new avenues for innovation in emerging fields like flexible and wearable electronics.[65–73]

While traditional techniques hold an advantage in achieving ultra-high resolution for complex integrated circuits, printing surpasses them in its ability to produce functional devices with reduced waste, lower costs,

and greater substrate flexibility. These qualities position printing as a transformative force in modern electronics, addressing the growing demand for sustainable, adaptable, and efficient manufacturing technologies. By breaking free from the rigid constraints of subtractive techniques, printing represents a paradigm shift, offering unparalleled potential for innovation and accessibility in the field of electronics manufacturing.[39–41,74]

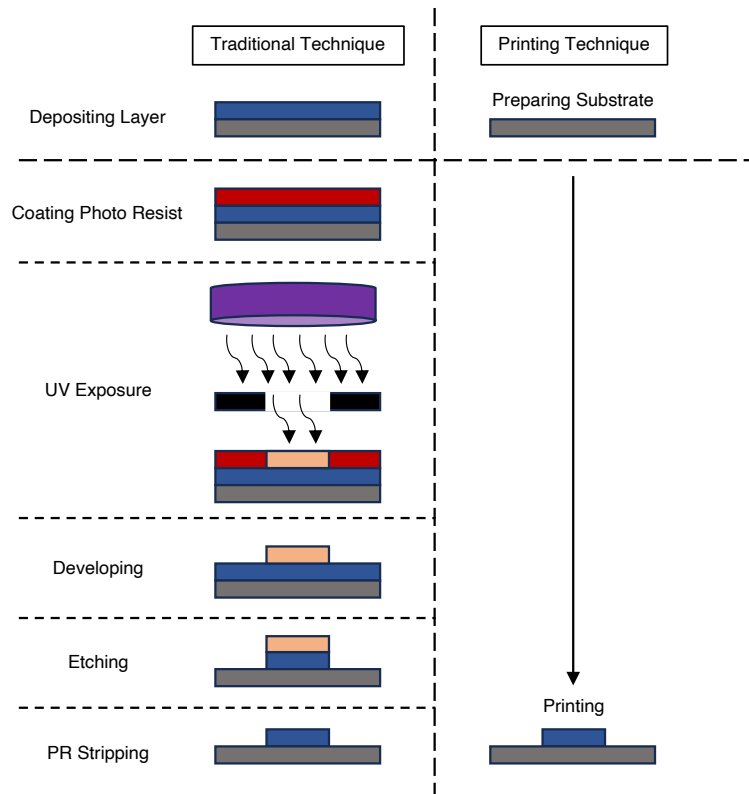


Figure 1-2. Comparison of the steps involved in subtractive manufacturing versus additive manufacturing of electronics.

1.3. Functional Inks

Functional inks are the backbone of printed electronics, enabling the deposition of materials with specific electrical, optical, or mechanical properties. These inks are formulated by dispersing functional materials—such as metallic particles, polymers, or organic compounds—into a solvent. The formulation not only governs the ink’s flow and deposition characteristics but also determines the performance of the final printed features.[75,76]

Functional inks can be broadly classified into three main categories: conductive, dielectric, and semiconductive. Conductive inks are used to create conductive traces, electrodes, and interconnects. Among the most widely used materials for conductive inks are silver flakes and silver nanoparticles, which offer excellent conductivity and are compatible with various substrates.[21,77–79] Alternatives include copper and gold inks, which are valued for their high conductivity.[80,81] Additionally, carbon-based materials like graphene and carbon nanotubes are increasingly explored for their flexibility and potential in stretchable electronics.[82,83]

Dielectric inks are essential for creating insulating layers between conductive elements or for encapsulating electronic components. These inks ensure electrical isolation, which is critical for device performance and reliability. Materials such as Teflon and other polymer-based dielectrics are common choices due to their high resistivity and chemical stability. Dielectric inks also play a significant role in protecting devices from environmental factors, enhancing their durability.[35,84–87]

Semiconductive inks enable the fabrication of active electronic components, such as transistors and sensors. PEDOT:PSS is a widely used semiconductive ink for organic electrochemical transistors (OECTs) due to its high conductivity and stability in aqueous environments.[88–91] For organic thin-film transistors (OTFTs), materials like TIPS-pentacene are preferred because of their relatively high charge mobility.[36,92–94] Unlike conductive and dielectric inks, semiconductive inks often require precise processing conditions to achieve optimal electrical performance. While this section introduces semiconductive inks, a more detailed discussion will follow in subsequent sections.

The viscosity of functional inks is a critical parameter that influences their printability and the resolution of the printed features. Viscosity defines the ink's resistance to flow and can vary significantly depending on the printing method. For instance, low-viscosity inks are suitable for inkjet printing, where fine droplets are ejected onto the substrate, while high-viscosity inks are better suited for extrusion-based techniques like dispense printing.[95–99] Functional inks can also exhibit Newtonian or non-Newtonian behavior. Newtonian inks maintain a constant viscosity regardless of the applied shear stress, while non-Newtonian inks change their viscosity in response to shear. Shear-thinning inks, a common type of non-Newtonian ink, decrease in viscosity under shear stress, facilitating smooth deposition and precise patterning.[96,100]

The interaction between functional inks and substrates is governed by surface energy, which dictates how well an ink spreads or adheres. One method that describes surface energy is contact angle measurements, a method that quantifies the angle formed between a liquid droplet and the surface it rests on. A hydrophilic surface, characterized by high surface energy, results in a small contact angle, promoting ink spreading. In

contrast, hydrophobic surfaces, with low surface energy, exhibit large contact angles, causing the ink to bead up. The advancing contact angle measures the maximum angle when a droplet spreads on a surface, while the receding contact angle represents the minimum angle when the droplet retracts. These measurements provide insight into the ink-substrate interaction, influencing the quality and uniformity of the printed patterns.[35,95,101–103] Figure 1-3 illustrates these concepts. Figure 1-3 (a) shows a contact angle measurement of a droplet on a plasma-treated glass substrate, highlighting the small angle associated with a hydrophilic surface. Figure 1-3 (b) demonstrates a droplet on a Teflon substrate, which is hydrophobic, leading to a larger contact angle.

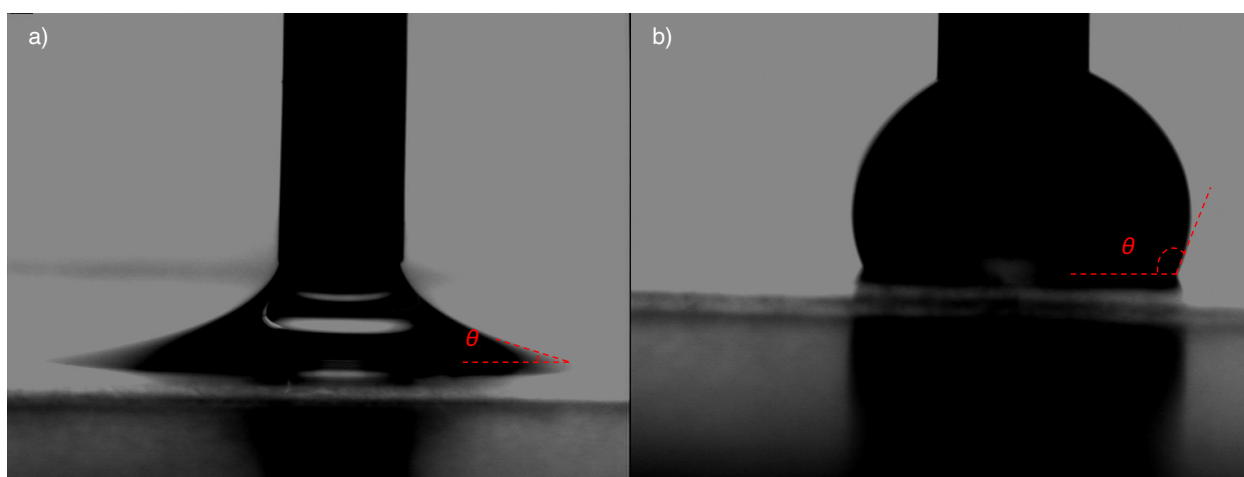


Figure 1-3. Contact angle measurement of water droplets on (a) hydrophilic plasma-treated glass substrate, (b) hydrophobic Teflon substrate.

1.4. Substrates

Substrates play a pivotal role in printed electronics, serving as the foundation onto which functional inks are deposited. The choice of substrate material and its surface properties significantly impact the quality and performance of printed devices. Substrate materials are diverse, ranging from rigid options such as glass and silicon to flexible and stretchable materials like polymers, paper, and textiles. Each material offers unique advantages depending on the application, with glass and silicon providing smooth, stable surfaces for high-resolution printing, while polymers and textiles enable flexibility and conformability.[104–109]

Surface roughness is a critical factor influencing the adhesion and spreading of functional inks. For many substrates, modifying the surface roughness or chemistry is essential to ensure uniform deposition and reliable performance. Techniques such as plasma treatment and the application of self-assembled monolayers (SAMs) are commonly used to enhance surface properties. Plasma treatment involves exposing the substrate to ionized gas, which can increase surface energy and improve wettability, making it more suitable for ink adhesion. SAMs, on the other hand, are molecular layers that form spontaneously on a substrate, creating a controlled interface that can improve ink wettability and reduce roughness. These treatments are particularly beneficial for substrates like silicon or metal oxides, where precise control over surface energy is needed. [41,102,110,111]

3D-printed substrates represent a unique challenge due to their inherent roughness, resulting from the layer-by-layer fabrication process. The ridges and valleys characteristic of 3D-printed surfaces can disrupt the uniformity of printed electronic patterns, affecting device performance.[112] To address this, various methods have been developed to lower surface roughness. Techniques such as post-printing polishing, resin coatings, plasma treatment, and surface smoothing processes like chemical treatments have been employed to create a more compatible surface for printed electronics. While these methods significantly enhance surface smoothness, they are often time-intensive or require additional materials.[43,95,112–114]

Although 3D-printed substrates introduce new possibilities for creating custom geometries and integrated electronics, their roughness remains a primary limitation. Surface modification methods like plasma treatment, chemical treatments, and mechanical smoothing offer viable solutions, but ironing techniques, which provide a high degree of smoothing, will be discussed in detail in a subsequent section.

1.5. Printing and Coating Techniques

The choice of printing method is one of the most important aspects of printing electronics. The printing method restricts the types of inks and substrates that could be used. It has a great effect on the quantitative and qualitative attributes of printed electronics, such as resolution, yield, and throughput. In addition, it controls the physical aspects of the printed features, such as orientation, size, thickness, and even shape.[12,46,115,116] As a result, the choice of printing method has a direct effect on the type and functionality of printed electronics. Generally, printing methods are not easily interchangeable, and it is a challenge to produce the same electronic devices using different printing methods. To choose a printing method for a certain application, knowledge of ink, substrate, and interface between them is required.

Ink viscosity is one of the main parameters to be considered when it comes to inks. Some printing methods are mechanically not compatible with lower viscosity inks, such as dispense and screen printing, while others, such as inkjet and gravure printing, are not compatible with higher viscosity inks. [117,118] Some inks used in printing electronics contain particles or flakes of bulk material in different sizes. Particle size has to be compatible with nozzle size in nozzle-based printing methods (i.e., inkjet, dispense) and feature size in mask-based printing methods (i.e., screen printing). [119]

In the case of substrates, the 3D shape of the substrate and the 2D surface being printed on must be compatible with the printing method. For example, many printing and coating methods, such as blade coating, spin coating and screen printing, depend on the surface being flat.[31,120–122] Nozzle-based methods tend to be more forgiving if the nozzle is far enough, but expensive nozzles tend to break if they hit parts of the substrate while in printing motion. [7,63,123,124]

The interface between ink and substrate is arguably the most important issue to be considered. Of course, the ink and the material of the substrate must be chemically compatible, so the materials would not attack each other.[125] The porosity of a substrate controls the viscosity of the ink required for it to stay on the surface of the substrate and not seep through the pores. As a result, a substrate with high porosity, such as textiles, requires printing methods compatible with high-viscosity inks or special surface treatment to decrease the porosity.[5,126] Surface roughness is another important aspect. It has a direct effect on the contact angle, which tells whether the ink would create straight lines or spread on the surface. Generally, higher-viscosity inks tend to be less affected by surface roughness.[114,127] Other aspects that are directly entangled with what was mentioned are surface energy, surface material hydrophobicity, and flow inducing chemicals in inks.[111,128,129] All these ink and substrate parameters with other printing method related parameters must be considered when choosing the printing method most suitable to manufacture the needed electronic devices.

Printing methods could be grouped in multiple clusters depending on the different printing attributes shown in Table 1-1. Combining multiple printing methods to create different layers in each electronic device enables exploiting the advantages of these methods. In this project, a combination of dispense printing and inkjet printing will be used to manufacture organic transistors.

Table 1-1. Attributes of several printing and coating methods. Ref. [10,31,72,121,124,130,131]

Printing Properties	Dispense Printing	Inkjet Printing	Screen Printing	Gravure Printing	Blade Coating	Spin Coating	Spray Coating
Ink Viscosity [cP]	$10^3 - 10^6$	5 – 50	$10^3 - 10^6$	$10 - 10^3$	$10 - 10^6$	<100	10 – 100
3D Printing	Yes	Yes	No	Limited	No	No	Limited
Mask Requirement	No	No	Yes	Yes	No	No	No
Patterning	Yes	Yes	Yes	Yes	No	No	No
Design Flexibility	High	High	Low	Low	Medium	Medium	Medium
Large Area Scalability	Limited	Limited	Yes	Yes	Yes	No	Yes

1.5.1. Dispense Printing

Dispense printing, also referred to as direct-write printing, is a highly versatile and precise printing method used in the fabrication of printed electronics. As a digital, contactless nozzle-based printing technique, dispense printing allows for the deposition of high-viscosity inks directly onto substrates to create intricate patterns and structures. This method relies on computer-aided design (CAD) tools to generate patterns, eliminating the need for masks and enabling high design flexibility. The high viscosity of the inks used (10^3 – 10^6 cP) makes this technique particularly suited for rough and porous surfaces, providing compatibility with a wide range of substrates, including glass, polymers, and textiles.[39,95,132–134]

The dispense printing process involves applying controlled pressure to an ink-filled cartridge, forcing the ink through a nozzle onto the substrate. The system's key parameters—such as nozzle size, nozzle height,

movement speed, and dispense pressure—must be carefully optimized for each application. Typical nozzles used in dispense printing have inner diameters ranging from 50–250 μm , allowing for precise patterning. Pressure control is achieved through a piston mechanism, which applies either positive or negative pressure to regulate ink flow, ensuring smooth deposition and preventing leaks.[95,96,107–109,124,135] Figure 1-4 illustrates the basic mechanism of dispense printing, highlighting the interaction between the ink cartridge, piston, and nozzle.

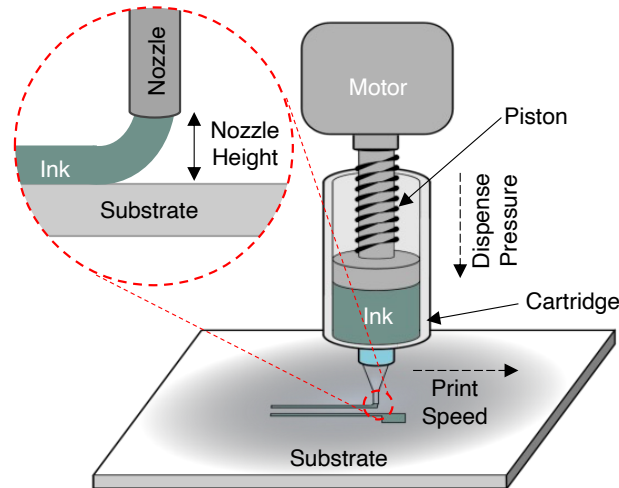


Figure 1-4. Illustration of the dispense printing technique, indicating the studied parameters: nozzle height, dispense pressure, and print speed. Nozzle height is the distance of the nozzle from the substrate during printing. When the piston moves down, it creates dispense pressure in the cartridge, pushing the ink out of the nozzle. Print speed is the nozzle movement speed during printing.[95]

One of the primary applications of dispense printing is in the fabrication of passive electronic components, including resistors, capacitors, and antennas. These components are often printed using conductive inks, such as those based on silver, gallium, or carbon-based materials.[96,132,136] The flexibility of dispense printing also extends to unconventional substrates, such as textiles and carbon fiber composites, where it has been used to create resistance-based sensors and heaters.[108,109,124,135]

One of the key advantages of dispense printing is its ability to use a wide range of inks, including conductive, semiconducting, and insulating materials. This allows for the creation of complex electronic structures with different layers and functionalities. Moreover, the inks used in dispense printing are often cheaper than those used in other printing techniques, such as inkjet printing, which can be a significant

advantage in large-scale production. However, dispense printing faces several challenges when producing active electronic components, mainly transistors, which require precise control over the material properties and highly accurate patterning of conductive and insulating materials. One of the primary challenges is achieving high-resolution patterning of the conductive and insulating materials required to make transistors. Inkjet printing has been the preferred method for producing high-resolution electronic components, but scalability and cost are often limited.[7,10,47,95,136]

To address these challenges, researchers are exploring ways to improve the resolution and accuracy of dispense printing. One approach is to modify the ink properties to achieve higher-resolution printing. Researchers have developed conductive inks with smaller particle sizes and improved rheological properties, enabling them to be printed with greater accuracy and precision. By enhancing the properties of the ink, it is possible to achieve higher-resolution printing without the need for additional processing steps.[66,76]

Dispense printing offers several advantages over other techniques, such as its ability to handle high-viscosity inks and its compatibility with a wide range of substrate materials. However, achieving high-resolution features and complex multilayer structures remains a challenge. With advancements in printer technology, such as multi-axis systems and real-time feedback control, and continued innovation in ink formulation, dispense printing is poised to play a significant role in the development of next-generation electronic devices.[79,132,137]

1.5.2. Inkjet Printing

Inkjet printing is similar to extrusion printing in some respects. It is also a contactless nozzle-based printing method. It is also a digital printing method as it only jets on demand. It does not require a mask, and patterns are a set of digital coordinates .[11] Inkjet printers are also relatively small and could be tabletop machines, which is ideal for prototyping in a research lab. Similar to extrusion printing, inkjet printing can be scaled for roll-to-roll printing by increasing the printing area and connecting multiple nozzles in parallel to print at the same time. However, inkjet printer nozzle sizes are typically between 20 – 80 μm , and this printing method requires low viscosity inks (5 – 50 cP).[7] As a result, this printing method is capable of printing with higher precision and resolution compared to extrusion printing. On the other hand, due to the low viscosity, the quality of inkjet printing is significantly more affected by surface roughness, surface energy, ink droplet contact angle, and ink drying. [63] Nevertheless, inkjet nozzles do not require to be as close to the substrate as extrusion printing nozzles because droplets are forcefully jetted towards the substrate.[34]

This is useful for printing on 3D curved objects without the risk of the nozzle hitting part of the substrate and breaking. With a more complex system, inkjet nozzles have been attached to 3D or 5D movement arms in some commercially available printers, which enables printing on all visible surfaces of a 3D object in-situ. This is also possible with extrusion printing, but due to the required nozzle proximity to the surface, an advanced 3D surface mapping system is required.

Inkjet printing works by applying air pressure in an ink reservoir to push the ink through a tube to the nozzle. Inside the nozzle, there is a piezoelectric actuator that generates pressure waves which force a droplet to jet through the nozzle. This actuator is controlled by an electric signal generated by a dedicated electric wave generator. By precisely controlling the voltage applied to the actuator, the size of the droplets can be adjusted. By moving the stage or the nozzle while jetting, features are printed on the surface.[44] In the case of the printer used for this project, the stage is being moved. A diagram of inkjet printing is shown in Figure 1-5. The main parameters to control an inkjet printer are nozzle size, which controls droplet size, air pressure regulation in the ink reservoir, and electrical signal generation (i.e., waveform shape, period, frequency, amplitude, rise time, fall time, print speed and drop spacing). [63]

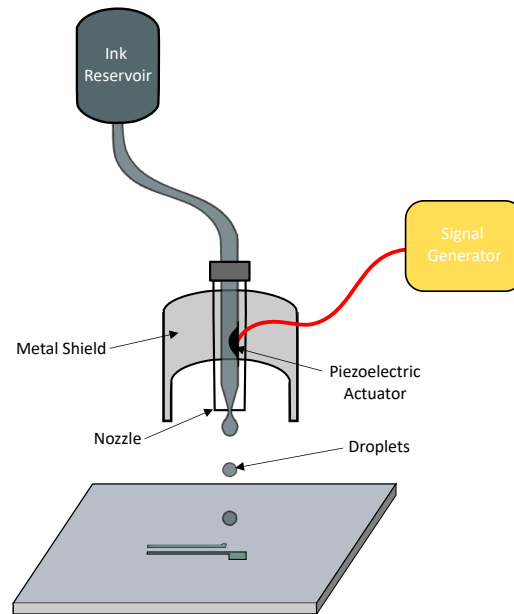


Figure 1-5. Inkjet printing. Illustration of the inkjet printing technique, indicating the nozzle, ink reservoir, signal generator, and piezoelectric actuator. The piezoelectric actuator generates pressure waves that force a droplet to jet through the nozzle.

1.6. 3D Printing

3D printing is an additive manufacturing technique that fabricates complex 3D objects from digital CAD files. 3D printers work by printing material in layers on top of each other to form 3D objects. The first 3D printing process was a stereolithography (SLA) printer developed by Charles Hull in 1986. As the patents for the original 3D printing methods are expiring, 3D printing is becoming more accessible and feasible to consumers. Commercial and low-cost 3D printers are being developed, thus making the technology available for consumers in homes, schools, libraries, and research labs. 3D printing has become increasingly popular in the last decades. User-friendly software and affordable machines have made additive manufacturing an important part of rapid prototyping in industry, research, and households. At the same time, researchers have been pushing the boundaries of what can be printed, finding ways to print metals, composites, ceramics, and even organic matter. While most of these prints serve only mechanical purposes, some attempts have been made to also incorporate electrical functionality directly into the 3D printed components. Traditionally, mechanical and electrical structures are manufactured separately as mechanical components and printed circuit boards (PCBs), which are then assembled by hand or using robotics. Albeit a proven concept, there are some drawbacks. PCBs often require more time to be manufactured externally than the in-house printed mechanical components, slowing down the rapid prototyping process. For production runs, the manual assembly step can be costly and time-consuming. Additionally, conventional PCBs are limited in their flexibility, making it more difficult to implement them into soft robotics. To overcome these limitations, researchers have explored many ways to integrate the printing of the electronics directly into the 3D printers, allowing for a bigger variety of substrate materials and 3D shapes.[138–141]

Over time, several methods of 3D printing have evolved to meet the great industry demand for manufacturing complex geometries at fine resolutions using different materials. The most common method of 3D printing is known as fused deposition modelling (FDM), which uses polymer filaments that are melted and deposited in layers to create 3D objects. Other methods include selective laser sintering (SLS), selective laser melting (SLM), which additively manufactures using powders, and inkjet printing, contour crafting, and stereolithography which manufacture using liquids. [44]

1.6.1. Fused Deposition Modeling (FDM)

Fused deposition modelling, also known as fused filament fabrication (FFF), is the most commercially common 3D printing method. This method is a form of extrusion printing where a filament of thermoplastic polymer is pushed through a nozzle. The filament is heated in a heating chamber to reach a semi-liquid

state. As the continuous filament is pushed through the nozzle, it is extruded on top of the substrate or the previously printed layers of filament. The melted filament fuses with the previously printed layers of the same material due to its thermo-plasticity. After the filament is extruded, it solidifies at room temperature. By moving either the bed or the nozzle in the x-y-z axis while extruding the filament, a 3D object is fabricated.[142] A diagram of FDM is shown in Figure 1-6. FDM has many parameters that must be optimized to achieve high quality prints with good mechanical properties. Some of the most important parameters are heating temperature, movement speed, movement distance (which controls layer thickness, width, and orientation), extruding speed, nozzle size, nozzle material, and filament material.[143] Due to the great advancement in the FDM industry, a great amount of research and optimization of these parameters have been done for the most common printing filaments: polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), thermoplastic polyurethane (TPU).[113,144] These optimized settings are distributed to users via slicing software that is used to convert 3D CAD models to the G-code the printer uses to print. However, this research currently focuses on the low temperature consumer filaments rather than the more expensive, high temperature materials with better mechanical properties, such as polysulfone (PSU), polyether imide (PEI), polyetheretherketone (PEEK). More on the printing filament material is discussed below. FDM is one of the most widely available table-top printing methods due to the low cost of printers and filaments, simplicity of the process, and ease of iteration and prototyping. However, FDM printed objects have relatively weak mechanical properties, poor layer-to-layer registration, and poor surface quality.[142]

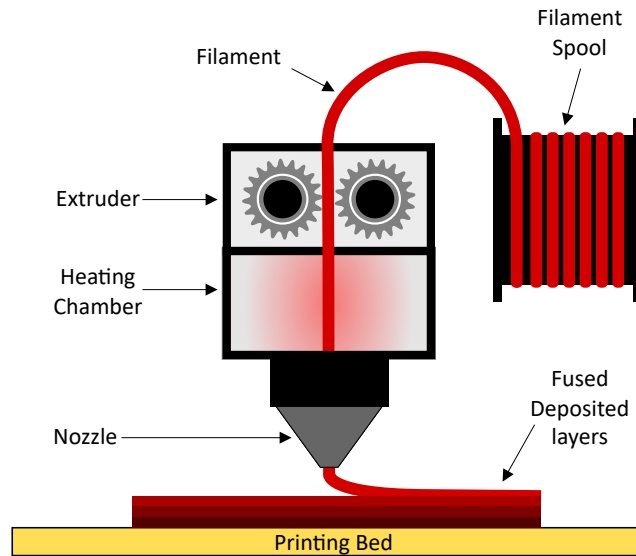


Figure 1-6. Illustration of fused deposition modeling (FDM)

1.6.2. 3D Printing Materials

3D printing filaments and materials have been developing with the advancement in FDM technology. New filaments have been emerging, including both pure polymers and composites. In this project, the concentration will be on pure polymers since composites add more complexity to both FDM and printing electronics. For a material to be suitable for FDM, it has to be a thermoplastic material where it melts at a certain high temperature and cools down again at room temperature without losing integrity in the process. This is important for printing and filament manufacturing. The material melting temperature needs to be a value that the nozzle and heating chamber of the FDM printing head could reach. This is currently limited by technology to about 460 °C. The quality of FDM printing is controlled by the printing temperature (i.e., nozzle temperature) of each material. This temperature at which the filament is melted, as well as the cooling rate of the material, can have a significant impact on the final properties of the printed part. Too low printing temperatures cause the material layers to not fully fuse together, resulting in weak interlayer adhesion and porous or brittle parts. On the other hand, too high printing temperatures cause the material to be too soft and degrade, leading to poor dimensional accuracy and surface finish. As a result, the printing temperature is directly related to the glass transition temperature (T_g) of the filament, which determines at

which temperature the thermoplastic material transitions from a hard, glassy state to a softer, rubbery state.[145] Commercially available filament materials and their printing temperatures include:

- Polylactic acid (PLA): The most common printing material. Widely considered the easiest polymer to print. It is bio-sourced and biodegradable. It is rigid and strong but very brittle. It has a low printing temperature (190 – 220 °C).[146]
- Acrylonitrile butadiene styrene (ABS): Has a higher temperature resistance and a higher toughness than PLA. Printing temperature is (240 – 270 °C).[147]
- Nylon: Possesses desirable mechanical properties such as high impact resistance. Has good chemical resistance. Printing nylon is challenging as layer adhesion poses several issues. Printing temperature is (230 – 260 °C).[148]
- Thermoplastic polyurethane (TPU): A flexible material with high impact resistance. It is a transparent material with resistance to oil products. Printing temperature is (220 – 250 °C).[149]
- Polyethylene terephthalate glycol (PETG): Provides significant chemical resistance. Safe for food and medical packaging as it is possible to sterilize PETG objects. Printing temperature is (230 – 250 °C).[150]
- Polyvinyl alcohol (PVA): A water soluble filament that is commonly used for supports in FDM printing. Printing temperature is (215 – 225 °C).[151]
- Polysulfone (PSU): Provides high temperature, chemical and water resistance. Has good mechanical properties. Often used in food and medical applications where repeated sterilization is required. Printing temperature is (350 – 380 °C).[152]
- Polyether imide (PEI): Has good mechanical properties. Provides high temperature and chemical resistance. Printing temperature is (360 – 400 °C).[153]
- Polyetheretherketone (PEEK): Provides high chemical and heat resistance. Has good mechanical properties. Extensively used in demanding applications such as the medical, aerospace, and automotive industries. Printing temperature is (365 – 440 °C).[154]

1.6.3. Surface Ironing

One of the biggest drawbacks of FDM printing is the surface roughness of the printed objects. This is due to the line-by-line printing process with a spacing of usually 0.4 - 0.6 mm. This is most problematic for

printing electronics on the surface of FDM 3D printed objects. The rough surface of the object (the substrate) will cause inconsistent line thicknesses and possibly breaks or shorts in the printed circuitry.

To overcome this issue, various approaches have been investigated in previous studies. One approach is surface polishing, which involves post-processing the printed object to remove the rough surface. This process increases the complexity of the manufacturing process and requires additional equipment. Another approach is epoxy layer printing, which involves printing a thin layer of epoxy on the surface of the FDM printed object. However, this approach also requires additional tool heads and increases the complexity of the process.[155] Milling channels is another approach explored to achieve a smoother surface. This approach involves milling channels on the surface of the printed object to reduce the surface roughness. However, this approach is time-consuming and increases the complexity of the manufacturing process.

To address the surface roughness issue, researchers have investigated the effect of the overall print flow on roughness and established an optimal flow. Ironing is one such process that can be employed to achieve a flatter and smoother surface. The ironing process involves passing the hot nozzle over the top layer of the printed object with a finer line spacing while extruding small amounts of material. Previous research has demonstrated the effectiveness of ironing in reducing surface roughness; however, no significant trends were identified. A diagram of FDM ironing is shown in Figure 1-7. The main parameters of FDM ironing are ironing flow, ironing speed, ironing line spacing, ironing temperature, and, as shown in the results section below, sample size.[113,114]

Sardinha et al. conducted a study that evaluated the effect of ironing on the superficial, mechanical, and dimensional properties of ABS parts produced by FDM. The results showed that ironing could reduce the average surface roughness (R_a) of ABS parts by up to 60% and distortion levels by 33%. Although ironing may influence the thermal behaviour of deposited layers, it was ineffective in enhancing parts' interlaminar strength (ILS) due to generating geometric irregularities. The study suggests ironing as an alternative post-processing technique for FDM parts.[113]

Griffiths et al. conducted a study investigating the impact of surface quality on the conductivity of an inkjet-printed silver nano-particle ink on 3D printed non-planar surfaces. The study found that the as-printed surface finish resulted in continuity breaks and reduced overall conductivity consistency. In addition, the study investigated several finishing methods to improve the surface finish, including non-planar nozzle ironing. The study identifies polishing as the most effective solution, ensuring high and consistent conductivity across the surface for subsequently printed nanoparticle tracks. However, as previously

mentioned, this process increases the complexity of the manufacturing process and requires additional equipment. Furthermore, this study did not directly evaluate the effect of ironing on surface roughness. It highlights the importance of surface quality in achieving consistent electrical conductivity and the potential benefits of ironing. [156]

Surface roughness and surface treatment are essential for integrating printed electronics with FDM 3D-printed objects. However, the number of reports investigating this area is too low. Furthermore, no reports investigate the surface roughness of high-temperature materials that provide superior mechanical properties. This leads to one of the main goals of this study, which is finding and tuning the relevant parameters to optimize the surface roughness to the point where electronics can be printed reliably and precisely.

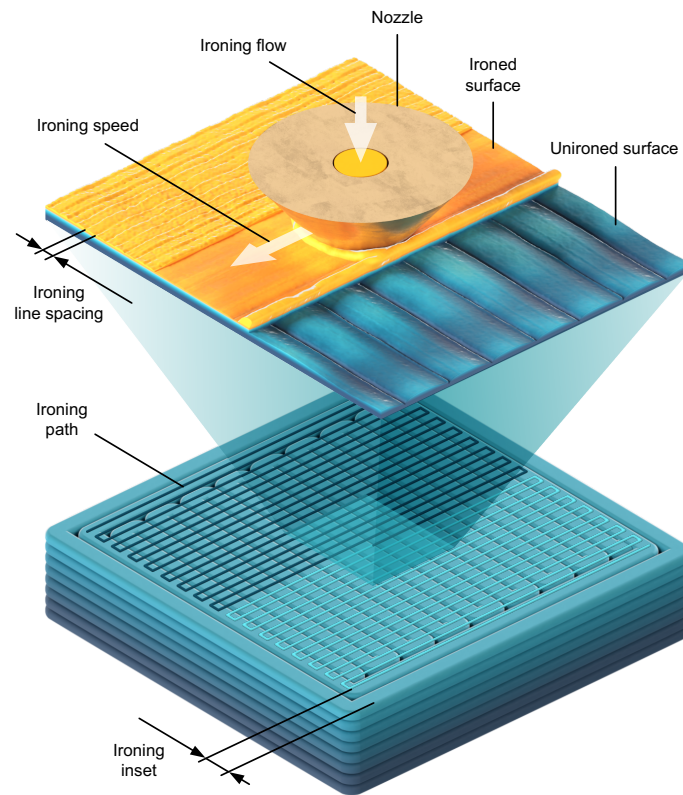


Figure 1-7. Cross-section of the general ironing process to achieve a smooth FDM printed surface to reliably print electronics on top. In this process, the hot nozzle goes over the printed top surface in a back-and-forth path with fine line spacing while adding and remelting material.

1.7. Organic Electrochemical Transistors (OECTs)

OECTs are a class of transistors that operate by modulating electronic conductivity in organic materials through doping with mobile ions from an electrolyte gate.[157] Unlike conventional field-effect transistors, OECTs rely on an electrolyte to enable efficient gating, which makes them highly sensitive to ionic environments.[25,75,90] This unique property has made OECTs particularly valuable in applications such as biosensing, neuromorphic computing, and environmental monitoring, where sensitivity to various ions and biomolecules is crucial.[89,158,159] An illustration of a typical OECT is shown in Figure 1-8. A key performance metric for OECTs is transconductance (g_m), which indicates the device's amplification efficiency. High g_m is essential for applications that require precise signal transduction, as it directly impacts the device's sensitivity. However, achieving high g_m in a scalable, cost-effective way remains a significant challenge in OECT fabrication, particularly in developing high-performance electrodes with suitable geometry, material properties, and manufacturability.[160]

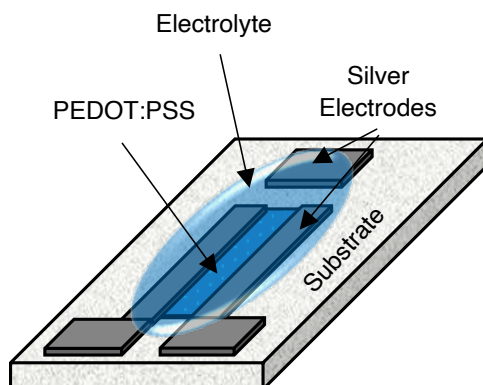


Figure 1-8. Structure of organic electrochemical transistors (OECTs). Silver electrodes create the source, drain, and gate electrodes. The organic semiconductor is printed in the channel. Finally, electrolyte liquid connects the gate and the channel.

1.7.1. Organic Semiconductors for OECTs

Organic semiconductors are essential in OECTs due to their ability to conduct both electronic charges and ions. These materials enable the operation of OECTs, which rely on volumetric ion-electron coupling to modulate conductivity. Among the various organic semiconductors investigated, PEDOT:PSS (poly(3,4-

ethylenedioxythiophene):polystyrene sulfonate) has emerged as a standout material due to its unique properties, such as high conductivity, stability, and processability. Organic semiconductors used in OECTs must meet several critical criteria, including conductivity, stability in aqueous environments, and scalability for fabrication methods. PEDOT:PSS fulfills these requirements through its intrinsic properties, where PEDOT acts as the conducting backbone, and PSS provides ionic transport pathways, enabling efficient ion-electron coupling.[88–91]

PEDOT:PSS has become the benchmark material for OECTs due to its unmatched combination of properties. Its high conductivity can be further enhanced through post-treatments with solvents like DMSO, making it suitable for applications requiring high electrical performance. Its mixed ionic-electronic conductivity enables simultaneous ionic and electronic transport, which is critical for OECT functionality. Additionally, PEDOT:PSS's water-dispersible nature makes it compatible with low-cost and scalable fabrication methods, such as spin-coating and inkjet printing. It also demonstrates excellent biocompatibility, allowing its integration into bioelectronics applications such as neural interfaces and biosensors.[82,158,161,162]

While other organic semiconductors have been explored for OECTs, none offer the comprehensive advantages of PEDOT:PSS. Materials like polyaniline (PANI) and polypyrrole (PPy) exhibit good electronic conductivity but suffer from poor ionic transport and environmental stability. Donor-acceptor polymers offer tunable properties but face challenges in ionic conductivity and fabrication. Hybrid composites, combining organic and inorganic materials, improve specific properties but increase complexity and cost, limiting their scalability. These comparisons highlight why PEDOT:PSS remains the dominant choice for OECT applications.[163–167]

These compelling advantages of PEDOT:PSS, its high conductivity, mixed ionic-electronic transport, scalability, and biocompatibility, form the basis for its selection as the material for the OECTs in this research.

1.7.2. OECT Electrodes

In OECTs, three primary factors characterize electrode fabrication: geometry (lateral resolution, thickness, and aspect ratio), material properties (primarily conductivity), and manufacturability (cost, scalability). Each of these factors has implications for OECT performance. Geometry impacts the electrode's lateral resolution, thickness, and aspect ratio. In most transistors, high-resolution electrodes are essential. [168–

171] However, in OECTs, precise resolution is less critical as the electrolyte-gated mechanism leverages the large volumetric capacitance of the semiconductor film to deliver very high currents at low voltages. Instead, thickness and aspect ratio are more influential, as they help in achieving low sheet resistance, which is critical when trying to pass large currents at low voltage. Material properties, especially conductivity, are crucial for minimizing electrode resistance. Yet traditional methods, such as material evaporation, often yield high-resistance electrodes with long traces and thin layers. Finally, manufacturability, including scalability and cost-effectiveness, determines the practicality of the fabrication technique for widespread OECT applications. Dispense printing, with its ability to deposit thick layers of high-viscosity silver flake ink, offers a trade-off by sacrificing lateral resolution to achieve low-resistance electrodes that enhance current.[24,87,172]

Despite this opportunity, current OECT fabrication methods often rely on traditional cleanroom methods such as evaporation that produce electrodes with relatively high resistance due to the low film thickness. Previous studies have predominantly employed methods like e-beam evaporation, lift-off processes, and chemical etching, as well as materials such as gold (Au) and silver (Ag) for electrode fabrication. For instance, e-beam evaporators with Au were used in several studies,[88,158–160,173] while inkjet printing with Ag was explored in others.[82] Despite employing materials with bulk-like properties with low intrinsic resistivity, it produced electrodes with high trace lengths and thicknesses below 200 nm. This combination of long traces and low thicknesses led to high-resistance source and drain electrodes, ultimately constraining device performance. [88,90,158–160,173,174] Even the highest g_m achieved among these studies was only 1.2 mS, as reported in one instance, underscoring the persistent challenge of enhancing OECT performance through conventional fabrication methods.[82] Other approaches include 3D printing with carbon-filled polylactide (c-PLA) and lasering to create laser-induced graphene (LIG).[175,176] One study stands out by using dispense printing for carbon-based electrodes, employing silver as interconnects to connect the carbon source and drain. However, this design produced high-resistance electrodes and a limited g_m of 7 μ S.[162] While a range of fabrication methods has been investigated for OECT electrodes, extrusion printing methods, such as dispense printing, remain largely underutilized, primarily due to challenges in achieving precise patterning.[82,88,158–160,162,176]

Gate electrodes in these studies have either been fabricated with similar methods as thin films or have been externally inserted into the electrolyte. Gate electrode materials have varied, including Ag/AgCl, multi-layer graphene (MLG), and Au, chosen for compatibility with the electrolyte gating mechanism.[9,82,90,157,158,160] PEDOT:PSS is used in this study, and all literature comparisons are with

studies using PEDOT:PSS. Channel fabrication in prior studies has typically relied on spin coating [88,90,158–160,173,174] or inkjet printing [82,172] for the deposition of PEDOT:PSS.

To address the limitations observed in existing OECT fabrication methods, this study introduces a hybrid approach that combines dispense printing for electrodes with inkjet printing for the channel. Disperse printing was chosen specifically to overcome the high-resistance limitations of electrodes seen in previous studies, as it allows for the deposition of higher-viscosity silver flake ink in thicker layers.[95] This results in low-resistance electrodes that enhance current flow and enable higher transconductance values than previously reported. This combination of methods achieves an average g_m of 98.2 mS, setting a strong benchmark for additive OECT fabrication.

1.8. 3D Printed Electronics

The integration of 3D printing and electronics has gained increasing attention as additive manufacturing technologies continue to evolve.[38,61,155,177] Unlike conventional electronics, which rely on planar fabrication techniques such as photolithography, printed circuit boards, and silicon-based microfabrication, 3D-printed electronics enable the creation of electronic structures with arbitrary shapes and embedded functionalities.[178–180] This advancement provides new possibilities in applications such as wearable electronics, soft robotics, biomedical devices, and structural electronics, where traditional manufacturing methods face limitations.[5,181–184]

There are three primary approaches for integrating electronics with 3D-printed structures: printing electronics onto the 3D structure, 3D printing using functional materials, and pre-manufactured component integration.[38,39,155] The first approach involves printing conductive, semiconducting, and dielectric inks directly onto 3D-printed surfaces. Common techniques include extrusion-based dispensing, screen printing, and aerosol jet printing, where functional inks such as silver, copper, or conductive polymers are deposited onto printed objects.[12,58,96,119,185] While this method allows for flexible and conformal electronics, challenges such as substrate roughness and resolution limitations must be addressed. The second approach integrates conductive traces, sensors, or functional polymers within a structure as it is being printed. Multi-material 3D printing techniques, such as hybrid additive manufacturing, combine polymer printing with conductive wires or using conductive polymers to create fully integrated electronic circuits. This method has been used to fabricate 3D-printed capacitors, inductors, antennas, and flexible electronic devices, but ensuring robust electrical connections between layers remains a challenge.[186–189] The third approach

involves inserting conventional electronic components, such as microchips, resistors, and sensors, into designated cavities in a 3D-printed object. Conductive inks or printed interconnects are then used to establish electrical connections. This method retains the benefits of 3D printing while leveraging the reliability of conventional electronic components. However, challenges such as mechanical alignment, adhesion, and long-term durability must be considered.[5,39,40,58,111]

Although 3D printing has shown immense promise across various fields, its integration with active electronic devices remains a challenging frontier. Despite advancements in combining 3D printing with electronic functionality, no studies to date have successfully fabricated high-performance OECTs within three-dimensional printed objects. Most efforts have either focused on embedding basic conductive elements or relied on flat, flexible substrates for OECT fabrication.[67,116,190–192] These approaches fail to exploit the full potential of 3D printing and its capacity to integrate electronic and mechanical functionalities within complex geometries.

Existing literature on 3D-printed electronics reveals several limitations in current methods. For instance, studies utilizing conductive filaments in FDM have demonstrated rudimentary electrical functionality, but the low resolution and high resistivity of these filaments significantly restrict their use in high-performance devices. These techniques lack the precision and material compatibility required for OECT fabrication, particularly for applications demanding low-resistance electrodes and high transconductance. [161,172]

As previously mentioned, research on OECTs has primarily been conducted on planar substrates, such as glass or flexible polymers, employing traditional fabrication methods like photolithography and spin coating. While these approaches enable high-performance devices, they are inherently limited by multi-step processes, high costs, and incompatibility with three-dimensional geometries. Attempts to adapt additive manufacturing for OECTs have been largely unsuccessful, with studies reporting poor device performance and limited functionality when applied to non-planar or rough surfaces. These limitations highlight the need for new methodologies that leverage the unique capabilities of 3D printing while addressing the specific requirements of OECT fabrication.[88,90,158–160,173,174]

To overcome these challenges, our approach integrates three distinct manufacturing techniques: FDM, dispense printing, and inkjet printing. FDM is used to create the three-dimensional substrate, employing surface ironing techniques to reduce roughness and enhance compatibility with subsequent printing processes. Dispense printing is employed to deposit high-viscosity silver flake inks, forming low-resistance electrodes critical for OECT performance. Finally, inkjet printing is used to fabricate thin, uniform films of the organic semiconductor PEDOT:PSS, ensuring high-quality channels with consistent electrical

properties. By combining these complementary methods, we achieve seamless integration of OECTs into 3D-printed structures, enabling the fabrication of transistors and sensors directly within custom geometries.

This novel methodology represents a significant advancement in the field of 3D-printed electronics. Unlike previous works that rely on flat or flexible substrates, our approach demonstrates the feasibility of embedding high-performance OECTs within three-dimensional objects. This integration not only addresses the limitations of traditional fabrication methods but also opens new avenues for developing advanced devices with applications in biosensing, environmental monitoring, and neuromorphic computing. By leveraging the strengths of FDM, dispense printing and inkjet printing, this work sets a new benchmark for integrating electronics into 3D-printed architectures.

1.9. Dissertation Organisation

This dissertation is structured as a series of journal papers, with each chapter addressing a critical step toward the integration of OECTs into 3D printed objects. Each chapter builds upon the findings of the previous one, collectively leading to the successful development of embedded OECTs for bioelectronic and environmental sensing applications.

The second chapter investigates the FDM process and surface ironing technique to create substrates suitable for printing electronics. A comprehensive study was conducted on both low-temperature and high-temperature materials to optimize the ironing process and achieve low surface roughness. This chapter demonstrates that ironing significantly reduces surface irregularities, enabling reliable integration with printed electronics. The insights gained in this chapter were published as a journal article: *Benno Neuhaus, Mohamad Kannan Idris, Paria Naderi, Yoland El-Hajj, Gerd Grau, "Low-Roughness 3D Printed Surfaces by Ironing for the Integration with Printed Electronics," Advanced Engineering Materials, 2024.*

The third chapter delves into the dispense printing process to fabricate electrodes on substrates with varying surface energies, ranging from hydrophilic to hydrophobic. By understanding the interplay between ink properties and substrate characteristics, this chapter identifies optimal printing parameters for creating low-resistance, durable electrodes. These findings are crucial for fabricating OECT electrodes and were published as a journal article: *Mohamad Kannan Idris, Gerd Grau, "Dispense Printing of Silver Flake Inks on Hydrophilic and Hydrophobic Surfaces," Advanced Engineering Materials, 2024.*

In the fourth chapter, the focus shifts to fabricating high-performance OECTs on planar glass substrates as a simplified step toward embedding these devices in 3D-printed structures. The chapter highlights a hybrid approach combining dispense printing for low-resistance electrodes and inkjet printing for high-quality PEDOT:PSS semiconductor channels. The transistors achieved one of the highest transconductance reported in the literature, setting a benchmark for OECT performance. The findings of this chapter are under review for publication: *Mohamad Kannan Idris, Saumik Dey Shovan, Gerd Grau, "Embedding Organic Electrochemical Transistors into 3D Printed Objects."*

The final chapter integrates all the insights from previous chapters to fabricate OECTs embedded within 3D-printed objects. By combining FDM printing with in-situ ironing, dispense printing for electrodes, and inkjet printing for semiconductor channels, this work achieves a novel methodology for embedding functional electronics into 3D geometries. The embedded transistors demonstrate exceptional electrical performance and stability, enabling applications in sensing electrolyte concentrations. These results are presented in a submitted paper: *Mohamad Kannan Idris, Saumik Dey Shovan, Gerd Grau, "Embedding Organic Electrochemical Transistors into 3D Printed Objects."*

In summary, each chapter contributes a crucial step towards the overarching goal of this dissertation: embedding OECTs into 3D-printed objects. Chapter 2 establishes a foundation by optimizing substrate preparation through ironing. Chapter 3 provides a detailed understanding of electrode fabrication via dispense printing. Chapter 4 achieves benchmark OECT performance through a hybrid fabrication process. Finally, Chapter 5 integrates these methods to realize OECT biosensors embedded in 3D-printed structures, demonstrating their potential for customizable, application-specific electronic devices.

Chapter 2. FDM Printing and Ironing

A version of this chapter was published as a journal article: Benno Neuhaus, Mohamad Kannan Idris, Paria Naderi, Yoland El-Hajj, Gerd Grau, "Low-Roughness 3D Printed Surfaces by Ironing for the Integration with Printed Electronics," *Advanced Engineering Materials*, vol. 26, no. 3, Art. no. 2301711, 2024, doi: 10.1002/adem.202301711.

2.1. Introduction

Integrating additive manufacturing techniques with functional applications continues to evolve, offering new possibilities for enhancing the mechanical and electrical properties of 3D-printed devices. Among these techniques, fused deposition modeling (FDM) stands out for its accessibility, versatility, and ability to work with various materials. However, one of the persistent challenges in FDM is the inherent surface roughness of printed parts, which limits their usability in high-precision applications, including integration with printed electronics.

Surface roughness in FDM arises from the layer-by-layer deposition process, leaving printed surfaces with peaks, valleys, and inconsistent geometries. These imperfections are especially problematic when subsequent layers or functional elements, such as conductive traces, require a smooth and stable substrate. Traditional post-processing methods, such as sanding or chemical treatments, can improve surface quality but add complexity, time, and cost to the fabrication process. To address these issues, innovative techniques such as ironing—where a heated nozzle remelts the top layer to achieve a smoother finish—have gained traction.

This chapter investigates the use of ironing toolpaths as an integrated solution for reducing surface roughness in FDM-printed parts. By systematically optimizing ironing parameters such as flow, speed, line spacing, and temperature, this work provides a comprehensive understanding of their impact on surface quality. A range of materials is studied, including both low-temperature filaments, like PLA and ABS, and high-temperature filaments, such as PSU and PEEK, which are suited for advanced applications. The results demonstrate significant improvements in surface smoothness, with reductions in roughness exceeding 90% in some cases. These findings highlight the potential of ironing to streamline the integration of FDM prints with advanced functionalities, reducing reliance on external post-processing methods.

2.2. 3D printing of the test samples

All samples to study the surface roughness were printed on a Hydra 16A printer (Hyrel, United States) with a layer height of 0.2 mm. For the low-temperature filaments, a 0.5 mm nozzle was used in combination with an MK1-250 print head, whereas a 0.4 mm nozzle was used for the high-temperature filaments in combination with an HT3-450 print head. For the printer bed, a high-temperature glass-ceramic was used, which was additionally coated with Nano Polymer Adhesive (Vision Miner, United States). The filament materials used are listed in Table 2-1. All high-temperature materials were stored inside a vacuum desiccator and were dried in a vacuum oven for 4 hours at 120 °C before printing as they quickly absorb noticeable amounts of water under room atmosphere, which causes the material to foam up while it is being printed significantly affecting the surface quality. While printing the high-temperature filaments, the nozzle fan was turned off to prevent warping. For all ironing experiments, unless stated otherwise, a standard 0.1 mm line spacing was chosen. While there are different options for the orientation and shape of the ironing pattern, we found that going in straight lines perpendicular to the layer below yields the best and most homogenous results.

Table 2-1. List of 3D printing materials used in this study.

Material	Manufacturer	Recommended printing temperature	Color
PLA	AMZ3D (Canada)	180°C – 210°C	White
PETG	Hatchbox (Canada)	230°C – 260°C	White
ABS	Inland (United States)	240°C – 260°C	Black
ThermaX™ PSU	3DXTECH (United States)	360°C – 375°C	Natural
ThermaX™ PEI made Using ULTEM 9085	3DXTECH (United States)	365°C – 385°C	Natural
PEEK Pro	eSun (China)	380°C – 410°C	Natural

2.3. Sample design for optimization

The initial step in enhancing surface roughness is to adjust the general flow, ensuring a satisfactory filling without any gaps or over-extrusion. General flow refers to the printing of the layers that make up the 3D object as opposed to the ironing flow that is applied after the last layer has been printed. To study the general flow, a sample design consisting of sixteen cuboids, each printed with a different flow value, is used. For each material, the 100% flow rate is calibrated by printing a cube with only one perimeter, measuring the wall thickness, and adjusting the extrusion parameter accordingly until the wall thickness matches the line width. The 3D model of the samples is depicted in Figure 2-1 (a). The cuboids are printed using parallel lines along the full length of 50 mm and are characterized in the center to eliminate any effects from the turning points at the edges of the cuboids. Since each layer has the same printing path, the surface profile should accumulate with each added layer, making it easier to detect slight differences in roughness. All cuboids are printed simultaneously to minimize variations from temporal humidity and temperature changes and are held together by a frame that serves as a guide to align the samples on the optical profilometer.

The second step in enhancing surface roughness is taking a similar optimizing approach for the ironing parameters. The results of ironing somewhat depend on the quality and filling ratio of the layer it is applied onto. Therefore, the samples are designed in a way such that all ironing paths are applied to the same uniform surface with a 5 mm distance to any borders of the print to allow for accurate comparisons. The uniform surface is created by alternating the layer direction to prevent the local accumulation of material that is intentionally brought about in the previous experiment. Each of the four ironing parameters (ironing flow, speed, line spacing, and temperature) is swept with sixteen values, as shown in Figure 2-1 (b). For every value of the ironing parameter, three different rectangle sizes were printed and characterized to test if the length of the ironing path had any effect.

To compare ironing with traditional smoothing methods, some samples were submerged in acetone for 10 minutes or carefully sanded on a straight surface using 1200 and 1800-grit sandpaper before being measured with the profilometer.

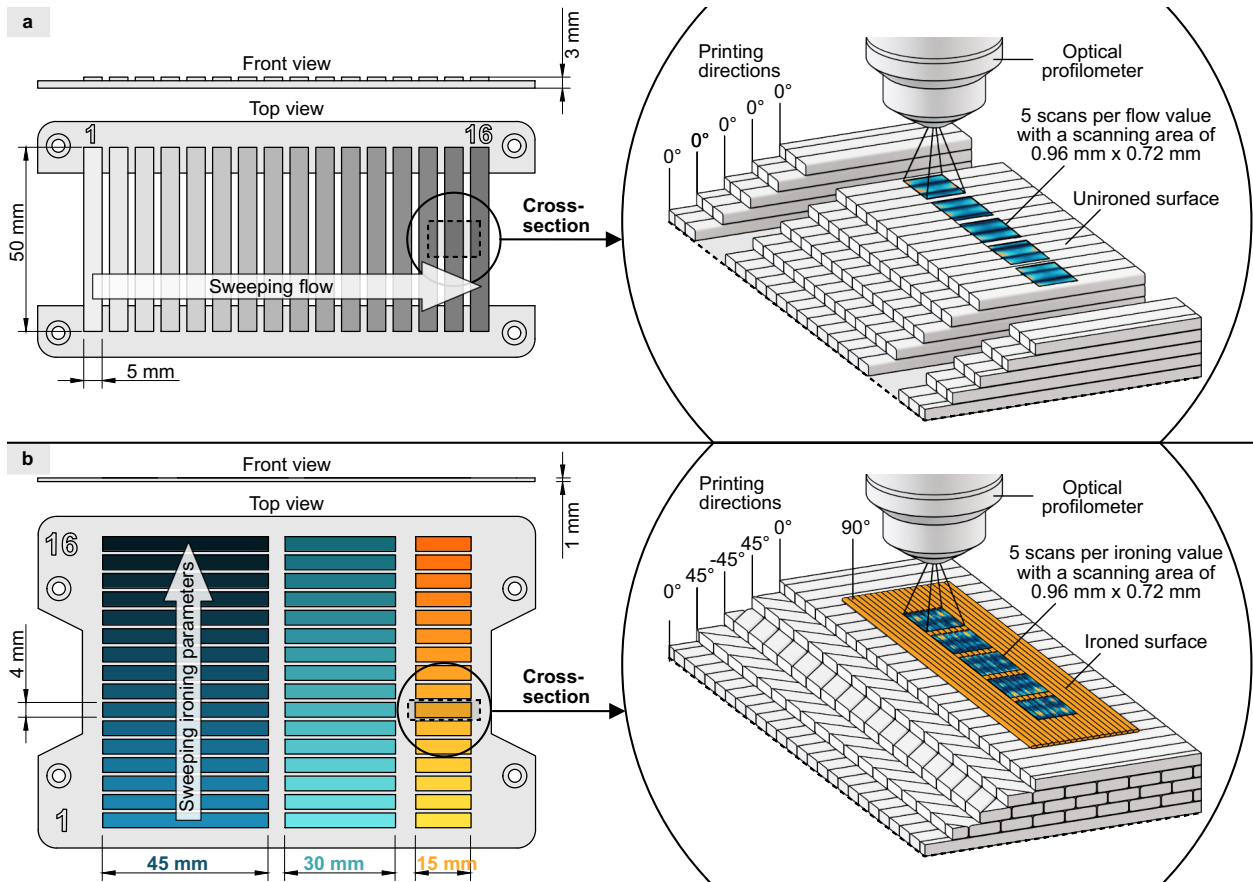


Figure 2-1. a) Sample design used to sweep the overall printing flow from left to right with 16 different settings. All layers have the same printing orientation to amplify the buildup of the material over all layers. Each of the sixteen rectangles is scanned on five different spots in the middle as shown on the right. b) Sample design used to sweep each of the ironing parameters from top to bottom. To prevent artifacts from the edges of the model and the lower layers, the ironing is performed in the middle of one uniformly printed surface. To get this base layer as evenly as possible, the printing direction of the layers beneath is alternated. Each rectangle represents the areas that are ironed perpendicular to the top layer orientation. Additionally, the width of the ironed area is varied in 15 mm steps to study whether the length of each ironing path line has an effect.

2.4. Path generation

Generating the machine commands for the printer from the 3D models is a process known as slicing. In all tests, samples were sliced using Cura (Ultimaker, Netherlands) and printed with 100% solid infill. It is

important to note that the ironing parameters changed from version 4.11 to 5.0. In the earlier versions, the ironing flow value is represented as a percentage of the material that is extruded for the regular lines (per millimeter of travel). This value remained constant regardless of the ironing line spacing, resulting in an overall increase in the total amount of material used during the ironing process when the line spacing was set to smaller values. With the introduction of Cura 5.0, which was used for all our experiments, the ironing layers are treated as another regular layer with their ironing flow value which is independent of the regular flow. Additionally, the total material consumption during the ironing process is no longer affected by line spacing variations, as the flow rate is now automatically adjusted accordingly. Consequently, the flow rate can get very low for finer line spacing or low printing speeds. Low flow rates are challenging to control as gravity can cause the molten material to extrude from the hot nozzle prematurely and irregularly. Additionally, low flow rates increase the likelihood of heat creeping up from the nozzle into the heatsink, softening the material too early and causing the material to expand and blockade the metal tube when pressure is applied from the extruder gear, as shown in Figure 2-2. To limit these effects, a high ironing flow was chosen for both experiments.

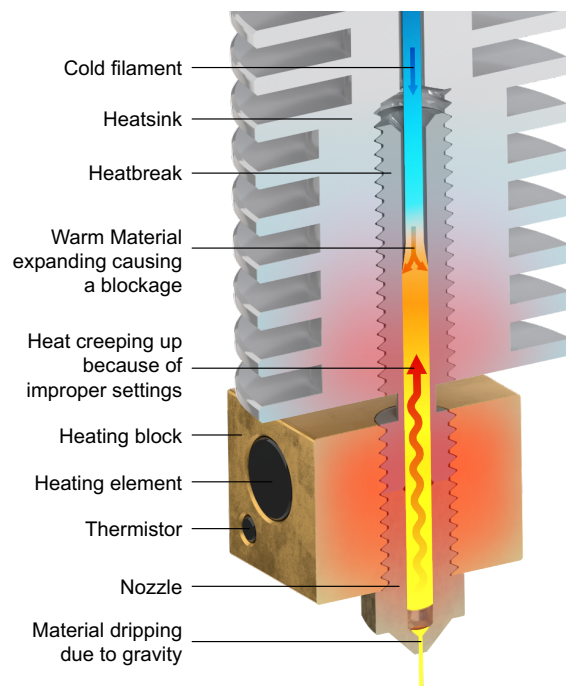


Figure 2-2. Cross-section of an extruder hot end affected by heat creep. The combination of slow extrusion speed, constant pressure, and heat creeping upwards in the filament causes the filament to expand in colder areas which causes higher friction inside the feeding channel or even total clogging of the hot end. In that case, the molten polymer can leak irregularly from the nozzle due to gravity.

2.5. Surface Characterization

All samples were scanned in two dimensions with an optical profilometer (Bruker, United States) in five different locations near the center and the roughness values were averaged. An image-processing algorithm was designed using MATLAB (Mathworks, United States) that calculates the roughness values from profilometry scans for two frequency ranges as illustrated in the flow chart in Figure 2-3 (a). These two frequency regimes could be interpreted as roughness and waviness. When printing (conductive) inks on top of these 3D printed surfaces, different regimes could be more important depending on the printing method used and the desired feature size. The first step of this algorithm involves a Gaussian blur with a kernel size of 5×5 pixels to remove initial noise from the profilometer scan. While this reduces the amplitude of very high-frequency noise with wavelengths lower than $10 \mu\text{m}$ as shown in Figure 2-3 (b), it removes most outliers and fills in missing data. Any remaining areas of missing data are mostly due to areas outside the z-scanning range of the optical profilometer, e.g., where the ironing layer was not printed completely because too little material was extruded or due to small deep holes that the profilometer could not illuminate and retrieve data from. Next, the tilt is removed from each sample and a 2D Fast Fourier Transformation (FFT) is carried out. Subsequently, low-pass and high-pass Butterworth filters of the first order with a cutoff wavelength of 0.2 mm are used to filter the scans into their high- and low-frequency features. This wavelength was chosen as it is situated between the line spacing for the regular lines ($0.4 - 0.5 \text{ mm}$) and the line spacing of the ironed lines (0.1 mm). In this way, the roughness value of the low-pass filtered image should allow studying if the wavy pattern of the regular lines has been removed by the ironing step without having to worry about newly introduced high-frequency noise. Analogously, we can also compare if new high-frequency noise has been introduced by the ironing operation. Then, all roughness values are calculated using the average absolute deviation and are shown for the two example samples in Figure 2-3 (c). The pixel size of each scan is $0.75 \times 0.75 \mu\text{m}$, thus, wavelengths smaller than double this cannot be detected. Similarly, the maximum scanning area of $0.96 \times 0.72 \text{ mm}$ does not allow much bigger wavelengths to be detected. Scans that had a high percentage of missing points or where no material was deposited during ironing causing the unironed surface underneath to be measured instead are greyed out in the graphs. In addition, the ironed and unironed surfaces were viewed with a scanning electron microscope (SEM) (Thermofisher Quanta 3D, United States).

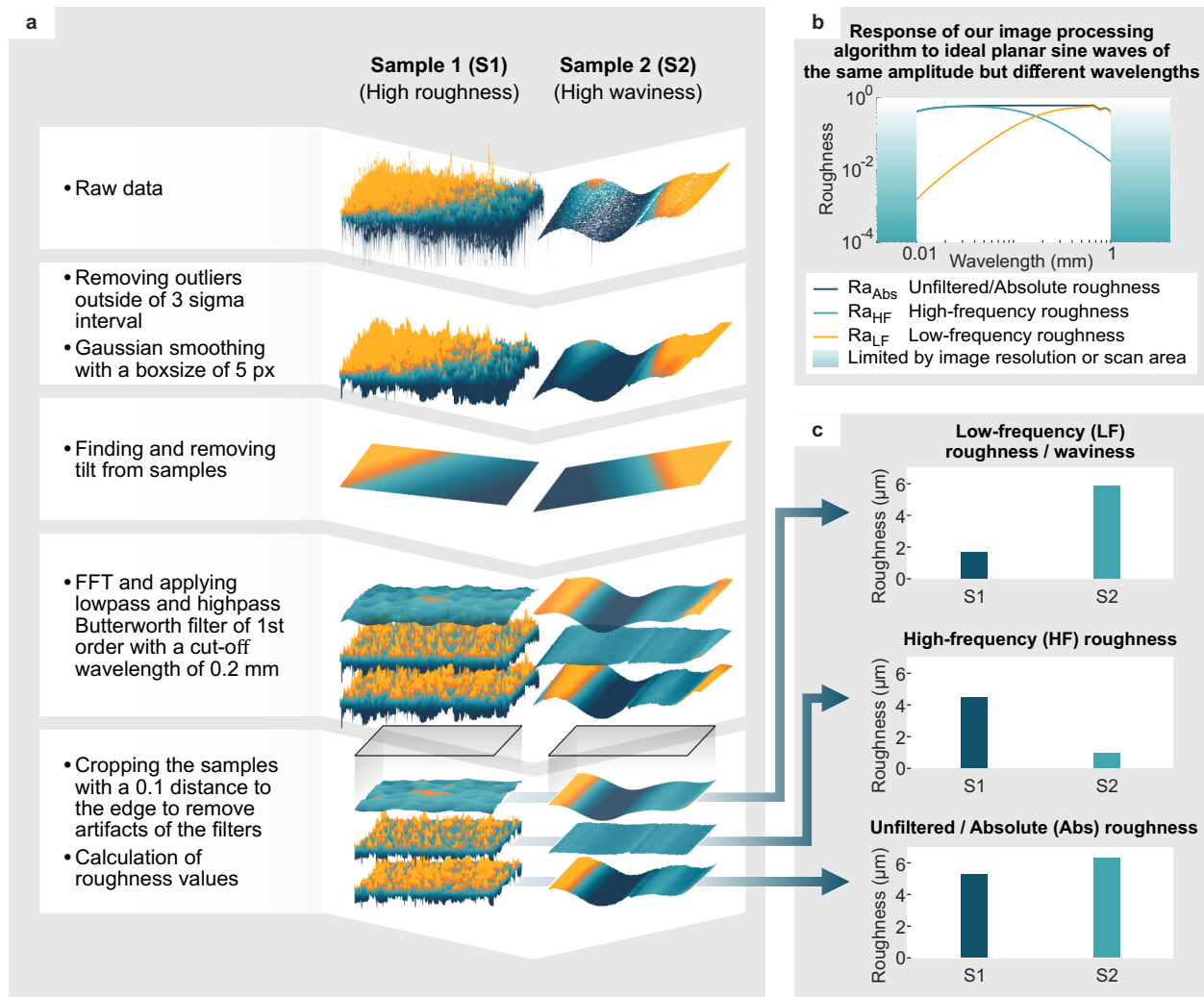


Figure 2-3. Overview of the image processing algorithm. a) Flow chart of the main processing steps for two selected samples from our study. b) Frequency response from values returned by the algorithm with ideal sine waves of different wavelengths as input. c) Resulting roughness values for the two printed samples. The two samples show high roughness values for different frequencies: Sample 1 is mostly flat but contains ripples with a shorter wavelength. Meanwhile, sample 2 has a smooth surface but is wavy with a much bigger wavelength. Depending on the application, one or the other roughness could be more important.

2.6. Parameter study: General flow without ironing

An important parameter for 3D printing is the general flow rate to build up the layers before any ironing is applied. This greatly affects the actual linewidth and height of all printed lines of the printed object. This flow rate significantly influences the actual width and height of all printed lines within the object, thus exerting a notable effect on surface roughness when no ironing is involved. Identifying the optimal flow rate can lead to a three-fold enhancement in surface roughness. This improvement in roughness is primarily observed in the longer wavelength regime, while the roughness remains relatively constant for smaller wavelengths. A comparable trend can be observed in every material in Figure 2-4 (a) but with an offset in flow values. At low flow values, gaps can be observed between the extruded lines. These gaps, which are not desirable, have a depth outside the range of our scanning method, resulting in missing data, and therefore do not greatly affect the calculated roughness values even though they lead to large surface roughness. As shown in the progression of the larger PLA profiles in Figure 2-4 (b), these gaps are filled with increasing flow, and the confined material spills over to the next line, resulting in ridges on the surface. This surface structure has also been observed in a previous study and has been used for lasering in and demolding flexible LIG circuits from the corrugated PEEK surface.[193] With further increased flow, the ridges grow larger, and the average surface height approaches the midpoint between the highest and lowest points of the ridges and trenches. This is where the standard deviation, used to measure roughness, reaches its peak, as indicated in the overall trend in Figure 2-4 (c). Beyond this point, roughness starts to decrease again as the overspills grow wider and the trenches smaller. With the lines becoming taller, they get closer to the nozzle and are more in contact with the previous line and under higher pressure. All these factors contribute to good fusion and fewer sharp edges between the lines. However, this higher flow value is unstable for larger prints as the excess material piles up with each added line, and the geometric accuracy of the parts suffers from the induced tilt. The ABS and PSU (Figure A-17) flow studies also shows that increasing the flow further will cause roughness to increase again.

In conclusion, the data suggest that there are two options for general flow values to achieve a smooth surface for most materials. The first option is to find the flow value just before lines start overlapping, and the second is to print with significant overlap. However, the first version has gaps that could potentially result in breaks in the conductive ink printed on top, and the second option may become unstable for larger samples. Therefore, neither option is ideal for printing small features on top.

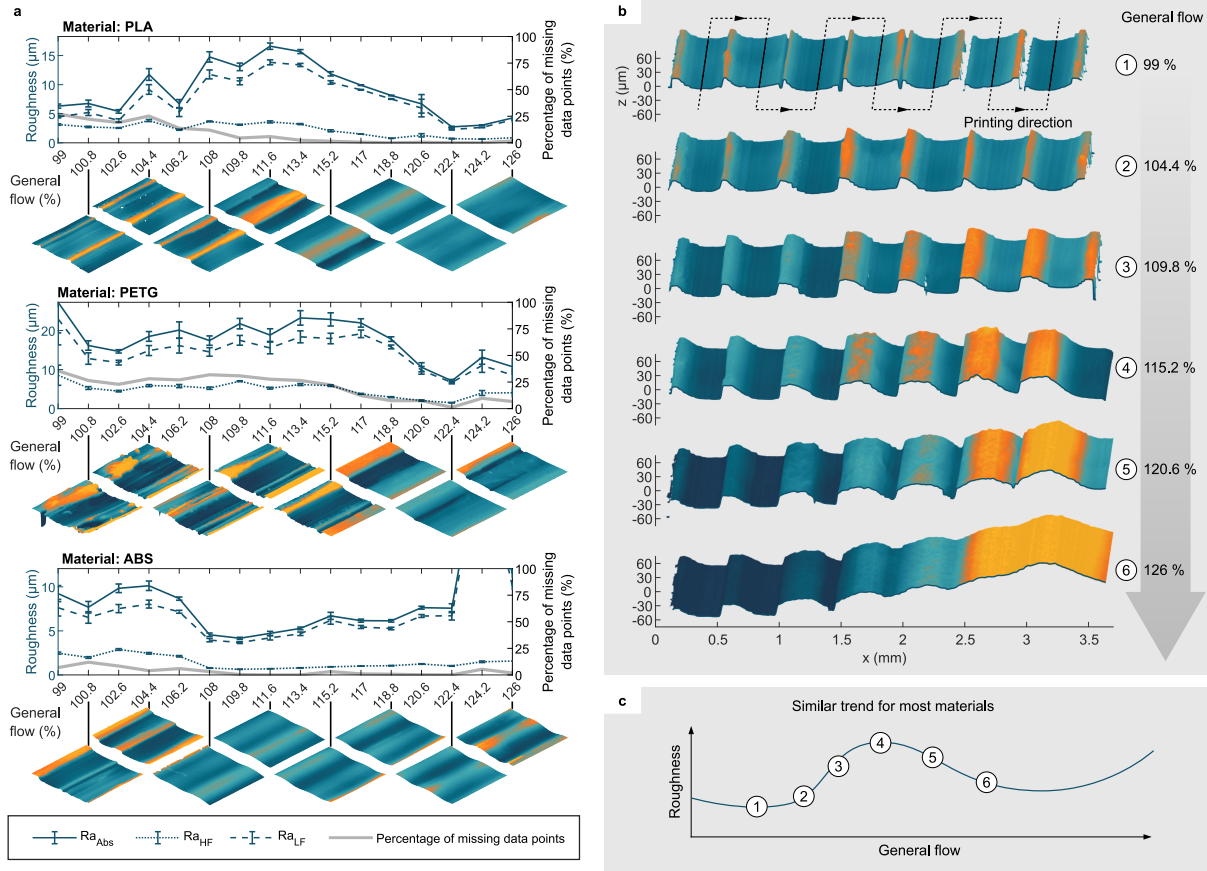


Figure 2-4. Effect of the general flow on surface roughness without ironing. a) Roughness data that was calculated with our algorithm for PLA, PETG, and ABS. Selected scans are shown for every second flow value below the graphs. The results for the three high-temperature materials PSU, PEI, and PEEK, and the other sample sizes are presented in Appendix A. b) Larger cross-section of the PLA surfaces with varying flow values. As the flow is increased, lines start overlapping and material spills over and accumulates. c) Schematic general trend of roughness for the general flow with some reference points from the scans in b). The peak of this general trend is found at around 112% for PLA, 115% for PETG, and 104% for ABS.

2.7. Parameter study: Ironing flow

To further reduce surface roughness beyond what is possible by optimizing the general flow, an ironing tool path is added and the effect of the ironing flow on the surface quality is investigated. The term "ironing flow" only refers to the amount of material that is extruded during the final ironing pass. A range from 17.4% to 83.4% was chosen for the ironing flow values while keeping the general flow of the underlying

layers constant. Throughout the ironing process, the z-position of the nozzle remains unchanged from the last layer. If the regular layer before the ironing step is filled with the appropriate amount of material (as discussed in the previous study), the average distance between the printed part and the nozzle should be close to zero. Therefore, an ironing flow of 50% results in half of the material volume from a regular layer being extruded into the top layer again. This close proximity between the nozzle and the completely filled surface enables the application of pressure and smoothing.

Interestingly, the ironing flow did not cause as much variation on the surface roughness compared to the general flow, and the roughness values remained consistently low even for high ironing flow values, as illustrated in Figure 2-5 (a). A drastic increase in surface roughness is only observed when there is an insufficient extrusion of material. In such cases, the limited material is unevenly deposited in small heaps on the higher regions of the surface, causing a significant rise in surface roughness. The limited impact of the ironing flow on surface roughness can be attributed to the behavior of excess material, which is akin to how a snowplow pushes aside any surplus snow it cannot compress. This excess material is displaced to the sides of the heated nozzle, where it accumulates neatly, as illustrated in Figure 2-5 (a). The ironing flow predominantly influences the height of these material stacks without significantly altering the actual topography or roughness of the ironed layer. In fact, the sample thickness increases linearly with higher ironing flow, which must be considered for components that require precise geometric dimensions (Figure A-32). As shown in Figure 2-5 (b), a ridge is formed on the left side of the nozzle due to the accumulation of excess material. This ridge is progressively carried along and grows throughout the entire ironing process. With a higher flow rate, a larger 'lip' is left at the final ironed line. While this lip doesn't affect the primary surface, it may pose clearance issues when subsequently printing electronics on top of it and should be minimized.

With low flow values, the ironing lines of PETG are more visible, and for high values, small ripples perpendicular to the lines appear. In the transition between these two regimes, optimum smoothness and flatness are achieved. For ABS, the smaller 15 mm samples exhibit an increase in roughness with increasing flow values while a downward trend in roughness was observed in the two larger sample sizes (Figure A-13). This observation suggests that over-extrusion is more problematic for smaller samples and thus requires finer tuning. In contrast, when analyzing the PEI samples (Figure A-23) it was found that the surface roughness of the largest sample drastically increases with the ironing flow. This implies that further adjustments are necessary for the larger samples in this case. Upon close inspection of the scans, the 0.4 mm wide lines of the layer beneath could still be seen for low flow values (especially noticeable for ABS)

but became less noticeable with a higher flow as more material is compressed into the surface and valleys are filled out better.

In summary, the surface roughness stays mostly constant for a wide range of ironing flow values and only has one significant peak when under-extrusion occurs. By avoiding easy-to-detect under-extrusion and excessive build-up around the edges of the ironed area, it should be straightforward to find good values for this parameter.

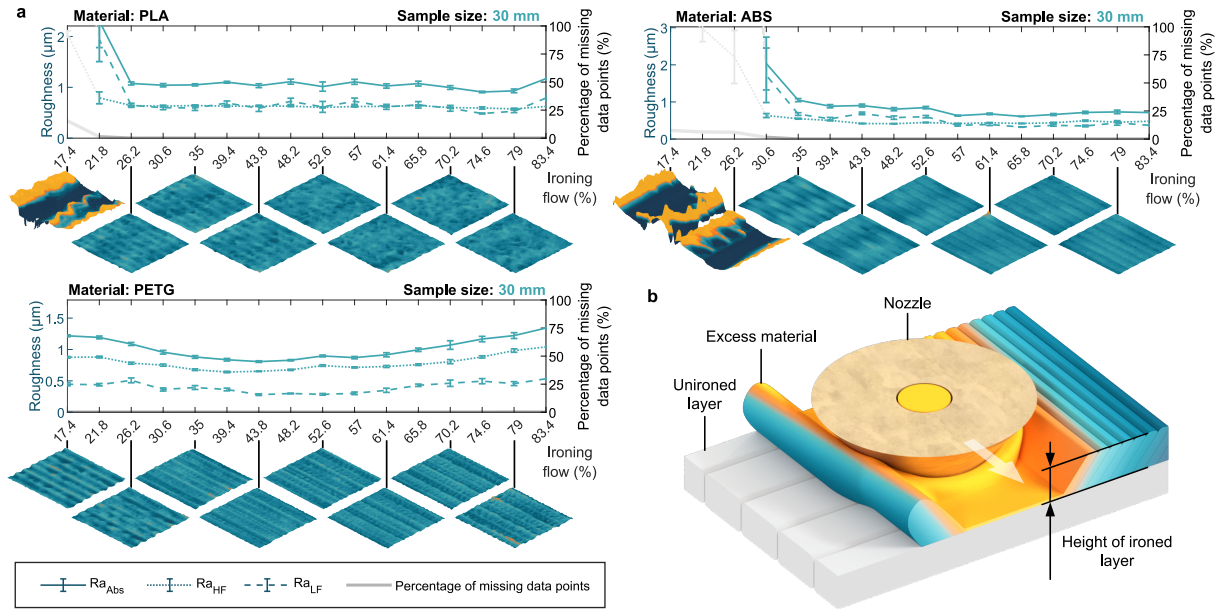


Figure 2-5. Effect of the ironing flow on surface roughness. a) Roughness data that was calculated from profilometry scans with our algorithm for PLA, PETG, and ABS. Selected scans are shown for every second flow value below the graphs. The results for the three high-temperature materials PSU, PEI, and PEEK, and the other sample sizes are presented in the supplementary material. b) Schematic cross-section of material build-up during ironing. Proportions are not to scale. The height of the ironed layer can be regulated by adjusting the ironing flow, even though the position of the nozzle in the z-axis always remains the same as the last layer. The results indicate that increasing the ironing flow has only a small impact on the surface roughness compared to the general flow, as the primary effect is only a shift of the surface profile in the z-direction.

2.8. Parameter study: Ironing speed

To investigate the effect of ironing speed, samples were tested using a range of values from 1 mm/s to 75 mm/s, which is the maximum print speed of our printer. Ironing slower than 1 mm/s would result in an extensive print duration and, although the obtained results are interesting at 1 mm/s, they lack usability and do not justify further expenditure of time.

In the low-speed regime, ranging from 1 mm/s to 10 mm/s, a maximum for the overall roughness, a maximum for the low-frequency roughness, and one for the high-frequency roughness can be found at different speeds in the graphs in Figure 2-6 (a). This common trend is depicted in Figure 2-6 (c). At the lowest speed of 1 mm/s, the nozzle is almost stationary. This allows heat to transfer into the material in all directions around the nozzle, resulting in the remelting of the entire surrounding area and the removal of small features and lines, as illustrated in Figure 2-6 (b). While this produces a very glossy surface finish, it also results in high low-frequency roughness (waviness). The reason for this waviness could be a combination of poor temperature stability of the nozzle and low flow rate. Depending on the tuning of the proportional-integral-derivative (PID) controller for the heating element and thermistor in the printing toolhead, the temperature can fluctuate by a few degrees over a period of a few seconds or minutes. The temperature variation can affect the flow rate, causing each ironed line to have a slightly different amount of material and height. With slower print speeds, this temperature variation has an effect within smaller distances. Another factor that could be responsible for the large waviness is the low material flow rate that is associated with low speeds. The hot molten material can leak from the nozzle due to gravity if the feeding speed is not fast enough and the heat can also travel upwards along the filament path softening the material too early. Additionally, the extrusion precision is inherently limited by the step resolution of the extruder stepper motor. At very low flow rates, this limitation becomes more apparent. For the higher-temperature materials, this method of slow printing and remelting appears more ineffective. A better heating chamber might reduce the dissipation of heat and allow for better remelting. Overall, further tuning of other parameters, such as ambient and nozzle temperature and a better extruder with high extrusion precision and good temperature stability might make this method suitable for cases where a glossy surface finish is desired.

At slightly higher speeds in the range of 5 - 20 mm/s, a decrease in the low-frequency roughness is observed, while a significant increase in the higher frequencies is found. The heat does not have enough time to transfer into the surrounding area and remelt the material. While the deposited material leaves a small trail of heat, it cools down too quickly before the nozzle can return to the warm material in the next line.

Therefore, newly added material does not fuse well, resulting in a defined profile of parallel lines with high roughness, especially at higher frequencies.

In the high-speed regime from 20 mm/s to 70 mm/s, all roughness values are overall lower and remain mostly constant with speed for the low-temperature materials. For the high-temperature materials, a slight upward or downward trend is observed depending on the material. For PSU (Figure A-19) and PEEK (Figure A-29), a transition from lines to perpendicular ripples is observed, with the optimal print speed being found at the transition point (20 mm/s for PSU and 30-35 mm/s for PEEK). The cause for the ripples at higher speeds could be that the flow rate is too high for these materials, resulting in the filament not being heated fast enough and causing it to extrude in bursts. In contrast, PEI, which has a significantly lower thermal conductivity, may heat up more quickly. This could explain why the surface roughness of PEI is optimal at a higher speed of 70 mm/s (Figure A-24).

In conclusion, higher ironing speeds (70 mm/s and upwards) produce a surface with low roughness for most materials while also being time efficient. For ABS, PSU, and PEEK, the speed should be lowered to 20 - 30 mm/s for more consistent results. While very smooth, these surfaces still appear matte (Figure A-1). A glossier surface finish can only be achieved with very low speeds in the range of 1 mm/s. However, these are very time-consuming and would require more fine-tuning to make them less wavy.

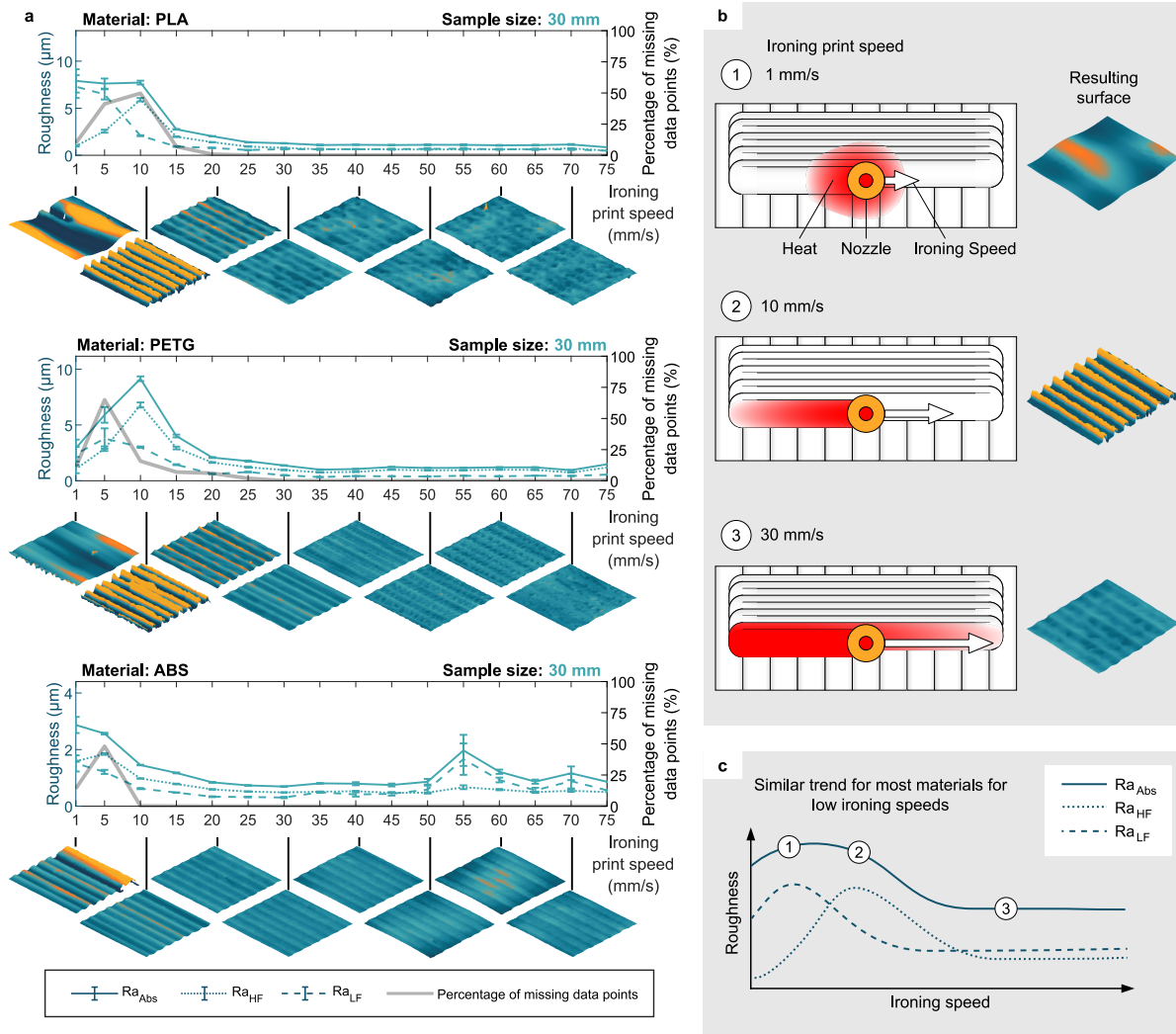


Figure 2-6. Effect of the ironing print speed on surface roughness. a) Roughness data that was calculated from profilometry scans with our algorithm for PLA, PETG, and ABS. Selected scans are shown for every second ironing speed value below the graphs. The results for the three high-temperature materials PSU, PEI, and PEEK, and the other sample sizes are presented in the supplementary material. b) Schematic top view of heat gradient for different ironing speeds with selected sample scans of PLA. Low speeds allow the heat to disperse deeper and wider into the material causing almost complete remelting of the surface. A slight increase in speed can result in a longer heat gradient, but the overlapping lines will still be cooled down by the time the toolhead moves to the adjacent line. High speeds will cause sufficiently larger areas of material to still be hot by the time the nozzle returns to the same area on the adjacent line, which allows better fusion between the last line and the newly printed line. c) General trend of roughness found for the ironing flow resulting from this.

2.9. Parameter study: Ironing line spacing

In terms of line spacing, an intuitive hypothesis would be that the surface roughness improves with finer line spacing. Indeed, a downward trend in high-frequency roughness is observed in Figure 2-7 as the line spacing is decreased from large values. However, when line spacing is reduced to a very small value, the flow rate becomes very low and the two issues discussed in the speed section arise. The first issue is inconsistent extrusion, which is particularly apparent in ABS and PEEK. The second issue is that temperature oscillations and the resulting variations in flow rate become more noticeable as the lines are brought closer together. These oscillations are clearly visible in the profilometer scans of PLA and PETG for a line spacing of 0.01 - 0.03 mm and affect the low-frequency roughness as the wavelengths of the planar waves now fall within the 0.4 - 1 mm range. Another issue is that line spacing of 0.01 mm is close to the precision limit of the printer, which has an xy-resolution of 0.005 mm. For these reasons, the finest line spacing of 0.01 mm does not produce the best surface roughness except for PEI where an impressively low surface roughness (compared to the unironed PEI surface) of 701 ± 19 nm can be achieved on the larger samples. This might be possible because the temperature fluctuations of the high-temperature hot end (HT3-450) are not as severe compared to the low-temperature hot end (MK1-250) with which the PLA, PETG, and ABS samples were printed. Also, PEI appears to exhibit a high level of precision in dosing and extrusion at low flow rates. For PSU, the effect of line spacing is dependent on the size of the sample (Figure A-20). Whereas the smallest PSU sample exhibits the smoothest surface with a fine 0.02 mm line spacing, the other two sample sizes show the lowest roughness at 0.15 mm. For PEEK, line spacing has almost no effect on roughness, unless it is too fine causing under-extrusion (Figure A-30). ABS shows the smoothest surface for a wider line spacing of 0.15 mm while for PLA and PETG, a medium line spacing of 0.04 - 0.05 mm was found to produce the best results.

In summary, line spacing is a vital factor in controlling the ironing process. Our findings contradict the expectation that a very fine line spacing of 0.01 mm would consistently produce the best smoothness because the limitations that come with low flow rates are already reached at this line spacing. Instead, the results of this study indicate that the optimal line spacing falls within the range between 0.05 and 0.15 mm. However, with improvements in the temperature stability of the nozzle and improvements in the filament path of the hot end, the waviness caused by the temperature oscillations and problems with low flow rate could be mitigated. This would allow for a further reduction in line spacing until the maximum resolution of the printer is reached, potentially leading to very low surface roughness in the higher frequencies, which may justify the additional printing time that comes with a finer line spacing.

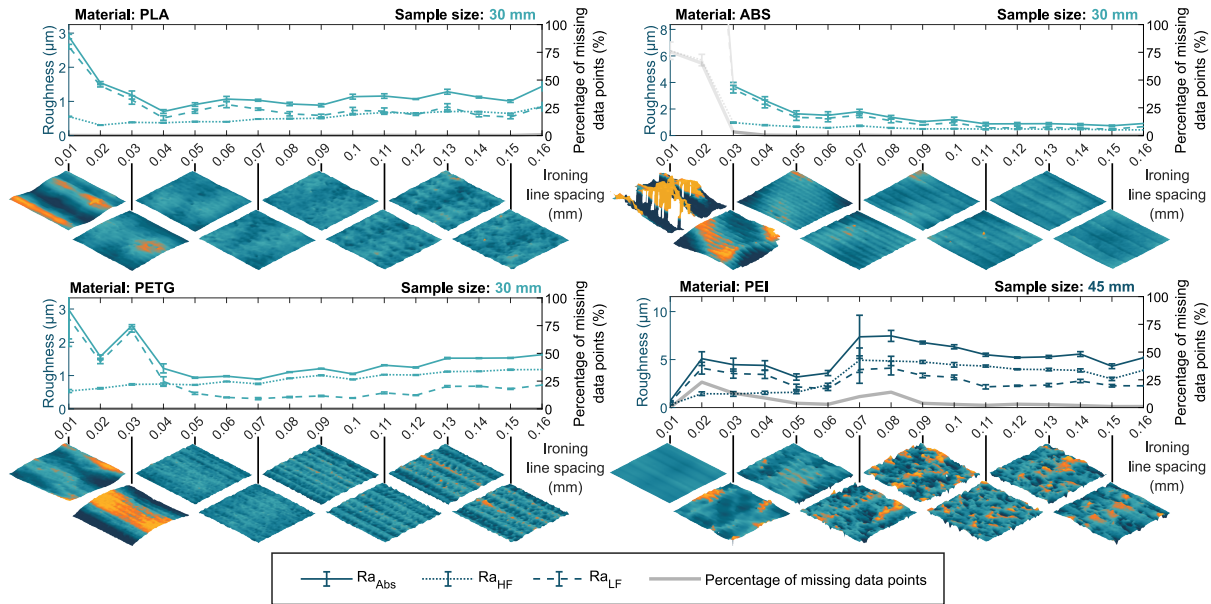


Figure 2-7. Effect of the ironing line spacing on surface roughness. The graphs show the roughness data that was calculated with our algorithm for PLA, PETG, and ABS. Selected scans are shown for every second line spacing value below the graphs. The results for the other two high-temperature materials PSU and PEEK and all other sample sizes are presented in the supplementary material. While a large line spacing is preferable for ABS, in the case of PEI a very smooth surface can be created by choosing the smallest line spacing.

2.10. Parameter study: Ironing Temperature

The influence of ironing temperature on the surface roughness was found to be mostly negligible except at extremely high or low temperatures. At low temperatures, the extruder is unable to sufficiently soften and extrude the material, resulting in poor surface roughness. Conversely, at very high temperatures, the material can degrade and the moisture within the filament may lead to increased foaming and poor surface quality. Furthermore, high temperatures can result in heat creeping into the heatsink of the extruder, which can cause the material to become soft too early, resulting in expansion and blockage of the feeding tube when pressure is applied from the extruder motor. Both extremes of the temperature range and their effect on roughness can be seen in the ABS graph in Figure 2-8. Between these extremes, no significant change in the surface roughness values can be found for almost all materials. However, a common trend can be observed across various materials where the surface structure transitions from irregular ripples to straight

lines with increasing temperatures. This is especially noticeable for PSU where the roughness decreases steadily with higher temperatures. For PETG, the best roughness values are found in the transition between the two regimes.

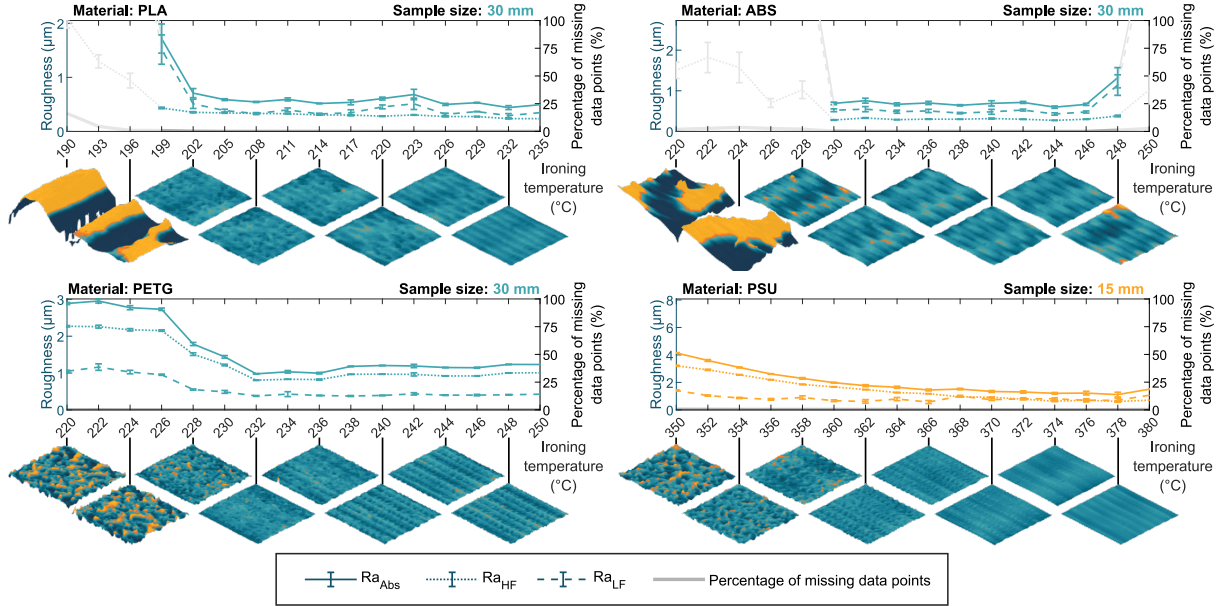


Figure 2-8. Effect of the ironing temperature on surface roughness. The graphs show the roughness data that was calculated with our algorithm for PLA, PETG, and ABS. Selected scans are shown for every second temperature value below the graphs. The results for the other two high-temperature materials PEI and PEEK and the other sample sizes are presented in the supplementary material. For the PETG and PSU samples, a transition from ripples to straight lines can be observed in the surface plots with increasing temperature.

2.11. Parameter study: Sample size

All the ironing parameter studies have been performed for three different sample sizes (15, 30, and 45 mm) corresponding to three different lengths of the ironing lines. All detailed results for 15 and 45 mm can be found in the supplementary information. For shorter lines, the nozzle returns sooner to the already printed area, and the heat concentration is higher. This either allows for better merging of the material or causes unpredictable reflow of the soft material. Another factor to consider is the decrease in the average speed with smaller samples since more time is spent with acceleration and deceleration. For very small samples, the desired speed might not even be reached while printing the lines. Also, the waves caused by the

temperature fluctuations are spaced differently depending on the width of the sample, which is especially noticeable in the PLA line spacing study.

For further analyses, the roughness values from all our ironing studies are averaged based on the sample size and presented in Figure 2-9. The whiskers and quartiles in the boxplot indicate the magnitude of the effect that each parameter has on roughness in that study. The outliers are mostly due to samples where the parameter values did not allow for a defect-free ironed top surface. While the overall shape of the roughness trends in Figure 2-4-Figure 2-8 was usually similar for all three sample sizes, noticeable variations in magnitude and scaling become apparent in the averaged roughness values presented in the boxplot. Therefore, optimal settings remain constant regardless of sample size, but differences in the overall surface quality can be expected for different sizes and shapes of the sample. Therefore, to generate the best result for a given geometry, the ironing path could be rotated or split intelligently so that the optimal path length is used. In some cases (e.g., ironing flow of PEI), the sample size greatly increases the standard deviation towards higher roughness values. This suggests that optimal settings need to be chosen especially carefully if the path geometry cannot be altered. In some rare cases, opposite trends are found within a given material-parameter combination, such as the ironing flow in ABS and PSU or the line spacing in PSU (Figure A20), where the slope of these graphs changes from positive to negative for different sample sizes. In such cases, the optimal surface finish on irregularly shaped samples can only be achieved by adjusting the print settings for each line based on its length. Alternatively, the machine path could be designed to always have a similar ironing path length, for example, by adding slight curves.

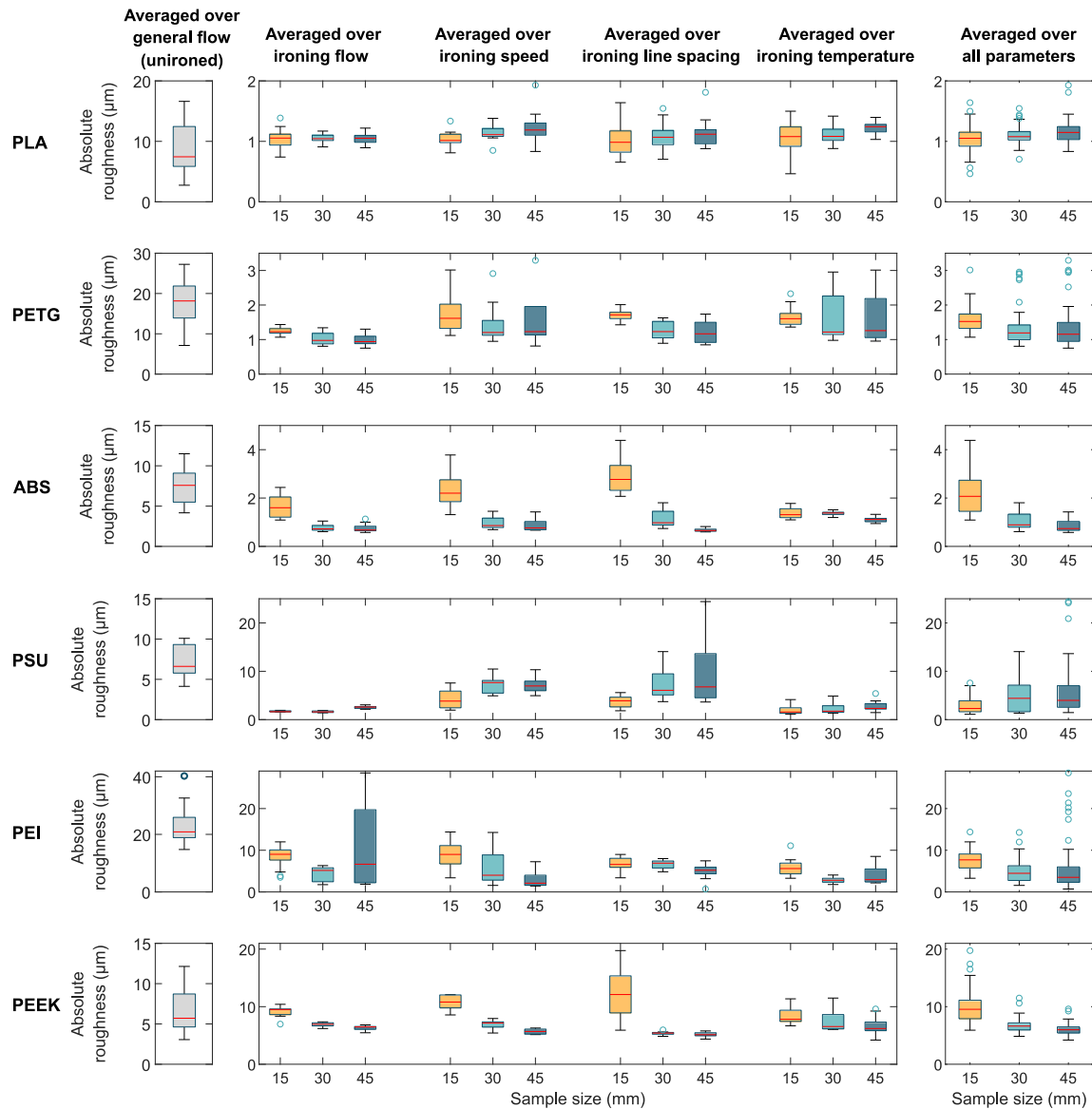


Figure 2-9. Boxplot of the roughness values grouped by sample size and averaged for each parameter experiment. The whiskers and quartiles reflect how much variation in roughness was achieved by varying the parameter of that study. For PLA and PSU, the average roughness decreases slightly with smaller samples while for the other materials roughness increases with smaller samples. The sample size directly translates to the path length in the ironing process and therefore is an important factor to consider when designing the geometry of the ironing path. Box plots are also shown for the unironed samples averaged over the general flow study. Note the scales of the y-axes are different in different graphs to improve readability.

2.12. Microscale characterization with SEM

Upon examination with an SEM, one can observe large-scale waviness disappearing with ironing. However, at the microscale, the ironed PETG and PSU samples appear rougher than their unironed counterparts as can be seen in Figure 2-10. The profilometer was not able to pick up this microscopic roughness correctly due to its limited resolution and the prefiltering method in the image processing algorithm. This roughness may be attributed to the hygroscopic nature of these materials, as the expansion of trapped moisture during the ironing process could be a possible cause. As ironing is performed with a much lower flow rate than the regular lines, the filament is pushed more slowly through the orifice of the nozzle. This increased contact time allows for more heat to be transferred from the nozzle to the material, potentially leading to an increase in foaming. Additionally, the nozzle drags parts of previously laid lines because the outside surface of the nozzle comes into greater contact with the material during the ironing operation causing fine peaks and even tiny hair-like structures which are particularly noticeable in the ironed PEEK sample. Furthermore, the SEM images reveal that the ironing lines on the PEI surface are very consistent, confirming its high level of controllability and steadiness, which PEI has shown for tight line spacings and low flow rates. Similarly, the ironed ABS sample also demonstrates straight and steady lines.

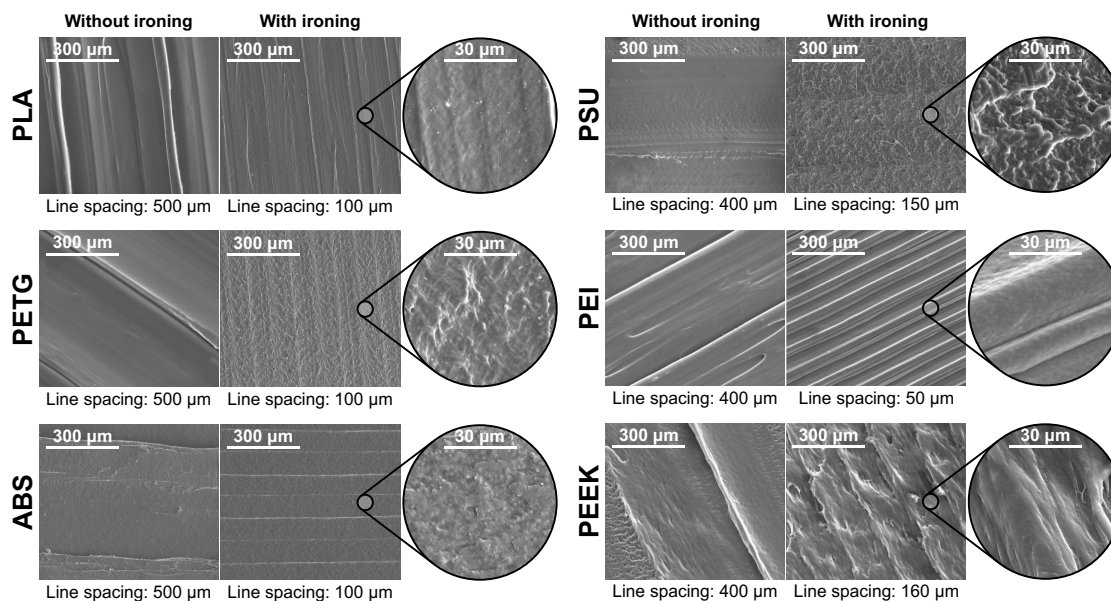


Figure 2-10. SEM images of ironed and unironed surfaces. While PETG and PSU show a more roughened-up surface on the micrometer scale compared to the unironed version, PLA, ABS, and PEI remain mostly the same after the ironing step but with less waviness. In the case of PEEK, the large profile of the wide lines is replaced with finer lines but with an inferior high-frequency roughness.

2.13. Comparison with other smoothing methods and substrates

In Figure 2-11, the smoothness of 3D printed samples with and without ironing is compared to the smoothness of traditional smoothing methods. For the treatment in acetone, the samples were submerged inside acetone for 10 minutes and then left to dry before being measured with the profilometer. While this method is usually only used on ABS prints, it also shows an effect on PLA and PETG. Interestingly, for PLA and PETG, the low-frequency waviness of the samples is reduced while the smaller features and lines remain mostly intact. On the other hand, for ABS, the low-frequency waviness remains almost the same while all high-frequency noise is reduced drastically, confirming that a glossy surface can be achieved on ABS with acetone. Still, the roughness values of the ironed samples surpass the improvements by acetone. The overall roughness after ironing is comparable to a surface that was sanded with sandpaper somewhere between 1200 and 1800 grit. The waviness of the sanded samples is slightly less than that of the ironed samples, indicating that the sanding process results in good flatness, as expected. However, the improvement does not justify the effort and added complexity that an integrated sanding toolhead would entail in a multi-toolhead printer. Compared to substrates used for printed electronics, the roughness of the ironed samples is comparable to an FR1 PCB board but higher than a flexible PET substrate. This means that ironed 3D printed surfaces can likely be used for printed electronics, but there is still room for improvement to match higher-quality substrates.

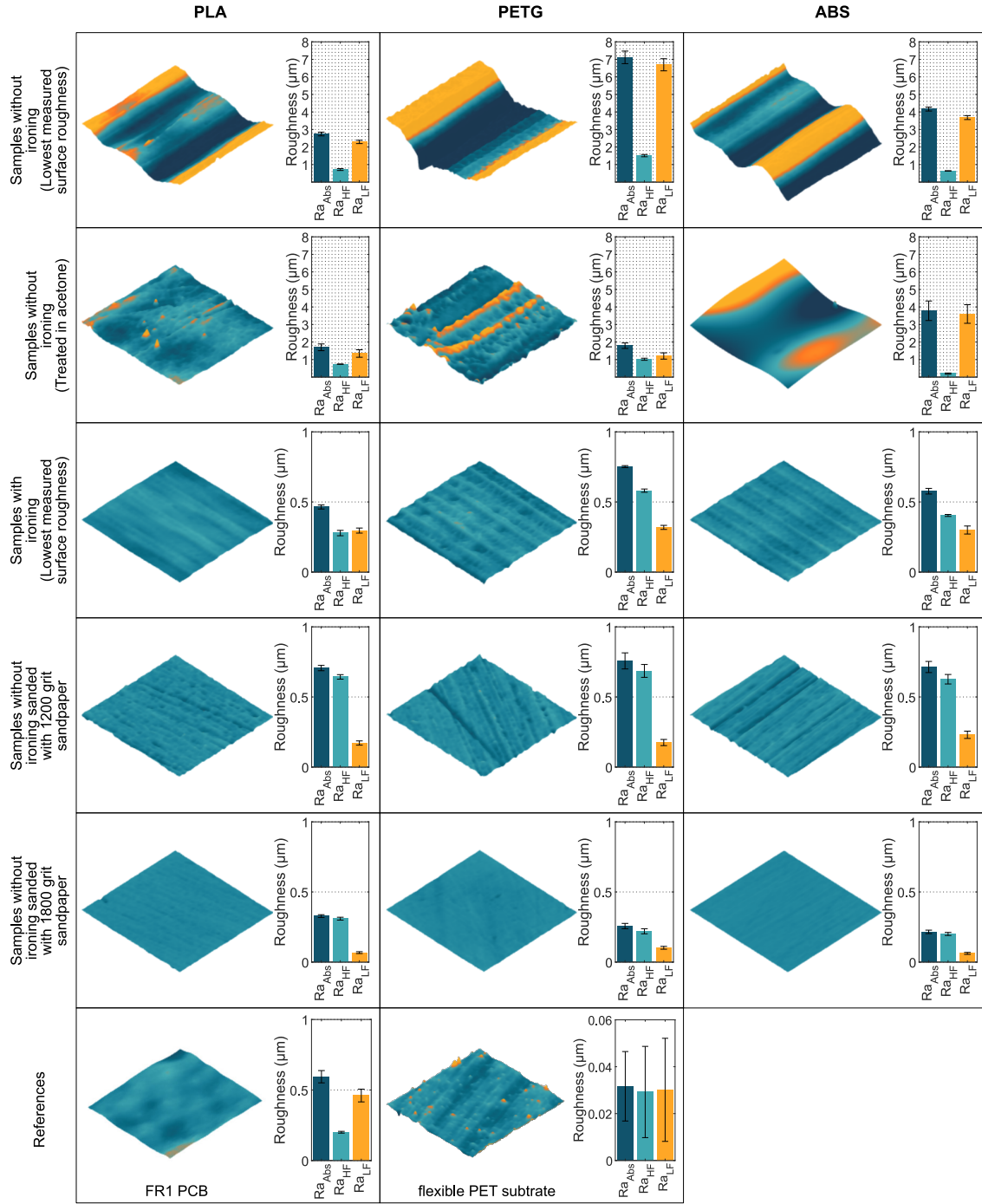


Figure 2-11. Comparison of different methods to improve surface quality. The histograms and surface plots share the same scale in the first two rows and a different scale bar is shared for the third to fifth row. The ironed samples exhibit similar roughness as traditional PCBs and sanded 3D printed surfaces, but higher roughness than flexible PET substrates.

2.14. Final assessment of surface roughness improvement by ironing

A summary of the improvement in roughness by ironing is shown in Table 2-2. It should be noted that, for a fair comparison, we use the lowest roughness that we found in the samples with and without ironing. Therefore, improvements are even larger compared with unoptimized 3D printing parameters. These results show that ironing has a very substantial impact on the overall roughness of the commonly used materials PLA, PETG, and ABS with reductions in roughness ranging from 83 – 89%. Most of this improvement is found for the low-frequency roughness. Therefore, we can conclude for these materials that ironing is very effective at eliminating the line patterns greater than 0.2 mm in width while there is only a minor improvement if not worsening of the microscopic surface as confirmed by the SEM images.

In contrast, the results for engineering-grade filaments such as PSU, PEI, and PEEK exhibit more varied outcomes. PEI demonstrates the highest level of controllability throughout our studies, allowing for a remarkable roughness reduction of approximately 95% when optimal settings are employed. Conversely, with PEEK, we observed a more modest reduction in roughness, around 26%, and an increase in high-frequency roughness when using ironing. An alternative approach for enhancing PEEK's surface quality could involve the use of carbon fiber-reinforced PEEK, as it has been shown to yield a superior surface roughness [194]. PSU falls somewhere in between, with an improvement that is slightly less than that of PLA.

Notably, some of the parameter boundaries in our tests are tied to the limitations of our printer. Recent advances in printer technology, such as higher print speeds up to 500 mm/s and improved extruders that can apply more feeding force on the filament and have sharper temperature gradients, may be able to push these boundaries and achieve more precise control of flow rates and print speeds. Additionally, the integration of Lidar scanners into the printhead of consumer printers has the potential to enable auto-tuning of flow and ironing values without the need for expensive equipment in the future.

Table 2-2. Lowest roughness values found in the studies for the samples with and without ironing. The last column shows the reduction that can be achieved by ironing for the absolute, high-frequency, and low-frequency roughness.

Material	Roughness type	Lowest roughness found without ironing [nm]	Lowest roughness found with ironing [nm]	Reduction in roughness by ironing [%]
PLA	Ra _{Abs}	2743 ± 106	464 ± 14	83.1 ± 0.9
	Ra _{HF}	634 ± 15	278 ± 19	56.2 ± 3.2
	Ra _{LF}	2290 ± 95	296 ± 18	87.1 ± 1
PETG	Ra _{Abs}	7114 ± 359	752 ± 7	89.4 ± 0.6
	Ra _{HF}	1508 ± 65	514 ± 4	65.9 ± 1.5
	Ra _{LF}	6691 ± 345	268 ± 3	96 ± 0.3
ABS	Ra _{Abs}	4164 ± 111	577 ± 20	86.1 ± 0.7
	Ra _{HF}	638 ± 11	364 ± 4	42.9 ± 1.2
	Ra _{LF}	3679 ± 112	255 ± 11	93.1 ± 0.4
ThermaX™ PSU	Ra _{Abs}	4131 ± 176	1013 ± 576	75.5 ± 14
	Ra _{HF}	1272 ± 7	449 ± 215	64.7 ± 17
	Ra _{LF}	2962 ± 153	383 ± 16	87.1 ± 0.9
ThermaX™	Ra _{Abs}	14750 ± 248	701 ± 19	95.2 ± 0.2
PEI made	Ra _{HF}	5060 ± 157	296 ± 8	94.2 ± 0.3
Using				
ULTEM	Ra _{LF}	11345 ± 349	555 ± 20	95.1 ± 0.3
9085				
PEEK Pro	Ra _{Abs}	3058 ± 47	2257 ± 1150	26.2 ± 37.7
	Ra _{HF}	1093 ± 59	1448 ± 716	-32.5 ± 65.9
	Ra _{LF}	2085 ± 225	1074 ± 593	48.5 ± 29

2.15. Conclusion

In the first part of this chapter, the potential of ironing for creating smooth top surfaces on parts printed by FDM printers was quantified. Activating the ironing feature results in significant improvements in the surface roughness of PLA, PETG, and ABS. Optimization of each ironing parameter yields only a minor improvement for these low-temperature materials, suggesting that ironing can remain effective across a broad range of settings. The lowest roughness value was observed for PLA, where an absolute roughness of 464 ± 14 nm was achieved, which is much lower than previously reported values, although this may be partly due to differences in sample design, measuring tools, and data processing. Based on the comparison with other smoothing methods, it can still be concluded that the ironed samples in PLA, PETG, and ABS are similar in smoothness to surfaces that were sanded with 1200-grit sandpaper or FR1 boards. In other research, the lowest roughness of the ironed samples is compared to the average roughness of unironed samples and a reduction of 72.2% is reported.[195] Making the same comparison for our research, we find reductions from 93.7%-95.8% for the three low-temperature materials and a very high reduction of 96.6% for PEI, 84.8% for PSU, and 61.4% for PEEK. If we compare the mean values of both the ironed and the unironed samples, we still find a reduction ranging from 83.7-92.9 % for PLA, PETG, and ABS, 46.2% for PSU, and 75% for PEI. In the case of PEEK, the roughness increases on average by 29.4% with ironing. This is because these average values also include samples where the parameter values led to suboptimal results. Therefore, we additionally compared the lowest values of both the unironed and ironed samples and found reductions in roughness ranging from 83.1-89.4% for the three low-temperature materials and 75.5% for PSU, 95.2% for PEI and 26.2% for PEEK showing that with the correct settings the ironed samples always surpass the unironed samples even for PEEK. However, the trends and results for PSU, PEI, and PEEK varied more, therefore tuning of ironing settings is crucial for these materials, and more extreme values were found to be optimal. Overall, the collected data shows that there is a higher potential in ironing than previously reported and the recorded trends can guide a fine-tuning process for each material. Further optimization for different materials could be achieved by characterizing the material properties of 3D printing filaments at the relevant temperatures and modeling the temperature distribution during printing. Since ironing speed, line spacing, and temperature should be comparable across different FDM printers, these parameters could be set first and then be followed by the adjustment of the printer-specific ironing flow so that no under- or over-extrusion occurs.

Chapter 3. Dispense Printing of Conductive Silver Inks

A version of this chapter was published as a journal article: Mohamad Kannan Idris, Gerd Grau, "Dispense Printing of Silver Flake Inks on Hydrophilic and Hydrophobic Surfaces," *Advanced Engineering Materials*, vol. 26, no. 23, Art. no. 2401302, 2024, doi: 10.1002/adem.202401302.

3.1. Introduction

The findings from the previous chapter provide insights into how to 3D print substrates with relatively low roughness that are suitable for dispense printing conductive traces. Building on the work in Chapter 2, this chapter focuses on the dispense printing of electrodes on surfaces of various wettability. Dispense printing has emerged as a promising technique for creating conductive patterns on diverse substrates with high precision and versatility.[95,132] Unlike other additive manufacturing methods, such as inkjet printing, dispense printing excels in depositing high-viscosity inks, allowing for the fabrication of intricate patterns with micron-scale accuracy. This capability makes it particularly suited for applications requiring robust and reliable electronic components, such as sensors, flexible circuits, and antennas.[58,96,107]

An integral aspect of dispense printing is its ability to handle substrates with varying surface characteristics. While hydrophilic surfaces like glass are well-suited to many printing techniques due to their favorable wettability, hydrophobic surfaces, such as Teflon, present unique challenges. Teflon's low surface energy, which enhances its resistance to moisture and chemical interactions, simultaneously impedes ink wetting and pattern precision. Addressing these challenges requires a comprehensive understanding of how printing parameters, ink properties, and substrate characteristics interact to influence the final printed structures.[35,95]

This chapter focuses on the application of dispense printing for depositing high-viscosity silver flake inks onto hydrophilic and hydrophobic substrates. The research investigates key printing parameters—nozzle height, dispense pressure, and print speed—and evaluates their impact on trace morphology, and reproducibility. The chapter explores the role of substrate wettability in determining ink behavior during extrusion, spreading, and drying phases. By systematically analyzing these factors, this work advances the understanding of how to optimize dispense printing for both standard and challenging substrates, paving the way for improved precision and functionality in printed electronics.

3.2. Materials and Methods

3.2.1. Material Preparation

The main ink used in this study is NovaCentrix Metalon HPS-FG77, which is a silver flake ink. According to the technical data sheet, the silver flake diameter is 0.3 μm . The solvent is butyl carbitol, the silver content is 85 wt%, and the ink viscosity is 25000 cP. The second ink used for comparison is Creative Materials 120-07(LPS), which is also a silver flake ink. The silver flakes are larger (3 μm), the solvent is dipropylene glycol monomethyl ether (DGME), the silver content is 88%, and the ink viscosity is 22000 – 28000 cP. Both inks were prepared for printing in 2 mL cartridges (Voltera, Waterloo, Canada). The cartridges were centrifuged at 500 rpm for 10 minutes 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 %.

3.2.2. Measurement Techniques

The rheometric measurements were taken using a Discovery Hybrid Rheometer (DHR) 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 10 data points. The line images (2D) and the height profiles (3D) were taken using a Keyence VHX-970F Digital Microscope.

3.2.3. Surface Preparation

Experiments were conducted on four surfaces: glass, Teflon, plasma-treated glass (Glass (P)), and plasma-treated Teflon (Teflon (P)). To create the surfaces, 1x1 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 minutes 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 minute and then cured at 150 °C for 30 minutes 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.

3.2.4. 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 3-1. Reference printing parameters. Nozzle height, dispense pressure, and printing speed were identified as the main parameters that affect 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 well-controlled temperature for printing. These parameters, illustrated previously in Figure 1-4, 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 paper 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 paper.

Table 3-1. 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]
Relief Pressure	80 [a.u.]
Dispense Threshold	100 %
Relief Pressure	0 %
Ink Preheat Temperature	35 $^{\circ}\text{C}$

3.2.5. 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 minutes, 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, 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 3-1 (a, b). Figure 3-1 (c-f) show the images of traces printed using the NovaCentrix HPS-FG77 ink and reference parameters on the four different surfaces, i.e., 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.

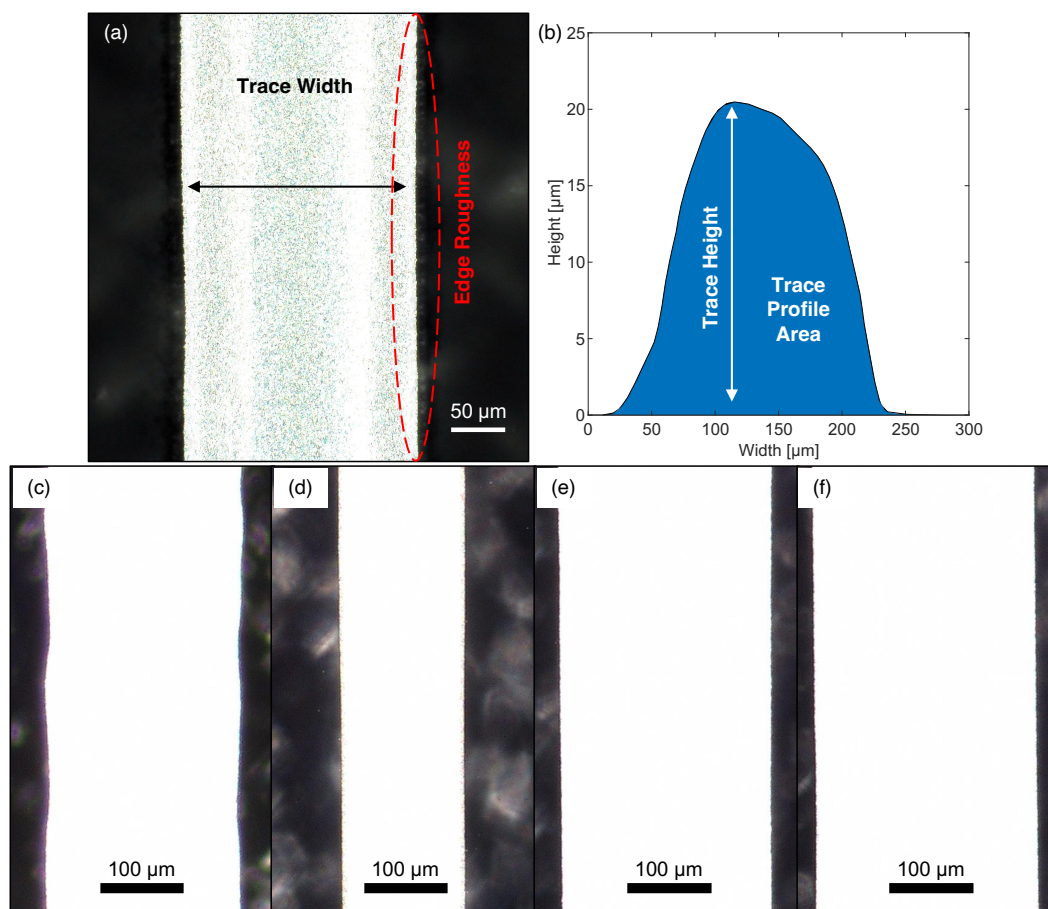


Figure 3-1. Printed trace parameters extracted from a microscope. a) 2D image of printed trace showing trace width and edge roughness. b) Trace profile extracted from 3D image showing trace height and trace cross-sectional profile area. High-brightness 2D images of lines printed using the NovaCentrix 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)

3.3. Ink Characterization

To characterize the flow of the two inks, their viscosity was measured at 35°C. As shown in Figure 3-2, 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.

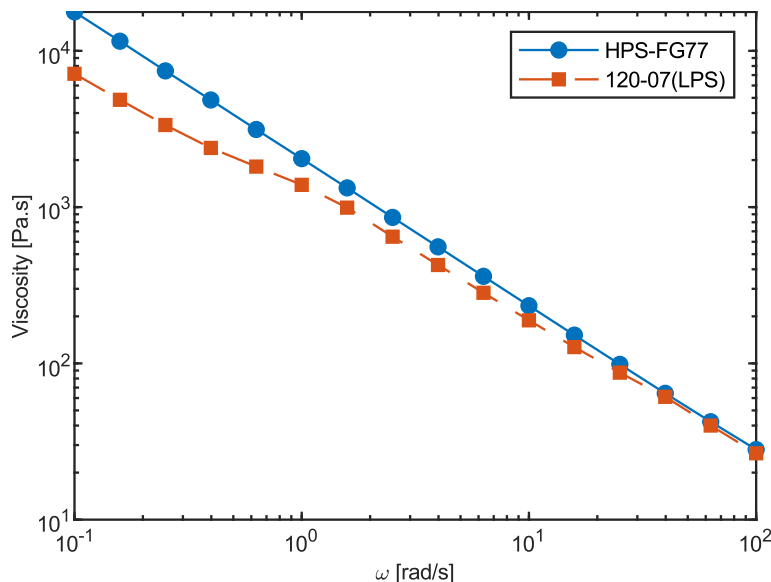


Figure 3-2. Viscosity change of NovaCentrix HPS-FG77 ink and Creative Materials 120-07(LPS) ink at 35°C with varying oscillation angular frequency. The measured viscosity of the NovaCentrix HPS-FG77 ink is higher than the viscosity of the Creative Materials 120-07(LPS) ink.

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, i.e., 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 3-3, showing the interaction of each liquid with the four aforementioned surfaces. As shown from the DI water measurements in Figure 3-3 (a), 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 3-3 (b, d), except for DGME on Teflon (P), where both the advancing and receding contact angles decrease compared to Teflon, but the hysteresis still increases.

Figure 3-3 (c, e) show 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 de-wet the surface with a receding contact angle until the liquids are mostly or entirely pulled back into the nozzle. An illustration of the behavior is shown in Figure 3-4 (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 3-4 (d – g). Representative images of droplets for each data point in Figure 3-4 are shown in Figure 3-5, Figure 3-6, Figure 3-7, Figure 3-8, and Figure 3-9. 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.

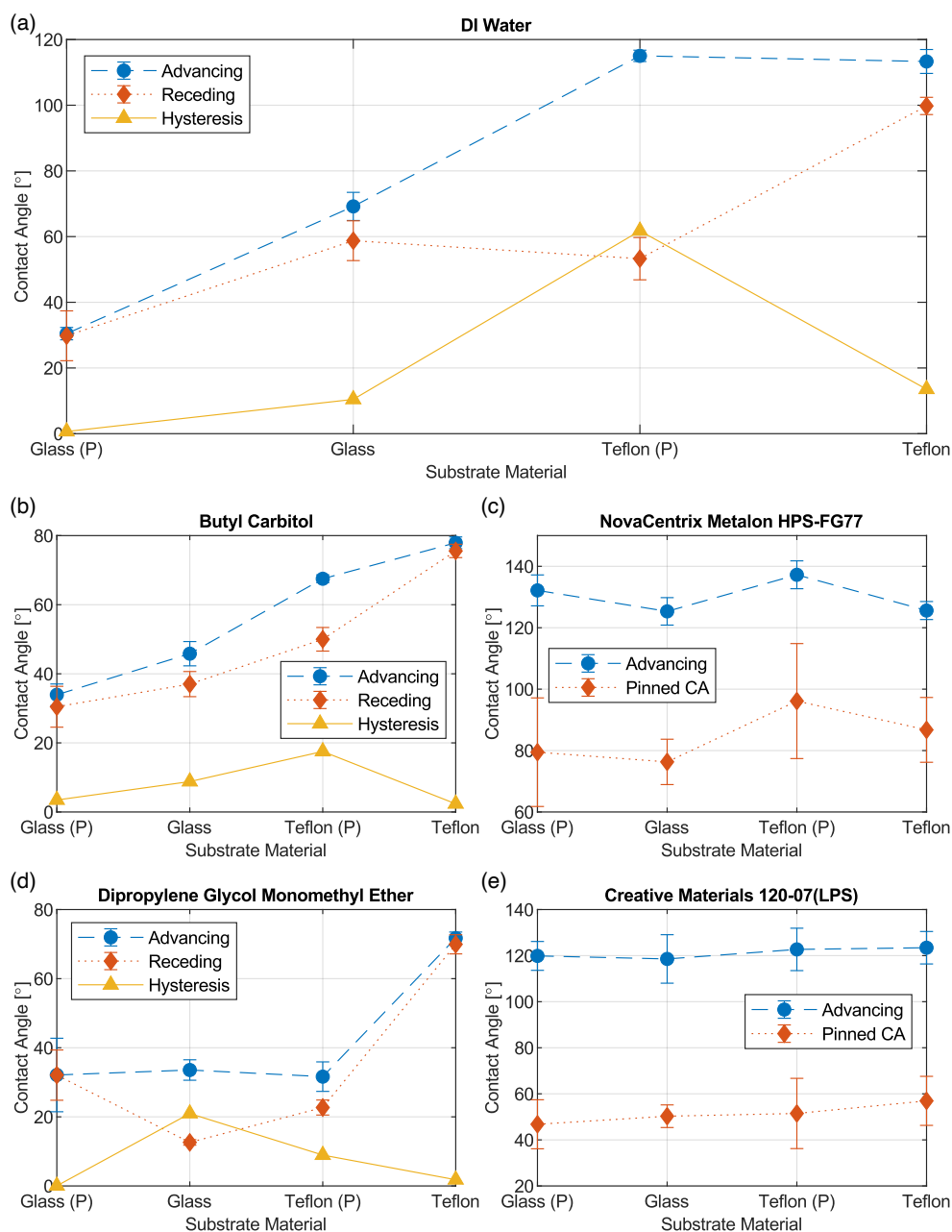


Figure 3-3. Contact angle measurements on four surfaces: Glass, Teflon, plasma-treated glass (Glass (P)) and plasma-treated Teflon (Teflon (P)), using a) DI water, b) butyl carbitol, c) NovaCentrix Metalon HPS-FG77, d) dipropylene glycol monomethyl ether (DGME), e) Creative Materials 120-07(LPS). Each 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.

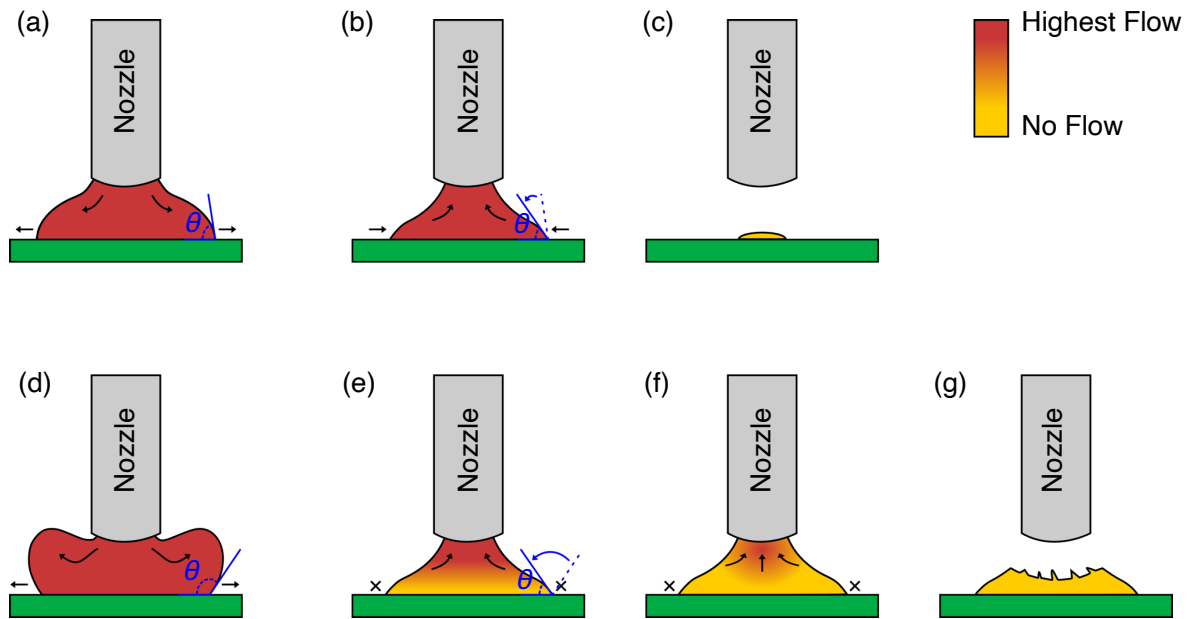


Figure 3-4. Contact angle behavior comparison between low-viscosity and high-viscosity (non-Newtonian) inks. a) Low-viscosity fluid is pushed out of the nozzle. The ink is dispensed from the nozzle, spreading on the substrate, showing an advancing contact angle. b) The ink is pulled into the nozzle, 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, de-wetting 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, as illustrated in (g).

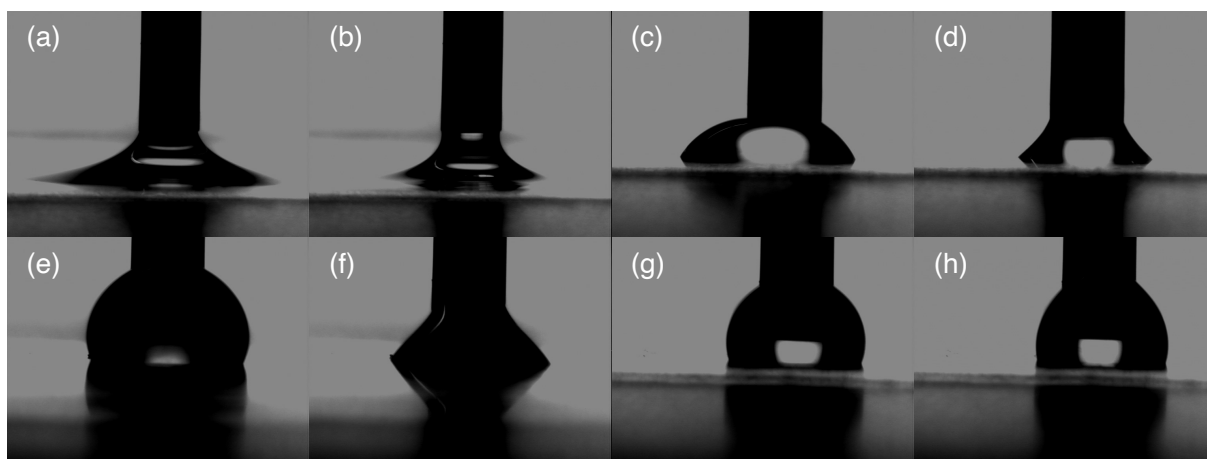


Figure 3-5. Advancing and receding contact angle images of DI water droplets on multiple surfaces. a) Advancing on plasma-treated glass; b) Receding on plasma-treated glass; c) Advancing on glass; d) Receding on glass; e) Advancing on plasma-treated Teflon; f) Receding on plasma-treated Teflon; g) Advancing on Teflon; h) Receding on Teflon;

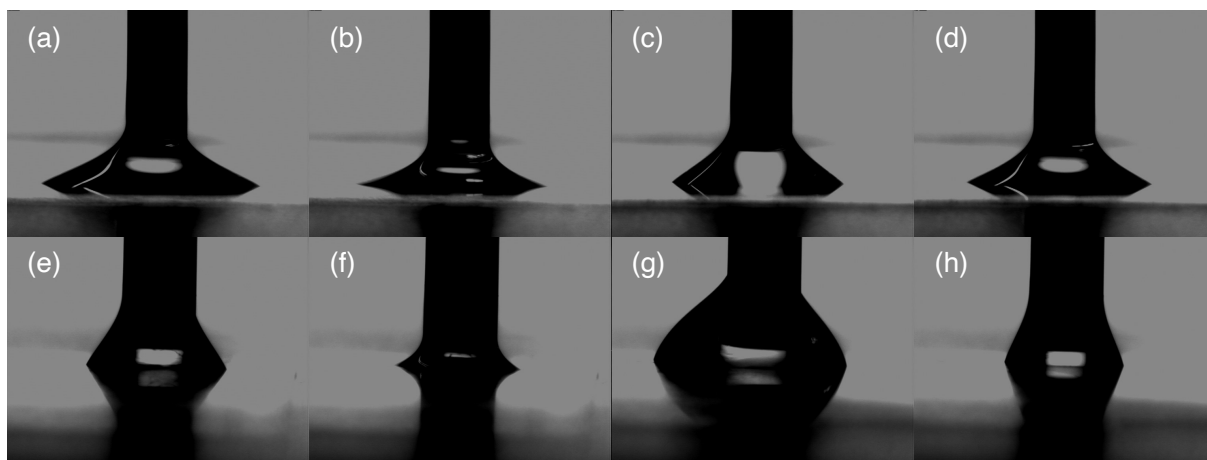


Figure 3-6. Advancing and receding contact angle images of butyl carbitol droplets on multiple surfaces. a) Advancing on plasma-treated glass; b) Receding on plasma-treated glass; c) Advancing on glass; d) Receding on glass; e) Advancing on plasma-treated Teflon; f) Receding on plasma-treated Teflon; g) Advancing on Teflon; h) Receding on Teflon;

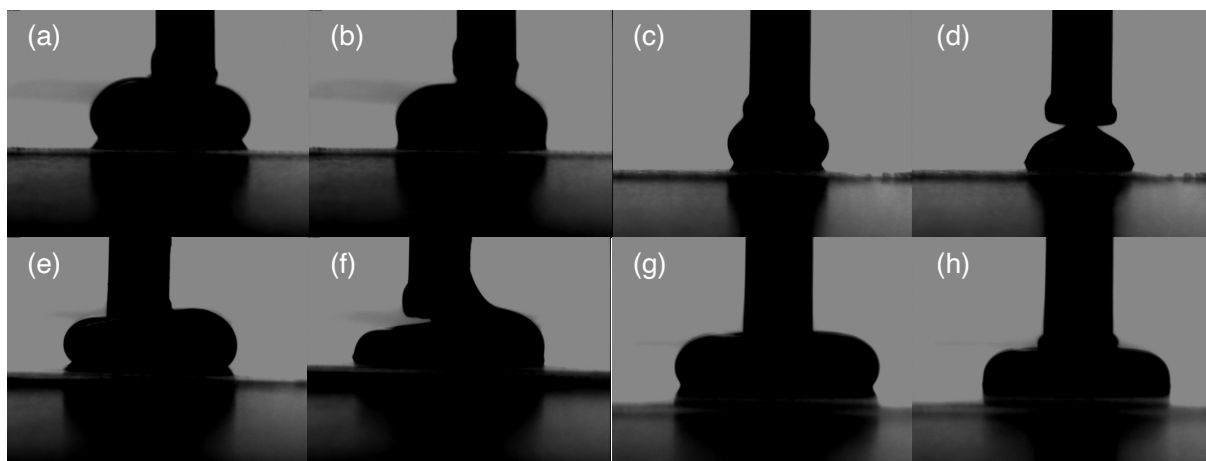


Figure 3-7. Advancing and receding contact angle images of NovaCentrix Metalon HPS-FG77 droplets on multiple surfaces. a) Advancing on plasma-treated glass; b) Receding on plasma-treated glass; c) Advancing on glass; d) Receding on glass; e) Advancing on plasma-treated Teflon; f) Receding on plasma-treated Teflon; g) Advancing on Teflon; h) Receding on Teflon;

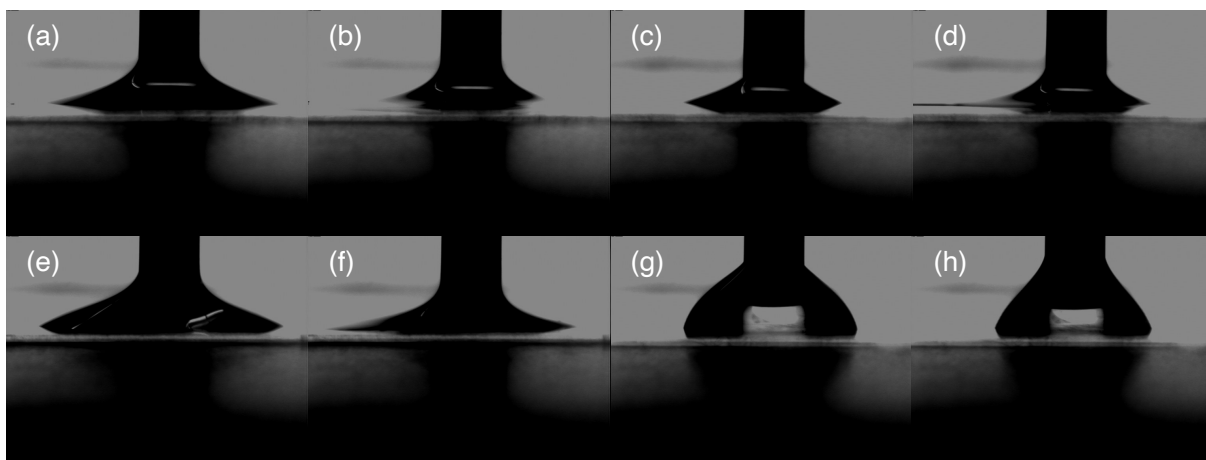


Figure 3-8. Advancing and receding contact angle images of dipropylene glycol monomethyl ether (DGME) droplets on multiple surfaces. a) Advancing on plasma-treated glass; b) Receding on plasma-treated glass; c) Advancing on glass; d) Receding on glass; e) Advancing on plasma-treated Teflon; f) Receding on plasma-treated Teflon; g) Advancing on Teflon; h) Receding on Teflon;

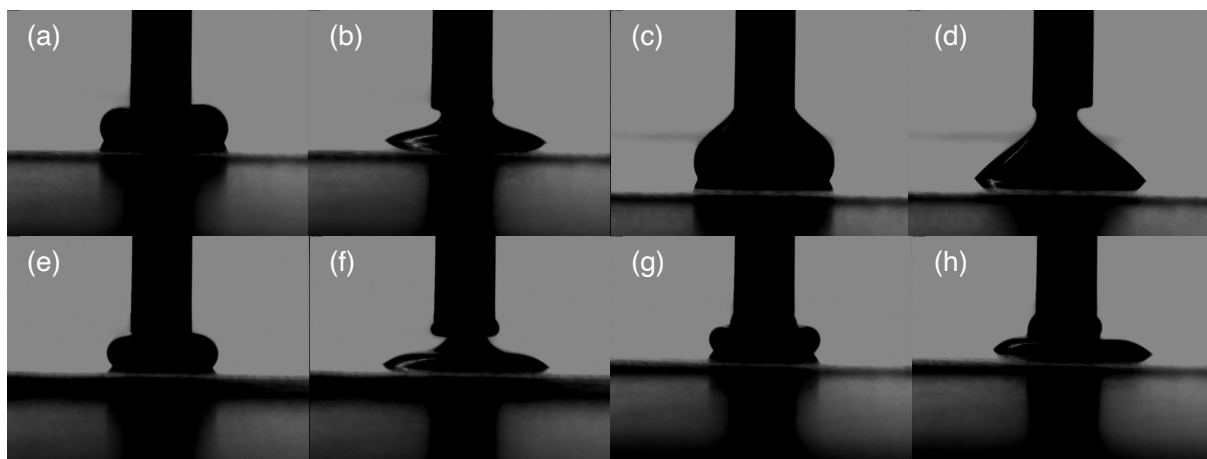


Figure 3-9. Advancing and receding contact angle images of Creative Materials 120-07(LPS) droplets on multiple surfaces. a) Advancing on plasma-treated glass; b) Receding on plasma-treated glass; c) Advancing on glass; d) Receding on glass; e) Advancing on plasma-treated Teflon; f) Receding on plasma-treated Teflon; g) Advancing on Teflon; h) Receding on Teflon;

3.4. Dispense Printing Parameters

3.4.1. Nozzle Height

To understand the impact of nozzle height, illustrated in Figure 3-10 (a), on printing, the parameter was swept from 30 μm 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 3-10 (b). 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 3-10 (c). The height-to-width ratio exhibits a similar trend to trace height, as shown in Figure 3-10 (d). 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 3-11. 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 Appendix B in Figure B-1.

Comparing trace width, height-to-width ratio, and cross-sectional profile area on different surfaces (Figure 3-10), 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 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.

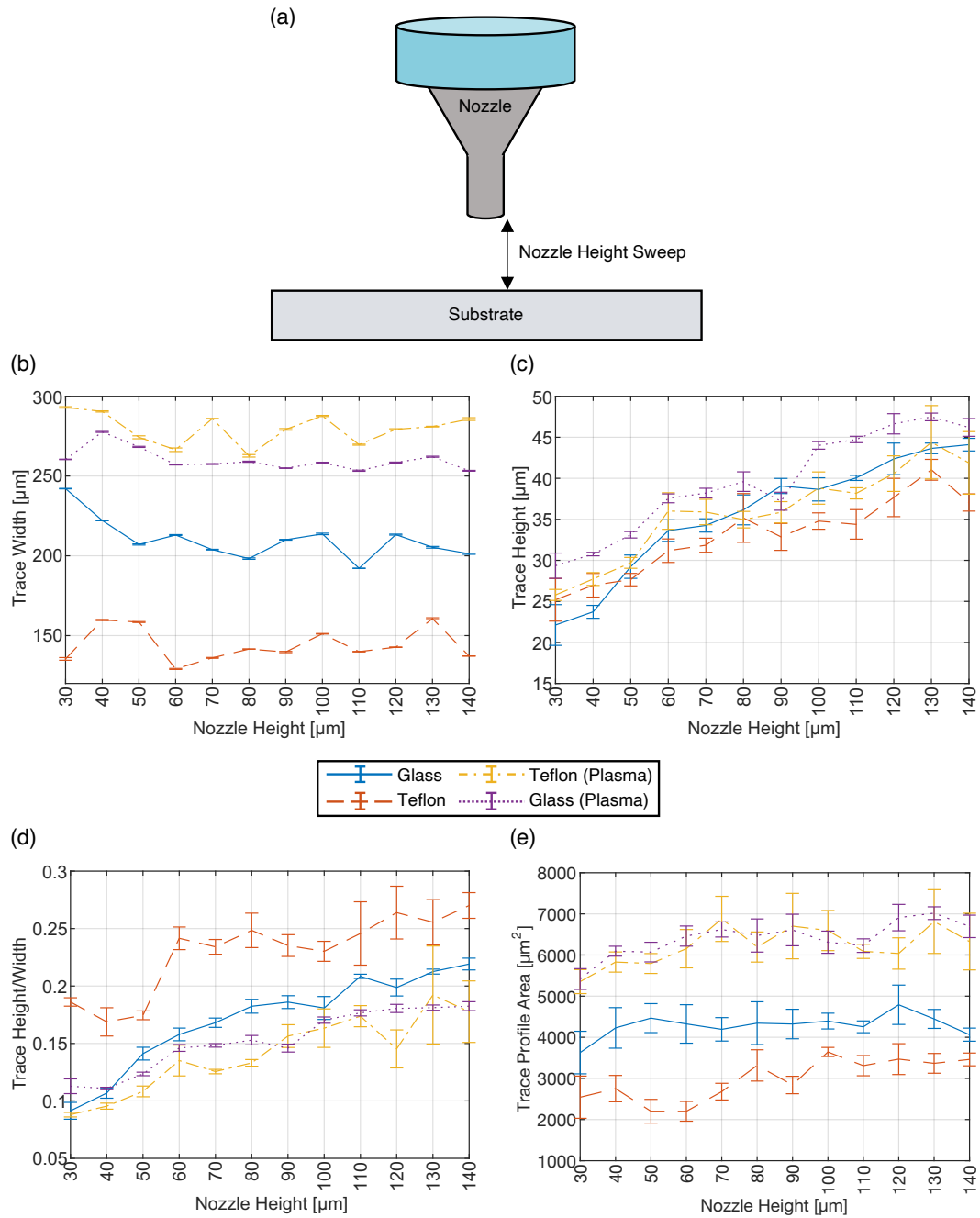


Figure 3-10. Nozzle height sweep printing on the four surfaces using NovaCentrix Metalon HPS-FG77. a)

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.

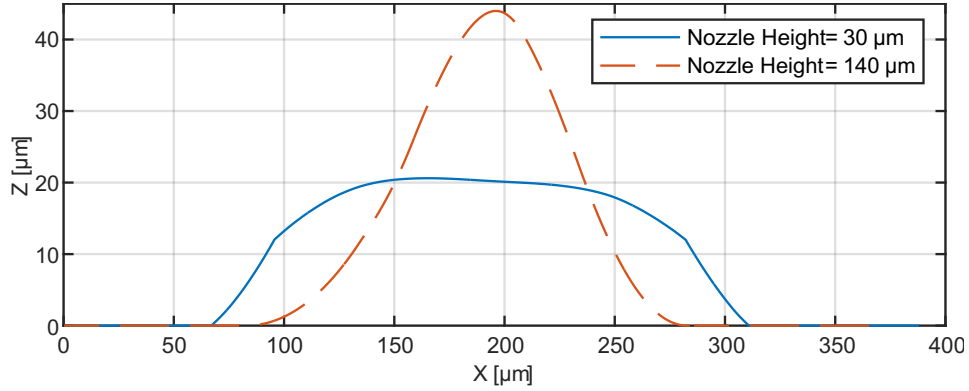


Figure 3-11. Profiles of traces printed using nozzle heights 30 μm and 140 μm showing a triangular profile with higher aspect ratio for larger nozzle height even though the cross-sectional profile area remains the same.

3.4.2. Dispense Pressure

To investigate the impact of dispense pressure, illustrated in Figure 3-12 (a), on the printing process, this parameter was varied within the range of 300 to 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 Appendix B in Figure B-2. 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 3-12. 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 Appendix B in Figure B-3.

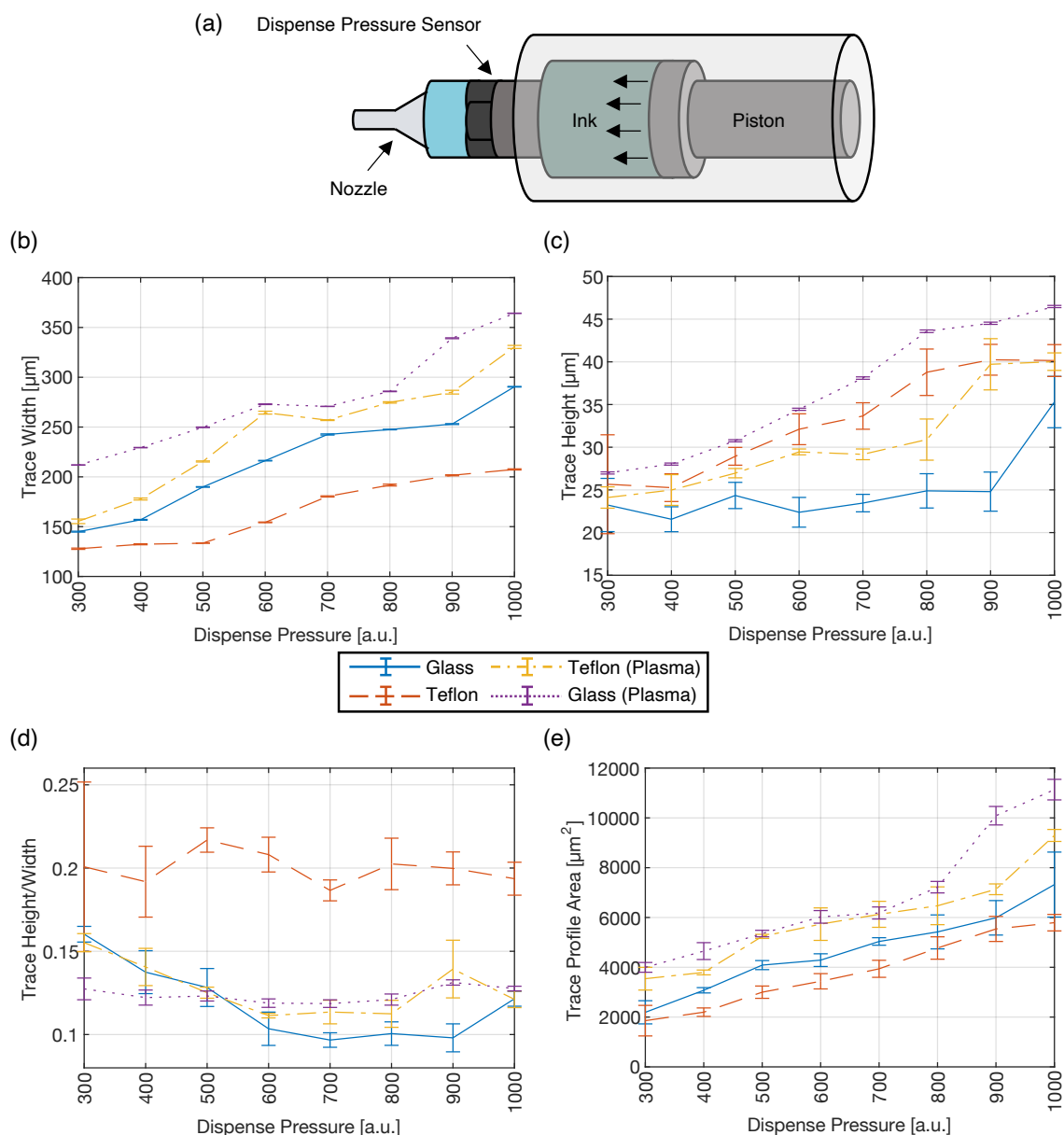


Figure 3-12. Dispense pressure sweep of printing on four surfaces using NovaCentrix Metalon HPS-FG77. a) An illustration showing the piston that applies pressure on the ink cartridge and the pressure sensor used to measure the dispense pressure. The effect of dispense pressure on b) trace width, c) trace 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.

3.4.3. Print Speed

Finally, the effect of print speed, illustrated in Figure 3-13 (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 mm/min to 1200 mm/min, 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 3-13 (b) and (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 3-13 (d). 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 Appendix B in Figure B-4.

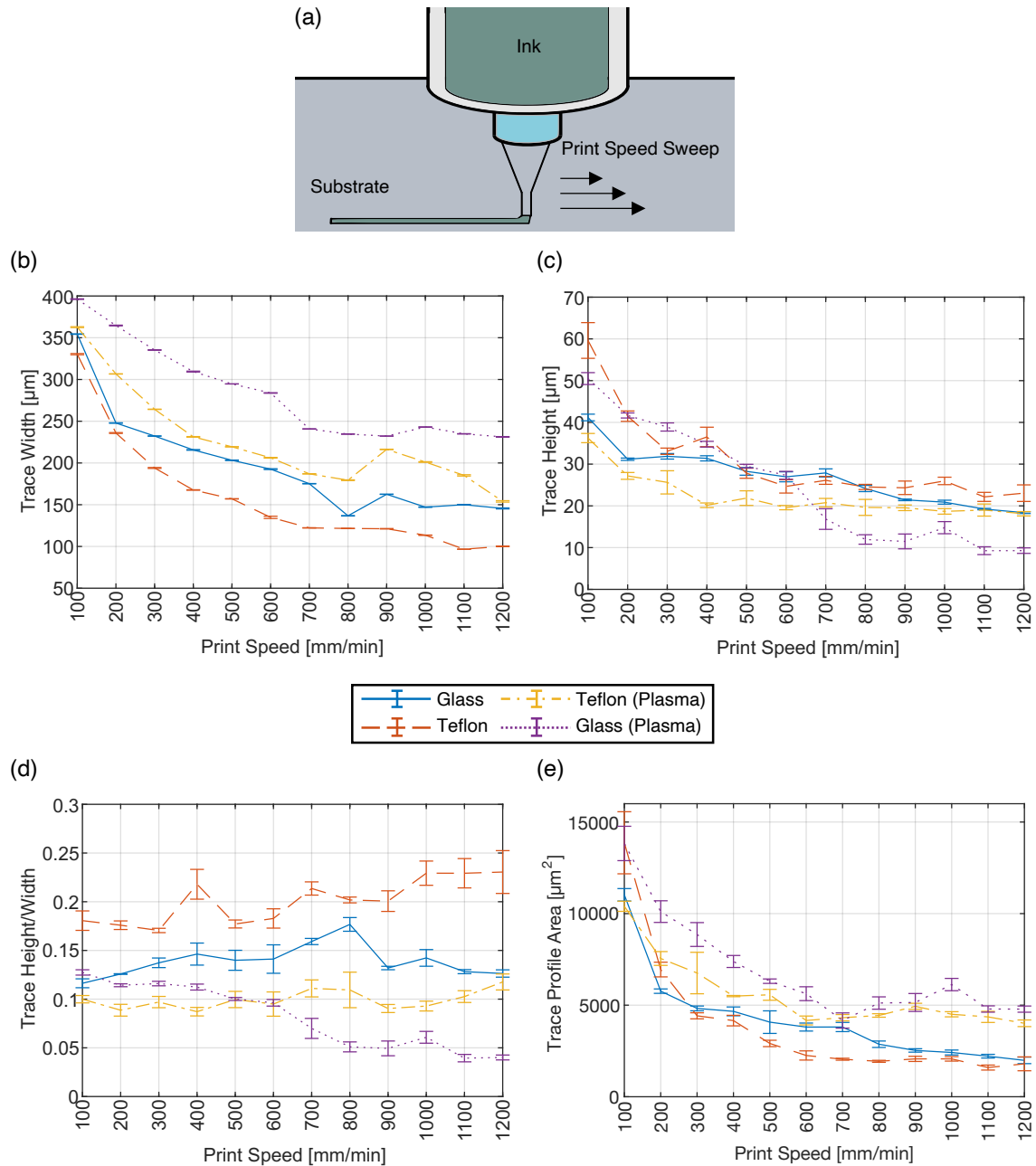


Figure 3-13. Print speed sweep on the four surfaces using NovaCentrix Metalon HPS-FG77. a) An illustration showing the print speed, which is the nozzle movement speed during printing. The effect of print speed on b) trace width, c) trace height, d) trace height-to-width ratio, e) trace cross-sectional 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.

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.

3.5. 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. 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 3-14 (a) 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 pre-curing 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.

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 decreased to a greater extent after the curing process, as demonstrated in Figure 3-14 (b).

Figure 3-14 (c) 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.[49]

Figure 3-14 (d) 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 Figure 3-14 (e). The profiles of lines before curing (wet lines) and after curing (dry lines) printed on both glass and Teflon are shown in Figure 3-15. Representative images of these lines are shown in Figure 3-16 (a, b, c, d).

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

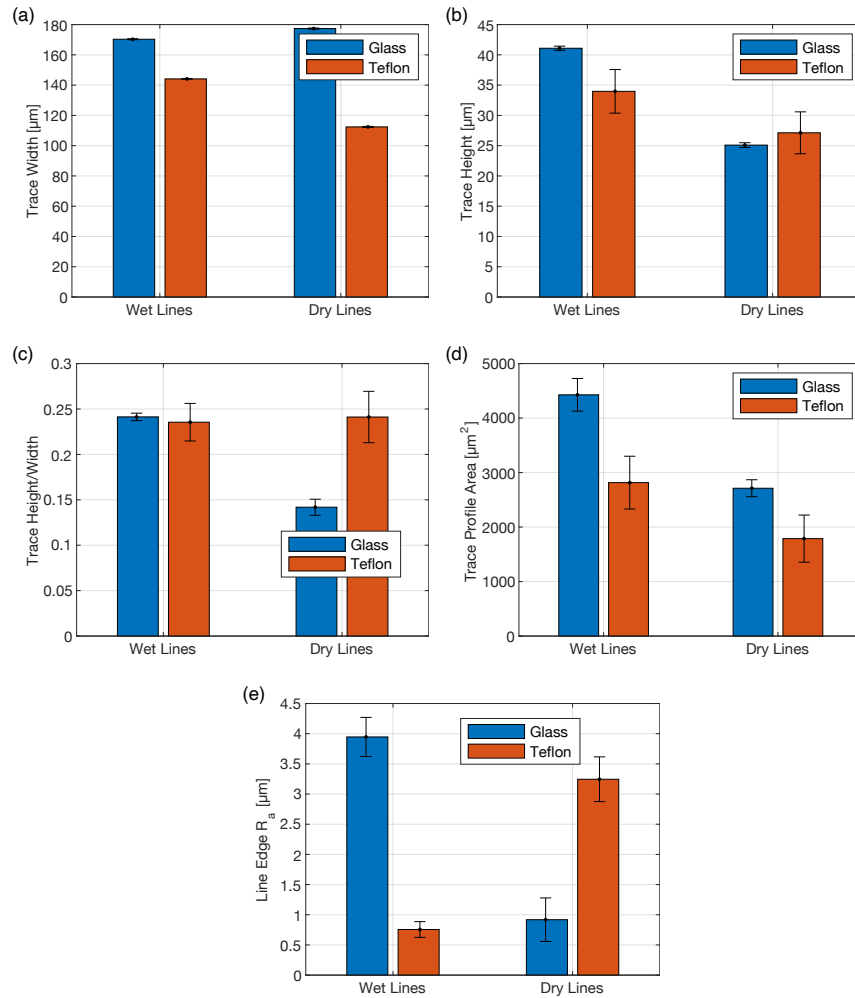


Figure 3-14. Comparison of NovaCentrix HPS-FG77 printed on glass and Teflon using reference parameters before drying (wet lines) and after drying (dry lines) a) trace width, b) trace height, c) trace height-to-width ratio, d) trace cross-sectional profile area, e) trace edge roughness (R_a). Each data 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.

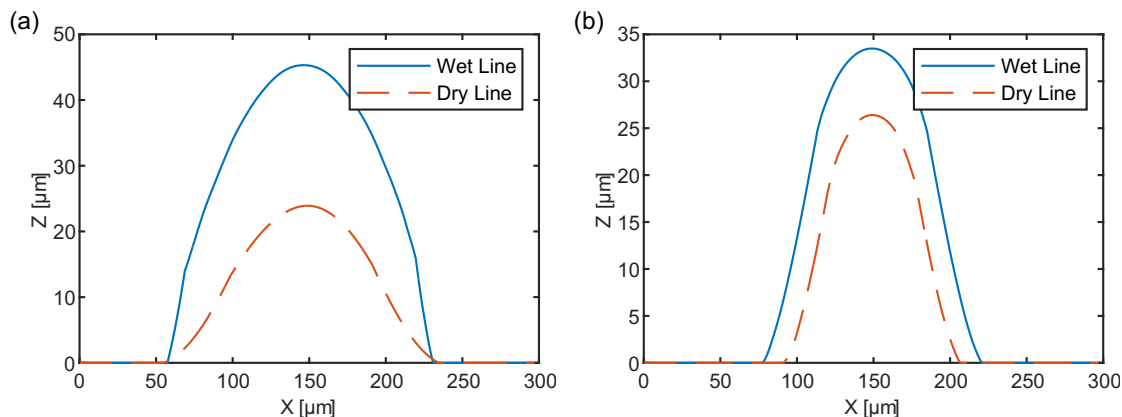


Figure 3-15. Profiles of lines before curing (wet lines) and after curing (dry lines) printed on different substrates: a) Glass; b) Teflon, showing shrinking on Teflon due to low wettability, while glass lines retain their width but decrease in height after curing.

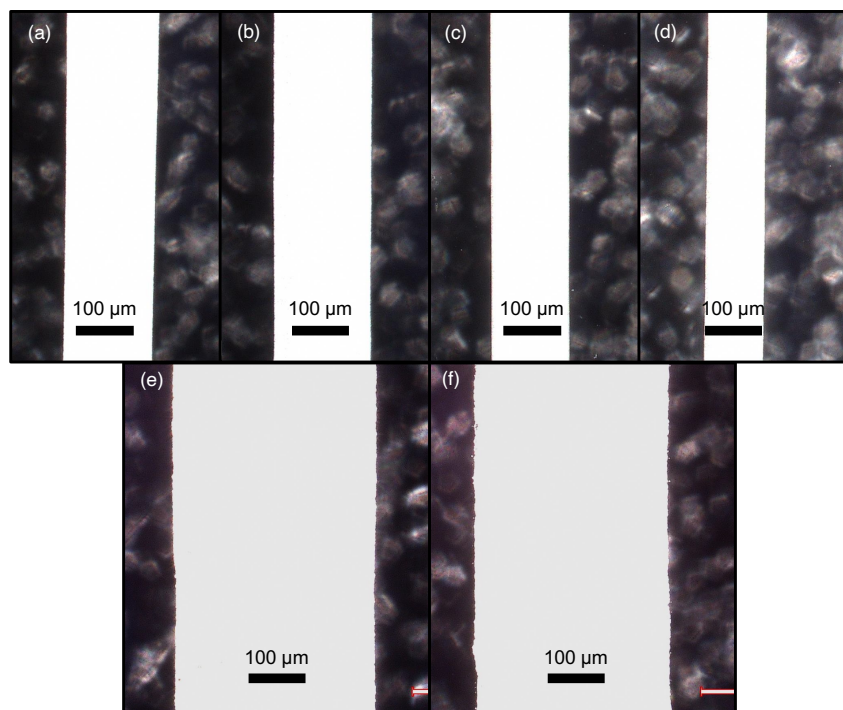


Figure 3-16. High-brightness optical micrographs of wet and dry traces printed using the reference parameters. a) NovaCentrix HPS-FG77 on glass before curing (wet), b) NovaCentrix HPS-FG77 on glass after curing (dry), c) NovaCentrix HPS-FG77 on Teflon before curing (wet), d) NovaCentrix HPS-FG77 on Teflon after curing (dry), e) Creative Materials 120-07 (LPS) on glass before curing (wet), f) Creative Materials 120-07 (LPS) on glass after curing (dry).

3.6. 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 3-17 (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 3-17 (d), 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 minutes. This is not enough time for these high-viscosity inks to spread or shrink, i.e., they are pinned on glass. Any changes in the measured linewidth are within the experimental error. After the curing process, the NovaCentrix HPS-FG77, trace height reduces by ~40% while 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 3-17 (c, d). Representative images of these lines are shown in Figure 3-16 (c, d, e, f).

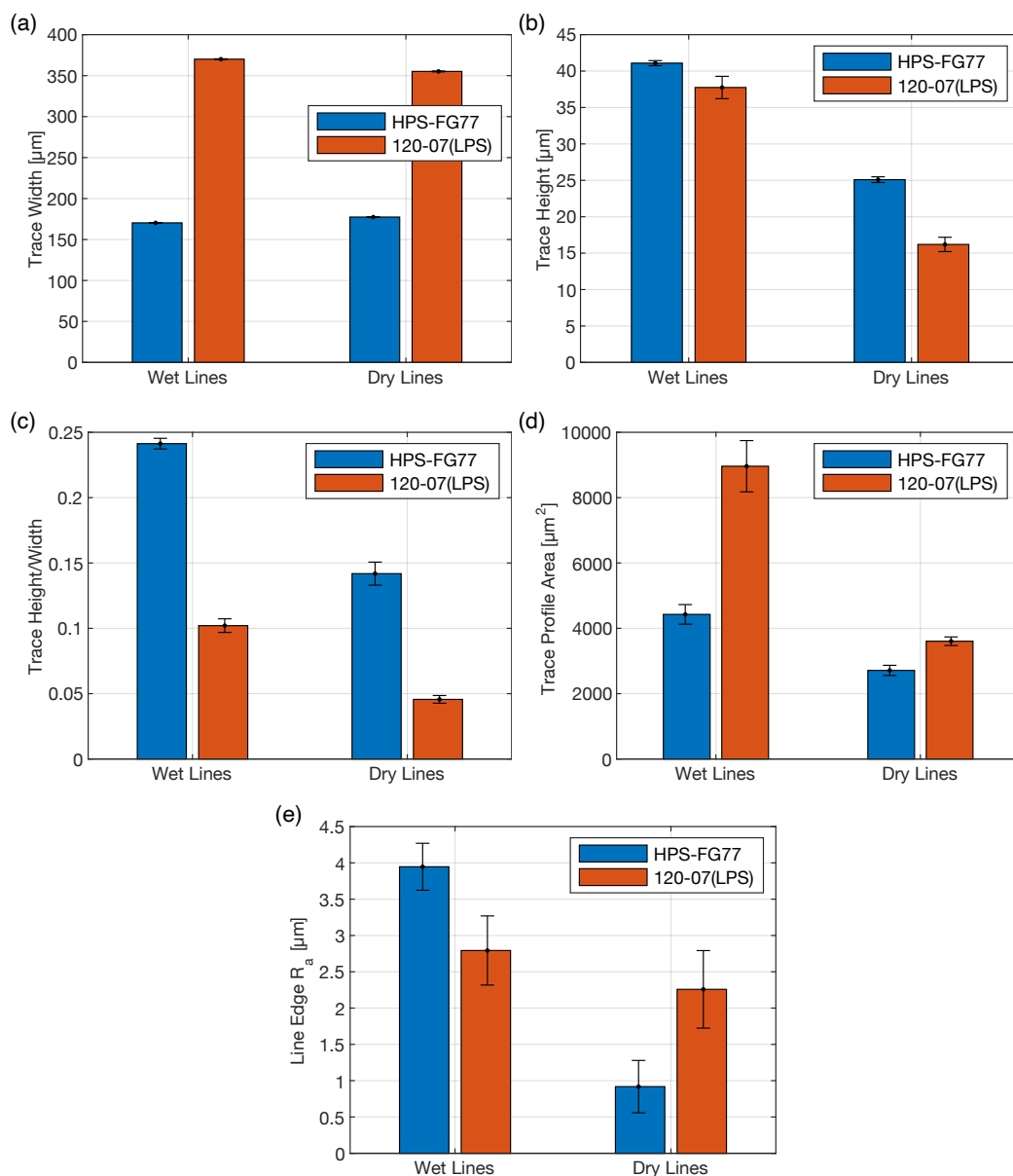


Figure 3-17. Comparison of two inks, NovaCentrix HPS-FG77 and Creative Materials 120-07(LPS), printed on glass using reference parameters before drying (wet lines) and after drying (dry lines) a) trace width, b) trace height, c) trace height-to-width ratio, d) trace cross-sectional profile area, e) trace edge roughness (R_a). 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 greater cross-sectional profile area due to its lower viscosity, with both inks reducing in height and cross-sectional profile area after curing.

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 3-18.

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 minutes), 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 3-18 (a). 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 trace heights for both inks, as depicted in Figure 3-18 (b, 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 3-18 (d), owing to its higher viscosity. This higher viscosity allows NovaCentrix 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 3-18 (e). Representative images of the lines printed using Creative Materials 120-07 (LPS) are shown in Figure 3-19.

In summary, 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 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.

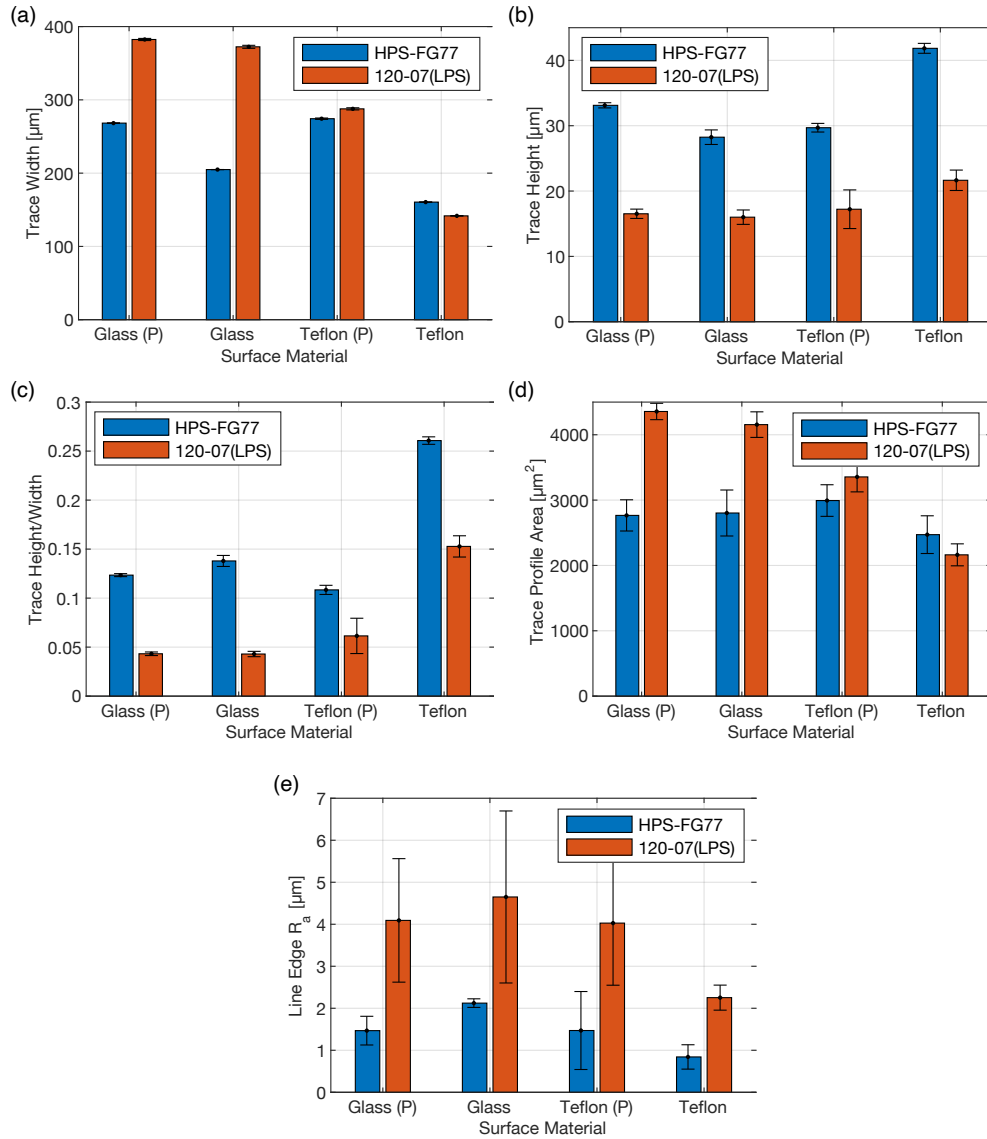


Figure 3-18. Comparison of two inks, NovaCentrix HPS-FG77 and Creative Materials 120-07(LPS), printed on the four surfaces, glass, Teflon, plasma-treated glass (Glass (P)) and plasma-treated Teflon (Teflon (P)), using reference parameters a) trace width, b) trace height, c) trace height-to-width ratio, d) trace cross-sectional profile area, e) trace edge roughness (R_a). 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.

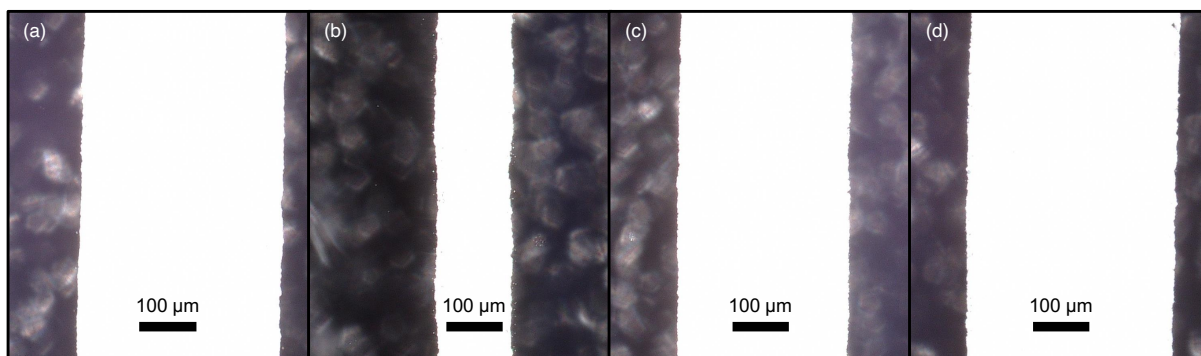


Figure 3-19. High-brightness optical micrographs of cured traces printed using Creative Materials 120-07 (LPS) and the reference parameters on a) glass, b) Teflon, c) plasma-treated Teflon, d) plasma-treated glass.

3.7. 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, i.e., 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 3-20, trace widths show a maximum of 3% variation from sample to sample and a maximum of 0.5% variation within the same sample, i.e., 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 paper. Representative images of these lines are shown in Figure 3-21.

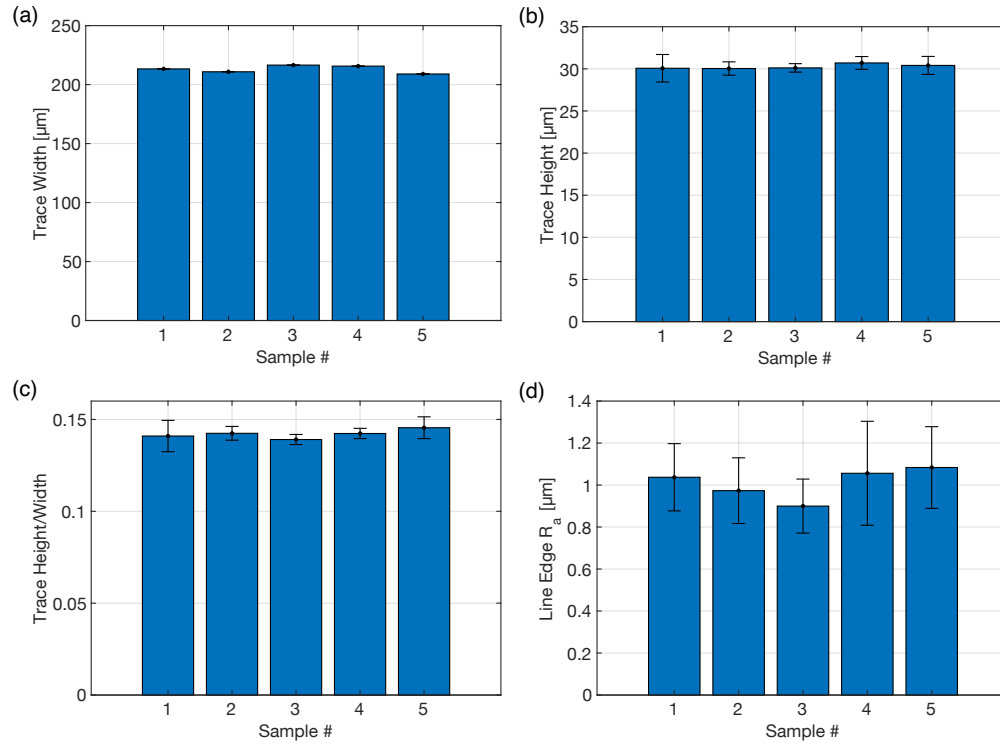


Figure 3-20. Sample to sample variation of NovaCentrix HPS-FG77 printed on glass using reference parameters. Evaluation in terms of a) trace width, b) trace height, c) trace height-to-width ratio, d) trace edge roughness (R_a). Each data point with error bars is the mean and standard deviation of measuring 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 variations do not affect data integrity.

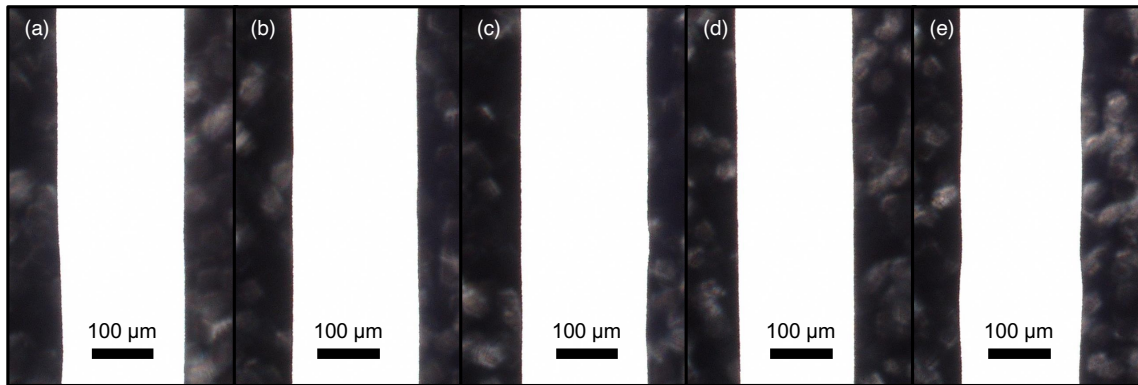


Figure 3-21. High-brightness optical micrographs of traces printed using NovaCentrix HPS-FG77 and the reference parameters on five different glass samples. a) Sample #1, b) sample #2, c) sample #3, d) sample #4, e) sample #5.

3.8. 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.

3.8.1. 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.

3.8.2. 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.

3.8.3. 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.

3.9. 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. 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. 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. This 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.

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 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.

Chapter 4. Printed Organic Electrochemical Transistors (OECTs)

A section of this chapter has been submitted for publication as: Mohamad Kannan Idris, Saumik Dey Shovan, Gerd Grau, " Embedding Organic Electrochemical Transistors into 3D Printed Objects."

4.1. Introduction

Building on the work in Chapter 3, which explored the dispense printing of silver electrodes on hydrophilic and hydrophobic substrates, this chapter focuses on the integration of these printed electrodes into organic electrochemical transistors (OECTs). The findings from the previous chapter provide insights into how printing parameters and substrate properties influence electrode morphology and electrical performance, which is critical for ensuring reliable OECT fabrication.

OECTs have garnered considerable interest in recent years due to their exceptional ability to operate in aqueous environments and their compatibility with low-voltage systems. Unlike traditional field-effect transistors, OECTs modulate electronic conductivity in an organic semiconductor by leveraging ionic exchange with an electrolyte.[163,165,168] This unique mechanism not only enhances their sensitivity to ionic and biomolecular interactions but also makes them a promising candidate for applications in biosensing, neuromorphic computing, and wearable electronics. These attributes, combined with the ability to function at low power, position OECTs as a transformative technology in bioelectronics and diagnostics.[47,162]

A critical parameter defining OECT performance is transconductance (g_m), which quantifies the amplification capability of the device. High transconductance is essential for achieving precise signal detection and amplification, particularly in applications requiring accurate responses to ionic changes.[160,161] However, achieving high g_m in a scalable and cost-effective manner remains a significant challenge. The performance of OECTs is often constrained by the fabrication techniques employed for their electrodes and channels. Conventional methods, such as e-beam evaporation and lift-off processes, yield thin electrodes with high resistance, limiting the current-handling capacity and overall device efficiency. These limitations are further exacerbated in applications requiring long trace electrodes, where resistance becomes a critical bottleneck.[89,157,158]

Dispense printing has emerged as a promising alternative to traditional fabrication methods, offering the ability to deposit high-viscosity inks that form thick, low-resistance traces. While this method sacrifices

lateral resolution, it compensates by achieving low sheet resistance and high aspect ratios, both of which are vital for OECTs designed to operate in high-current, low-voltage regimes. The use of silver flake inks in dispense printing further enhances electrode performance by providing excellent conductivity and mechanical flexibility.[95,132,196] Inkjet printing complements this approach by offering precise control over the deposition of the organic semiconductor channel, ensuring uniform thickness and optimal device geometry.[7,47,63]

This chapter introduces a hybrid fabrication approach that integrates dispense printing for the source and drain electrodes with inkjet printing for the PEDOT:PSS channel. This method addresses the limitations of traditional electrode fabrication by combining the strengths of both techniques. Disperse printing enables the creation of thick, low-resistance electrodes, while inkjet printing ensures precision in channel patterning and morphology. This synergy not only enhances the electrical properties of the OECTs but also provides a scalable and fully additive manufacturing solution suitable for advanced bioelectronic applications.

The significance of this work lies in its ability to achieve transconductance values significantly higher than those reported in prior studies using traditional fabrication techniques. For instance, the average g_m of 98.2 mS achieved in this study surpasses the 30.7 mS reported for previous dispense-printed devices and the 2.2 mS reported for evaporated electrodes.[92,161,176] This remarkable improvement underscores the potential of hybrid printing methods to redefine the performance benchmarks for OECTs. Furthermore, the integration of these printing techniques simplifies the fabrication process, reducing dependency on cleanroom environments and expensive equipment, thereby broadening the accessibility of OECT technology.

In addition to its technical advantages, this approach aligns with the growing demand for sustainable and scalable electronics.[197] The fully additive nature of the process minimizes material waste and enables the use of biocompatible materials, such as PEDOT:PSS and silver inks, which are essential for wearable and implantable applications.[5,6] By addressing the challenges of electrode resistance and channel uniformity, this work establishes a foundation for the development of next-generation OECTs with enhanced performance and broader applicability.

4.2. Materials

The substrates used for the OECTs were borosilicate glass slides obtained from Ted Pella. These substrates provide a stable and inert surface ideal for the deposition of electronic materials. The electrodes for the OECTs were fabricated using silver flake ink (Creative Materials 120-7 LPS).

For the semiconductor channel of the OECTs, the conductive polymer poly(3,4-ethylenedi-oxythiophene) polystyrene sulfonate (PEDOT:PSS) was utilized. The base material used was a 1.3 wt.% PEDOT:PSS aqueous dispersion (Clevios PH 1000, Heraeus), which was modified to enhance its printing and electrical properties. To improve the morphology and inkjet printing capability of the PEDOT:PSS, 6 wt.% ethylene glycol (EG, Sigma Aldrich) and 0.1 wt.% dodecyl benzene sulfonic acid (DBSA) were added. These additives help in optimizing the fluid dynamics of the ink during the printing process and enhance the electrical characteristics of the printed films. Additionally, to ensure the stability of the PEDOT:PSS films in aqueous environments, 1 wt.% (3-glycidyloxypropyl) trimethoxysilane (GOPS) was incorporated to cross-link the polymer, rendering it insoluble in water.

4.3. Device Fabrication

The glass substrates were sonicated in isopropanol, acetone, and deionized (DI) water successively, each for 10 minutes, and then dried with an air gun. The electrodes were dispense printed using a NOVA printer (Voltera, Waterloo, Canada) equipped with 100 μm diameter nozzles (Subrex, Carlsbad, United States). The key printing parameters, including nozzle height, dispense pressure, printing speed, etc., were crucial for affecting line printing and are detailed in Table 4-1. These parameters were studied in depth in the previous chapter.[95] The ink preheating temperature was set just above the lowest temperature above the heat output of the dispensing tool's electronics, ensuring a stable temperature during printing. After the electrodes were printed, they were cured at 100°C for 30 minutes on a hot plate.

After the semiconductor ink was formulated, it was filtered using a 0.1 μm nylon filter to remove any agglomerated particles. Then, it was patterned into a rectangular shape on the source, drain, and transistor channel areas using a custom piezoelectric drop-on-demand (DOD) inkjet printer. The movement of the printer stage was controlled by a LabVIEW program (National Instruments, Austin, TX) to ensure accurate placement relative to the printhead. The inkjet printer utilized a nozzle (MJ-ATP-0160-8MX, Microfab Technologies, Inc., Plano, TX) with a 60 μm orifice. The settings for printing maintained a drop spacing of

65 μm along each line, with a gap of 30 μm between lines in the rectangular pattern. Following the printing process, the ink pattern was cured by heating at 120°C on a hot plate for 20 minutes.

Finally, 50 μl of a 100 mM solution of NaCl in water was deposited on the semiconductor and gate electrode using drop-casting. Sodium chloride is commonly selected for use in organic electrochemical transistors because it offers high ionic conductivity, stability, and is cost-effective. Furthermore, it helps to stabilize the gate potential during transistor operation, enhancing signal amplification and ensuring consistent performance.

Five different transistor sizes were printed maintaining the channel width of $5050 \pm 15 \mu\text{m}$ and varying the channel length. The channel lengths used are $113 \pm 7 \mu\text{m}$, $205 \pm 16 \mu\text{m}$, $309 \pm 10 \mu\text{m}$, $437 \pm 12 \mu\text{m}$ and $526 \pm 15 \mu\text{m}$. For each channel length, a total of ten transistors were printed and characterized to produce the electrical characteristics reported below. The complete structure of the OECT is illustrated in Figure 4-1.

Table 4-1. Dispense printing parameters

Printing parameter	Value
Nozzle Orifice Diameter	100 [μm]
Nozzle Height	50 [μm]
Dispense Pressure	600 [a.u.]
Printing Speed	500 [mm/min]
Relief Pressure	80 [a.u.]
Dispense Threshold	100 %
Relief Threshold	0 %
Ink Cartridge Preheat Temperature	35 °C

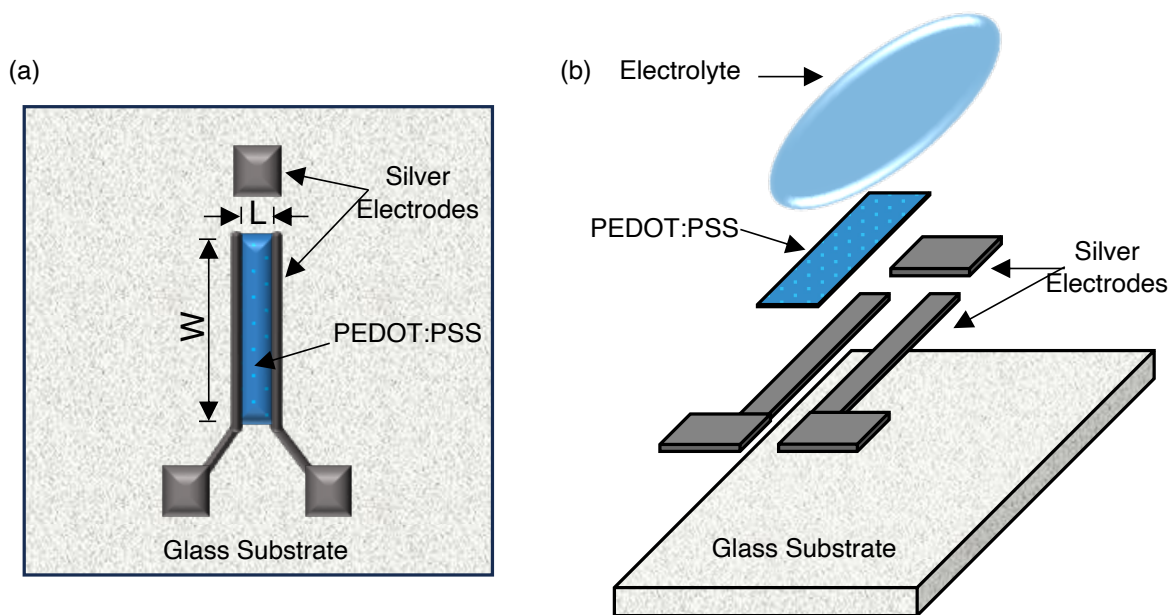


Figure 4-1. The structure of the OEET. a) top view, showing the printed design and channel dimensions. b) The layers of the printed OEET are glass for the substrate, dispense printed electrodes, inkjet printed OSC, and drop-casted electrolyte liquid.

4.4. Characterization

The thickness of the printed organic semiconductor was measured using a stylus profilometer (KLA-Tencor Alpha-Step D600) in the middle of the transistor along the width of the channel. The dimensions of the transistors and electrodes were measured using an optical microscope (Keyence VHX-970F). All electrical measurements were conducted using a probe station with a parameter analyzer (Keithley 4200A).

4.5. Results and Discussion

The printing process was designed for channel lengths of 200, 300, 400, 500, and 600 μm . Due to ink spreading on the substrate surface, the actual channel lengths measured were $113 \pm 7 \mu\text{m}$, $205 \pm 16 \mu\text{m}$, $309 \pm 10 \mu\text{m}$, $437 \pm 12 \mu\text{m}$, and $526 \pm 15 \mu\text{m}$. The channel width was designed to be 5000 μm , and the resulting measured width was $5050 \pm 15 \mu\text{m}$. The ink behavior during printing and on glass after curing has been studied in depth in the previous chapter.[95] The dispense printed electrodes have an average thickness of

$35 \pm 1.7 \mu\text{m}$ and an average width of $250 \pm 0.4 \mu\text{m}$ making the thickness-to-width ratio 0.14 for all devices, as shown in Figure 4-2 (a). This electrode aspect ratio is significantly larger than inkjet printed or evaporated electrodes,[47,90,160] which results in a low sheet resistance of our dispense printed electrodes. For individual devices, the measured thickness of the semiconductor layer is highly uniform. The average thickness is $1.87 \mu\text{m}$ with a variation of $\pm 0.12 \mu\text{m}$ over the width of the device, as shown in Figure 4-2 (b). Between multiple devices, the thickness varies slightly, with a device-to-device variation of $\pm 0.27 \mu\text{m}$.

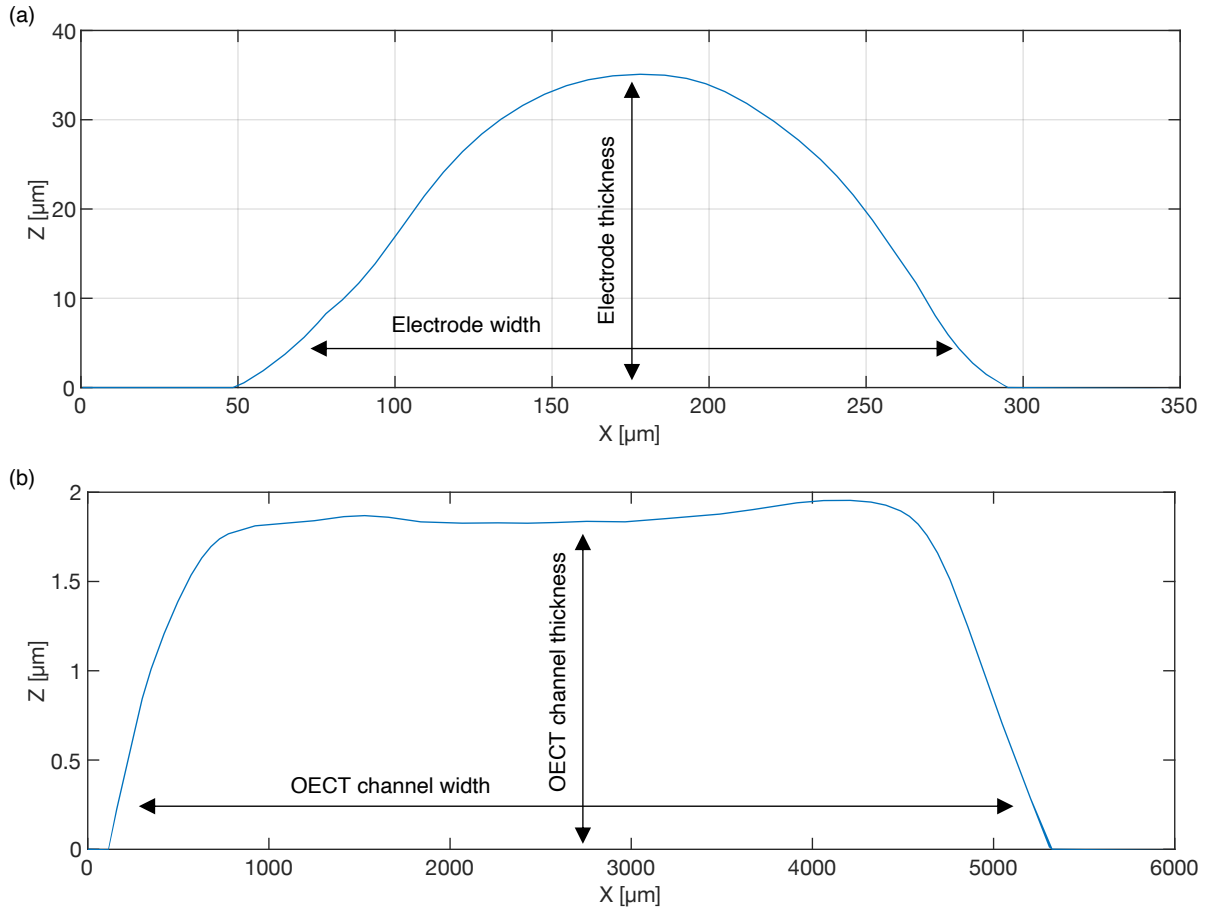


Figure 4-2. Profiles of a) the dispense printed electrodes showing the thickness and width of the electrodes; b) the inkjet printed organic semiconductor along the width of the OEET channel

As shown in previous research,[79] the silver sheet resistance is affected by the temperature used for curing. The printed silver electrodes undergo two curing phases, the first time after they are printed at 100°C for 30 minutes and the second time when the printed semiconductor is being cured at 120°C for 20 minutes. Sheet resistance was measured after each curing phase, and the results show that it decreased from $2.4 \pm 0.4 \text{ m}\Omega/\square$ after the first phase to $2.2 \pm 0.4 \text{ m}\Omega/\square$ after the second phase.

The electrical performance of the printed organic electrochemical transistors was characterized under varying gate voltages. Figure 4-3 illustrates the characteristics of a representative transistor with the smallest channel length (113 μm): transfer characteristics, transconductance, and output characteristics. The transfer characteristic curve (Figure 4-3 (a)) displays the drain current (I_D) and gate current (I_G) as a function of gate voltage (V_G). The drain voltage range (V_D) is -1 V. The data indicates a clear p-type behavior of the device, with the drain current decreasing as the gate voltage moves from negative to positive values. This behavior can be attributed to the increasing depletion of charge carriers (holes) in the PEDOT:PSS channel with increasing positive gate voltage. Due to the high current output of these devices, measurements were limited to $V_G = -0.7 \text{ V}$, as exceeding this value would surpass the current limits of our parameter analyzer (100 mA). However, longer channel devices were not subject to this limitation and were measured up to -1 V, with their corresponding plots in Figure 4-4. The transconductance graph (Figure 4-3 (b)) reveals a peak g_m of 103 mS, which marks the efficiency of current modulation. The average transconductance of all ten devices of the same channel length measured is $98.2 \pm 35.3 \text{ mS}$. The threshold voltage (V_{th}), determined by the extrapolation of the tangent from the peak g_m to the x-axis, is identified as 0.39 V. Finally, the output characteristics (Figure 4-3 (c)) demonstrate how the drain current responds to changes in drain voltage under different gate voltages. The device operates in depletion mode, characterized by an increase in current with more negative gate voltages, which is typical for p-type materials.

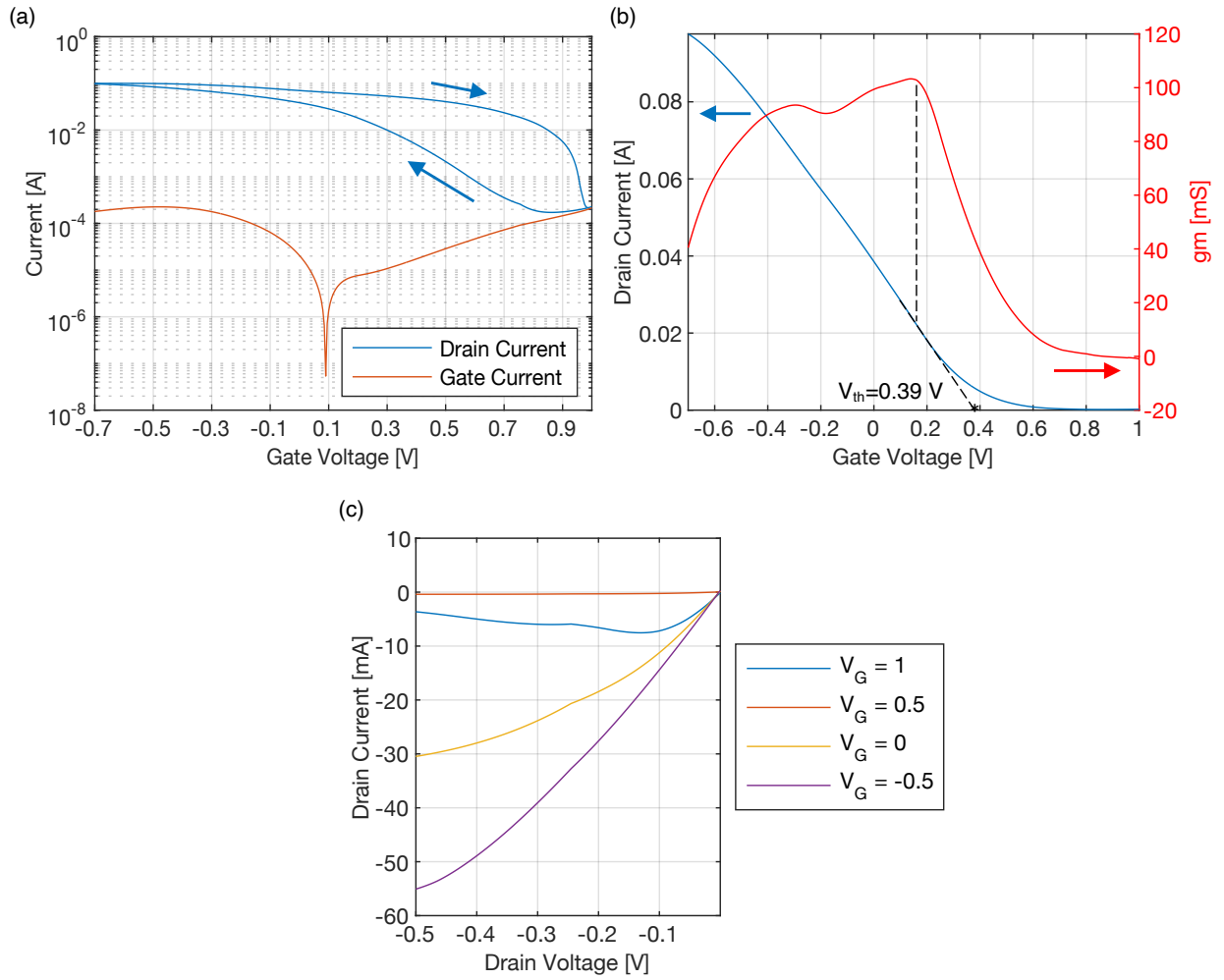


Figure 4-3. Electrical characterization of printed organic electrochemical transistor with smallest channel length ($113 \mu\text{m}$). (a) Transfer characteristics showing the drain and gate currents as a function of gate voltage. The drain voltage (V_D) is -1 V. (b) Transconductance (g_m) and drain current on a linear scale versus gate voltage, highlighting a peak transconductance of 103 mS and a threshold voltage (V_{th}) of 0.39 V. The drain voltage (V_D) is -1 V. (c) Output characteristics illustrating the drain current response to varying drain voltage at different gate voltages.

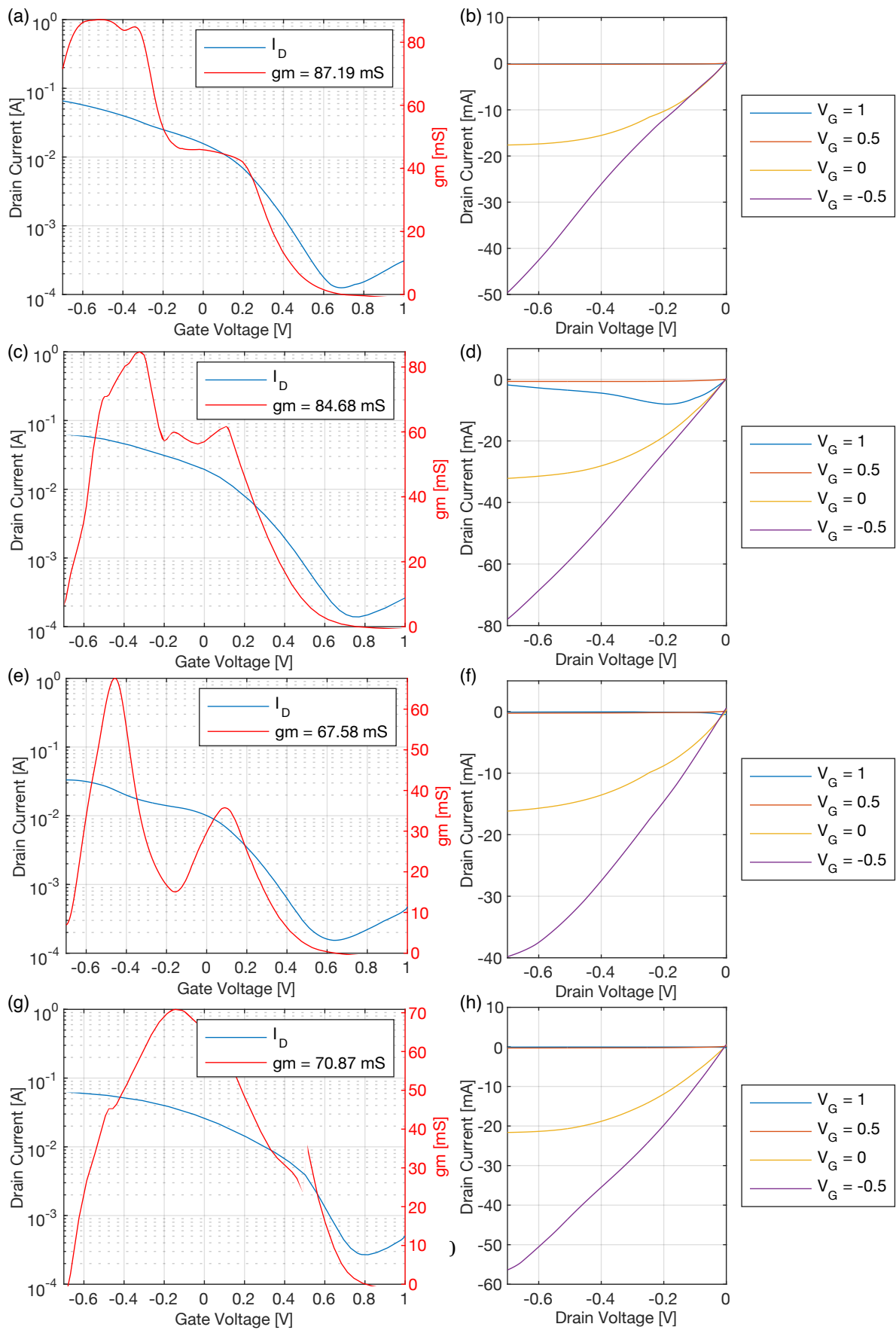


Figure 4-4. Electrical characterization of printed organic electrochemical transistors with varying channel lengths. a) Transfer characteristics (I_D - V_G) for a device with channel length $L=205\ \mu\text{m}$. b) Output characteristics (I_D - V_D) for $L=205\ \mu\text{m}$. c) Transfer characteristics (I_D - V_G) for a device with channel length $L=309\ \mu\text{m}$. d) Output characteristics (I_D - V_D) for $L=309\ \mu\text{m}$. e) Transfer characteristics (I_D - V_G) for a device with channel length $L=437\ \mu\text{m}$. f) Output characteristics (I_D - V_D) for $L=437\ \mu\text{m}$. g) Transfer characteristics (I_D - V_G) for a device with channel length $L=526\ \mu\text{m}$. h) Output characteristics (I_D - V_D) for $L=526\ \mu\text{m}$.

The influence of the channel length on the performance of printed OECTs was systematically investigated, as depicted in Figure 4-5. The results, presented in the form of box plots, analyze three critical parameters: g_m , g_m normalized by channel dimensions (W/L), and the ON/OFF current ratio (I_{ON}/I_{OFF}) across the different channel lengths (113, 205, 309, 437, and 526 μm). Figure 4-5 (a) demonstrates the absolute transconductance values for OECTs with varying channel lengths. The mean transconductance, indicated by red stars in the box plots, shows a trend where g_m generally decreases as the channel length increases. The highest mean transconductance is observed at the shortest channel length (113 μm), as expected. The spread in the data suggests variability in the device fabrication or material consistency, which could influence the electrical properties. Contrary to the absolute transconductance, the normalized transconductance shown in Figure 4-5 (b) exhibits an increasing trend with longer channel lengths. When transconductance is adjusted for the physical dimensions of the channel, longer channels exhibit improved performance relative to their size. Longer channel devices, while showing reduced absolute g_m , achieve higher g_m when normalized by channel geometry (W/L), indicating enhanced performance due to the reduced impact of contact resistance. Figure 4-5 (c) shows the ON/OFF current ratio, a vital measure of the transistor's switching capabilities and power efficiency. Shorter channels exhibit a higher I_{ON} and, as a result, a higher I_{ON}/I_{OFF} ratio, which is advantageous for applications that demand fast switching and low power consumption. These findings illustrate that while shorter channels generally offer superior performance in terms of g_m and I_{ON}/I_{OFF} ratios, the increased normalized transconductance of longer channels suggests an impact of contact resistance.

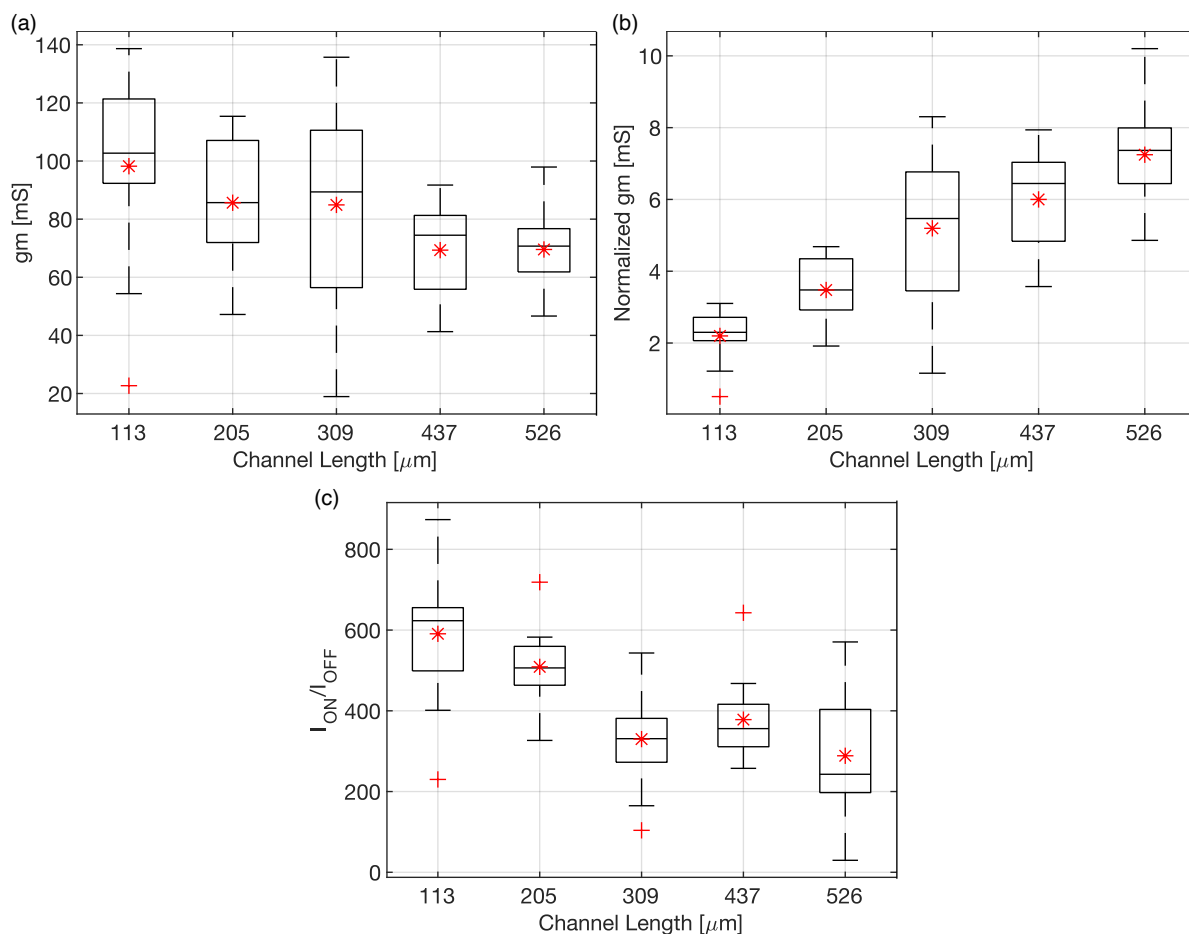


Figure 4-5. Analysis of the influence of channel length on the performance of printed organic electrochemical transistors. (a) Absolute transconductance (g_m) values for OECTs with varying channel lengths, showing a decrease in g_m with increasing channel length. (b) Transconductance normalized by channel dimensions W/L , indicating an increasing trend with longer channel lengths. (c) ON/OFF current ratio (I_{ON}/I_{OFF}) across different channel lengths, with shorter channels exhibiting higher ratios. Red stars denote mean values, highlighting the trend and variability in device performance.

The resistance characteristics of printed organic electrochemical transistors were analyzed using the transmission line method (TLM) to calculate contact resistance at different gate voltages from the variation of total device resistance with channel length.[24] In Figure 4-6, the total resistance of the transistors is plotted against channel length for different gate voltages ($V_G = 0, -0.5$ V) at $V_D = -0.1$ V. Each data point

is the average total resistance for 10 devices of the same channel length. A linear fit was performed on the total resistance versus channel length for all tested gate voltages. By extrapolating these lines to a channel length of 0 μm , the intercepts provide values for the total contact resistance at each gate voltage, which are divided by two to estimate the contact resistance for one contact. The calculated contact resistances multiplied by the channel width are $2.1 \pm 0.76 \Omega\cdot\text{cm}$ and $1.8 \pm 0.05 \Omega\cdot\text{cm}$ for $V_G = 0$ and -0.5 V , respectively. These results indicate no significant difference in contact resistance between the examined gate voltages, and the differences are within the experimental error.

This is consistent with the findings of Marková et al., who systematically studied the effect of contact and serial resistance on the transconductance of OECTs using a similar TLM approach. They showed that parasitic contact resistance significantly reduces the effective channel voltage and transconductance, especially in devices with short channels or highly conductive semiconductors. To mitigate this, they used planar devices with optimized gold contacts and achieved a high transconductance of 108 mS. However, their architecture relied on interdigitated electrodes—effectively five channels in parallel—to reach those values. In contrast, our approach uses thick silver electrodes, which inherently lowers contact resistance due to their large cross-sectional area and low resistivity. This allows us to achieve low-resistance contacts without the need for complex geometries and complex fabrication processes, thereby validating and extending the theoretical framework established by Marková et al. using a fully printed, scalable method.[198]

Unfortunately, most literature sources do not report total and contact resistance for comparison. One exception uses LIG electrodes and reports an average g_m of 2.2 mS and contact resistance values between 40 – 150 $\Omega\cdot\text{cm}$ and total resistance values between 150 – 700 Ω .[176] In comparison, another report deposited gold electrodes using sputtering that produced OECTs with contact resistance values between 10 – 80 $\text{k}\Omega\cdot\text{cm}$ and an average g_m of 1.8 μS .[199]

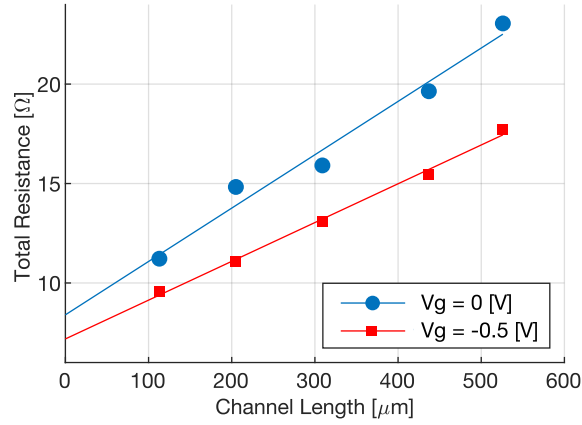


Figure 4-6. Resistance characteristics of printed organic electrochemical transistors using TLM. Total device resistance plotted against channel length for different gate voltages ($V_G = 0, -0.5$ V), showing an increase in resistance with longer channel lengths. Linear fits indicate the trend for each gate voltage.

Each data point is the average total resistance for 10 devices of the same channel length.

As previously mentioned, our device exhibits a high g_m and an excellent current on/off ratio, which can be attributed to the low electrode sheet resistance. This characteristic is crucial for the efficient operation of OECTs. In Table 4-2, we compare our devices to other devices reported in the literature. The devices are chosen according to the following criteria: all devices are OECTs, the semiconductor is pristine PEDOT:PSS without any modifications that increase transconductance, and the values of g_m and I_{ON}/I_{OFF} are reported. Figure 4-7 shows a comparative analysis of g_m of our OECTs against the devices from literature in Table 4-2.

Figure 4-7 (a) shows that our devices achieve a significantly higher g_m compared to other devices. The highest g_m is 108 mS from an interdigitated electrode device using silver plated gold electrodes that were manufactured using physical vapor deposition.[198] This device achieved a high g_m so it was included for comparison; however, it is the only device that was included using the max device g_m (108 mS) and not the average g_m because it was not reported. In comparison, the devices demonstrated in this work achieved a maximum g_m of 133 mS and an average g_m of 98.2 mS. Furthermore, the devices demonstrated in this work achieve the highest g_m for fully printed devices. Other devices utilizing dispense-printed electrodes follow closely, but their g_m values are lower due to thinner electrodes (10 μm) and higher resistance.[161] Devices with LIG electrodes perform well but lag behind dispense-printed ones, partially due to their higher sheet resistance.[176] Devices employing inkjet-printed silver electrodes [88] or evaporated gold [158,160]

cluster in the midrange, reflecting the limitations of these methods in achieving low-resistance electrodes. At the lower end are devices fabricated using materials like carbon, PLA or FTO due to their higher resistivity and sheet resistance. Generally, the graph indicates a trend where lower sheet resistance correlates with higher g_m values. The enhanced g_m can be attributed to multiple characteristics of the electrodes: low resistivity, large thickness, and the combined effect resulting in low sheet resistance. These factors contribute to the low ohmic resistance of the electrodes, which is essential for maintaining efficient charge transport in high-current, low-voltage OECTs. Dispense printing allows for the creation of high-thickness electrodes, enabling long electrode paths suitable for large channel width-to-length (W/L) ratios while preserving low resistance. This ensures that the ohmic resistance of the electrodes remains low, thereby enhancing the overall device performance. In Figure 4-7 (b), g_m is normalized by the width-to-length ratio (W/L) of the channel. Normalizing by W/L allows us to account for the geometric factors that influence the transconductance. Our device still demonstrates a superior normalized g_m compared to many other devices and is on par with the best devices in literature. This indicates that even when accounting for the device dimensions, our OECTs maintain high performance. For further comparison, the previously mentioned interdigitated device has a low normalized g_m due to its relatively high channel width.[198] Figure 4-7 (c) presents g_m normalized by the channel thickness. In this plot, our device achieves one of the highest g_m normalized by channel thicknesses. Figure 4-7 (d) displays g_m as a function of the channel thickness for different devices. Channel thickness is a critical parameter in OECTs as it directly affects the volume in which electronic charge transport occurs. Thicker channels have a larger capacitance, potentially increasing the transconductance. Our device benefits from a precisely controlled channel thickness achieved through inkjet printing. This method allows for thicker and more uniform films compared to other methods, such as spin coating, which may struggle to produce uniform films at larger thicknesses. The data shows that our device achieves a large channel thickness and high g_m compared to others, indicating that our process successfully produces an active layer with a good thickness for device operation. Figure 4-7 (e) shows the current on/off ratio as a function of sheet resistance for various devices. Our device exhibits a high I_{ON}/I_{OFF} ratio, mainly due to the high I_{ON} , compared to other devices, indicating superior switching performance. The superior performance of the devices reported here compared to others in the literature is primarily due to the low sheet resistance of the electrodes. The large electrode thickness ensures low resistance while maintaining mechanical flexibility of the electrodes enabled by the stretchable silver ink,[79,107,109] allowing our device to achieve high on/off ratios, which are crucial for many applications.

Table 4-2 (Part 1). OEETs in the literature using pristine PEDOT:PSS and the transistors that are presented in this work with five different channel lengths.

Electrode Material	Electrode Fabrication Method	Channel Fabrication Method	OSC Thickness [μm]	Transistor Channel Width [μm]	Transistor Channel Length [μm]	Electrode Thickness [μm]	R_s [$\Omega/\square$]	I_{ON} [mA]	I_{OFF} [mA]	I_{ON}/I_{OFF}	g_m [mS]	Volatges [V]	Ref
Au	E-beam evaporator	Spin coating	0.1	5	10	0.1	0.244 ^(a)	0.45	0.05	9	0.98	$V_d = -0.6\text{V} / V_g = 0.6\text{V}$ to 0V	[158]
Au	Lift-off process	Spin coating	0.1	5	5	0.1	0.244 ^(a)	4	0.5	8	1.2	$V_d = -0.6\text{V} / V_g = 5\text{ to }0\text{V}$	[160]
Ag	Inkjet printing	Inkjet printing	1	1000	3000	0.2	0.5	0.46	0.02	23	1.2	$V_d = -0.4\text{V} / V_g = 1.6\text{V}$ to 0V	[82]
Fluorine doped tin oxide (FTO)	Chemical etching	Spin coating	0.35	-	-	-	7	0.25	0.025	10	0.18	$V_d = -0.6\text{V} / V_g = 2.5\text{V}$ to 0V	[174]
Carbon-filled polylactide (c-PLA)	3D printing	Inkjet printing	2.15	10000	3000	60	3000	0.125	0.05	2.5	0.25	$V_d = -0.6\text{V} / V_g = 0.6\text{V}$ to 0V	[172]
LIG	Lasering process	Inkjet printing	1.8	5000	190	-	10.86	2.564	0.035	73.26	2.2	$V_d = -1\text{V} / V_g = 1\text{V}$ to -1V	[176]

Table 4-2 (Part 2). OECTs in the literature using pristine PEDOT:PSS and the transistors that are presented in this work with five different channel lengths.

Electrode Material	Electrode Fabrication Method	Channel Fabrication Method	OSC Thickness [μm]	Transistor Channel Width [μm]	Transistor Channel Length [μm]	Electrode Thickness [μm]	R_s [$\Omega/\square$]	I_{ON} [mA]	I_{OFF} [mA]	I_{ON}/I_{OFF}	g_m [mS]	Voltages [V]	Ref
Au	Lift-off process	Spin coating	0.06	20000	20	0.1	0.244 ^{a)}	1.3	0.05	26	0.079	Vd = - 0.5V / Vg = - 0.5 to 1V	[90]
Au	Lift-off process	Spin coating	0.2	200	5	0.1	0.244 ^{a)}	0.6	0.1	6	0.57	Vd = - 0.2V / Vg = 0 to 0.8V	[89]
Ag plated Au	Physical Vapor Deposition	Spin coating	0.3	25000	25	0.2	0.102	-	-	-	108	Vd = - 1V / Vg = 0 to 1V	[198]
Carbon	Dispense Printing	Felt-tip Capillary Printing	0.1	1000	400	-	30	-	-	1000	0.007	Vd = - 0.2V / Vg = 0.6 to -0.2V	[162]
Ag	Dispense Printing	Dispense Printing	2.6	912	694	10	0.01	4	0.007	570	11.7	Vd = - 0.2V / Vg = 0.6 to -0.2V	[161]
Ag	Dispense Printing	Dispense Printing	7.5	178	118	10	0.055	11	0.009	1130	30.7	Vd = - 0.2V / Vg = 0.6 to -0.2V	[161]

Table 4-2 (Part 3). OECTs in the literature using pristine PEDOT:PSS and the transistors that are presented in this work with five different channel lengths.

Electrode Material	Electrode Fabrication Method	Channel Fabrication Method	OSC Thickness [μm]	Transistor Channel Width [μm]	Transistor Channel Length [μm]	Electrode Thickness [μm]	R_s [$\Omega/\square$]	I_{ON} [mA]	I_{OFF} [mA]	I_{ON}/I_{OFF}	g_m [mS]	Voltages [V]	Ref
Ag	Dispense Printing	Inkjet printing	1.86	5050	113	35	0.0022	84.6	0.14	604.29	98.2	$V_d = -1V$ $/ V_g = 1$ to $-0.7V$	This work
Ag	Dispense Printing	Inkjet printing	1.86	5050	205	35	0.0022	71.1	0.14	507.86	85.6	$V_d = -1V$ $/ V_g = 1$ to $-0.7V$	This work
Ag	Dispense Printing	Inkjet printing	1.86	5050	309	35	0.0022	58.6	0.16	366.25	84.9	$V_d = -1V$ $/ V_g = 1$ to $-0.7V$	This work
Ag	Dispense Printing	Inkjet printing	1.86	5050	437	35	0.0022	63.4	0.16	396.25	69.3	$V_d = -1V$ $/ V_g = 1$ to $-0.7V$	This work
Ag	Dispense Printing	Inkjet printing	1.86	5050	526	35	0.0022	53.5	0.18	297.22	69.6	$V_d = -1V$ $/ V_g = 1$ to $-0.7V$	This work

^{a)} These values were calculated based on the bulk resistivity of the material and the physical dimensions provided in the referenced manuscript

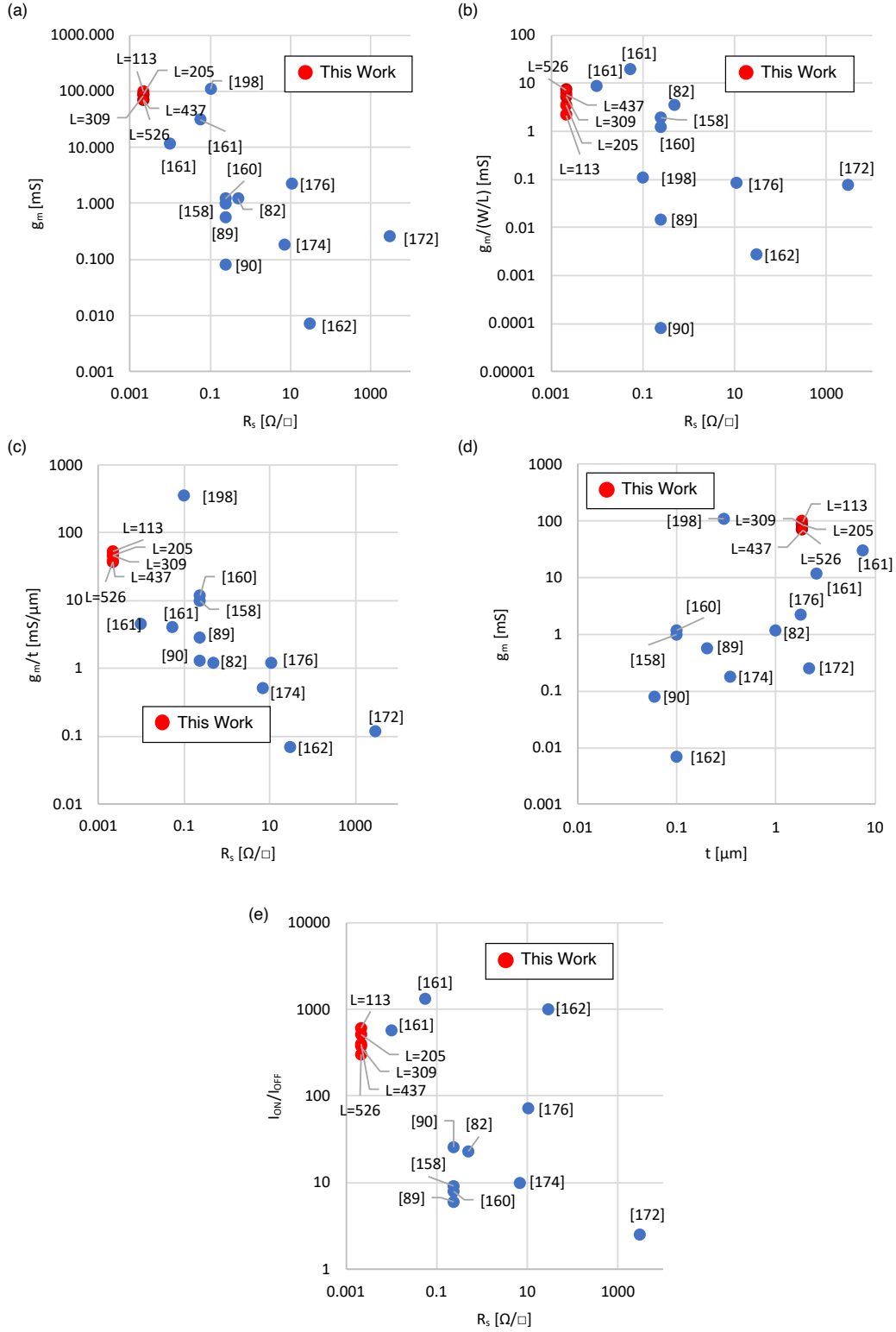


Figure 4-7. Comparative analysis of transconductance (g_m) and I_{ON}/I_{OFF} of printed organic electrochemical transistors against other reported devices. [82,89,90,158,160–162,172,175,176,198] (a) Transconductance (g_m) versus sheet resistance (R_s) demonstrating superior g_m for our devices due to low sheet resistance. (b) Normalized transconductance (g_m) by width-to-length ratio (W/L), indicating our device's high performance relative to its dimensions. (c) Normalized transconductance (g_m) by channel thickness (t), showing optimal balance and high performance of our device. (d) Transconductance (g_m) as a function of channel thickness, where our device achieves the highest g_m compared to others with similar channel thicknesses, highlighting the effectiveness of our fabrication process. Performance comparison of the on/off ratio (I_{ON}/I_{OFF}) for printed organic electrochemical transistors against other reported devices. (a) On/off current ratio versus sheet resistance, showing our device achieves a significantly high I_{ON}/I_{OFF} due to low sheet resistance.

4.6. Conclusion

This study presents a novel approach to fabricating organic electrochemical transistors by integrating dispense printing for silver electrodes and inkjet printing for the channel, resulting in a fully printed, high-performance device. The OECTs fabricated through this method exhibit outstanding electrical characteristics and scalability, which are especially relevant for bioelectronics. The exceptional performance of our OECTs is primarily attributed to the thickness of the dispense-printed silver electrodes and the large channel thickness. The dispense-printed electrodes exhibit very low sheet resistance, enabled by the large thickness achievable with this method, which minimizes overall device resistance and enhances transconductance. Furthermore, this large electrode thickness did not compromise the dimensions of the transistor due to the high aspect ratio of the dispense printed lines. The OECTs reported here have channel dimensions with a larger W/L ratio than other transistors reported in the literature, which is enabled by the low sheet resistance of the electrodes. Similarly, inkjet printing allows precise control of the channel thickness, further boosting the average transconductance, which reached up to 98 mS, along with a low threshold voltage.

Furthermore, devices were characterized in terms of the influence of channel length on transconductance and on/off ratio, as well as contact resistance. The results show that longer channel devices exhibit enhanced performance when normalized by channel length because of the reduced effect of contact resistance.

Furthermore, the low resistance of the electrodes increases transconductance. These insights offer guidance for future design for devices with improved performance.

The integration of dispense and inkjet printing simplifies the fabrication process, enabling a scalable and economical production method that broadens the potential applications of OECTs. The use of silver flake ink for the electrodes and PEDOT:PSS for the semiconductor layer ensures the biocompatibility and flexibility required for wearable health monitoring devices and other bioelectronic applications. The fully printed design offers a promising avenue for creating disposable diagnostic devices, which could impact fields like point-of-care testing and personalized medicine. Overall, this work illustrates the potential of advanced printing techniques in organic electronics, providing a scalable, cost-effective alternative to traditional fabrication methods and opening new possibilities for bioelectronic applications.

Chapter 5. 3D Objects with Embedded Transistors

A section of this chapter has been submitted for publication as: Mohamad Kannan Idris, Saumik Dey Shovan, Gerd Grau, " Embedding Organic Electrochemical Transistors into 3D Printed Objects."

5.1. Introduction

The integration of organic electrochemical transistors (OECTs) and sensors within 3D-printed objects enables the fabrication of fully functional, non-planar electronic systems. Unlike conventional approaches where printed devices are fabricated on planar substrates and later assembled into structures, embedding transistors directly within 3D-printed substrates provides a streamlined approach for developing functional, self-contained systems.[40,158,163,200,201] This method eliminates the need for additional mounting steps, reduces mechanical mismatch between the electronic and structural components, and expands the potential applications of printed bioelectronics, lab-on-chip systems, and flexible circuitry. However, achieving reliable electronic performance in 3D-printed structures presents significant challenges, particularly in terms of substrate roughness, electrode printing, and transistor fabrication.[95,112,114,127,172] This chapter builds on the findings of previous chapters to address these challenges and demonstrate a fully integrated, functional OECT sensor within a 3D-printed structure.

A key obstacle in integrating printed electronics with 3D-printed objects is the surface roughness introduced by fused deposition modeling (FDM) 3D printing. As detailed in Chapter 2, the layered nature of FDM printing creates a surface with significant height variations, which negatively impacts the uniformity of printed electronic materials. The study in Chapter 2 explored surface ironing as a method for reducing roughness, showing that it achieves a greater than 90% reduction in absolute roughness. This chapter builds on those findings by applying ironing to smooth the 3D-printed substrate before electrode deposition, ensuring a more uniform surface for printed electrodes and printing OECTs.[112]

Electrode deposition also presents a major challenge, particularly when printing functional conductive materials on rough or irregular surfaces. Chapter 3 investigated dispense printing as a technique for depositing silver electrodes with high precision and thickness control. It was found that dispense printing allows for the creation of low-resistance, high-thickness electrodes, which are critical for efficient charge injection in OECTs. In this chapter, dispense printing is used to directly deposit the source, drain, and gate electrodes onto the ironed 3D-printed substrate, leveraging the optimized parameters identified in Chapter

3. This ensures consistent electrode geometry and improved electrical contact with the printed organic semiconductor.[95]

Once the electrodes are successfully printed, the organic semiconductor layer is inkjet printed. Chapter 4 explored the fabrication and electrical characterization of fully printed OECTs, demonstrating that a combination of dispense-printed electrodes and inkjet-printed PEDOT:PSS results in high-performance transistors. The work in Chapter 4 established the key electrical parameters of these transistors, including their transconductance, threshold voltage, and ON/OFF current ratio. In this chapter, the same transistor architecture is integrated directly into the 3D-printed structure, ensuring seamless fabrication without the need for additional assembly steps. The electrical performance of these embedded transistors is then evaluated to confirm that they maintain high transconductance and stable operation over multiple cycles even when printed onto 3D printed surfaces.

A critical advancement in this work is the integration of the OECT into a 3D-printed fluidic channel, transforming the transistor into a sensor for electrolyte-based applications. Instead of fabricating a standalone transistor, the OECT is embedded within a microfluidic structure, allowing the controlled flow of electrolyte solutions directly over the transistor channel and gate. This setup is particularly useful for applications in bioelectronics and chemical sensing, where the transistor's electrical response is influenced by ionic interactions within the electrolyte. The fluidic channel is designed as part of the 3D-printed structure, ensuring precise alignment of the electrolyte path with the transistor's active region. This integration allows for real-time measurements of electrolyte composition, enabling new possibilities for biochemical and environmental sensing applications.

By combining surface ironing, dispense printing of electrodes, inkjet printing of the semiconducting layer and fluidic integration, this chapter demonstrates a scalable approach for embedding printed transistors within 3D-printed objects. This work establishes a foundation for future research in fully integrated electronic-structural systems, where printed circuits and sensors can be directly fabricated within functional, three-dimensional objects. The findings in this chapter contribute to advancing bioelectronic interfaces, wearable electronics, and lab-on-chip technologies, highlighting the potential of seamless electronics integration within complex geometries.

5.2. Materials and Methods

5.2.1. Materials

The materials used for fabricating the OECTs in this chapter are the same as those detailed in Chapter 4, including the silver-based conductive ink for the electrodes, PEDOT:PSS for the semiconductor channel, and the liquid electrolyte. The transistor fabrication follows the same dispense and inkjet printing processes as previously described. For the 3D-printed components, the base substrate and integrated fluidic channel were fabricated using polylactic acid (PLA) via FDM. PLA was selected for its mechanical stability, compatibility with ironing, and ability to support printed electronics. The surface of the 3D-printed structure underwent surface ironing, as detailed in Chapter 2, to improve smoothness and facilitate reliable electrode deposition. The electrolyte used in the fluidic system was sodium chloride (NaCl) solution, which serves as the gating medium for OECT operation. The fluidic system was designed to enable continuous electrolyte flow over the transistor channel, ensuring stable operation and facilitating real-time sensing.

5.2.2. Device Fabrication

The fabrication of the OECTs involved a multi-step process, as outlined in Figure 5-1. Each step was carefully optimized to ensure precision, reliability, and compatibility across the different fabrication techniques employed.

The process began with the fabrication of the substrate using PLA and a Voxelab Aquila C2 FDM printer. The substrate was designed in SolidWorks 2023 and was sliced using Ultimaker Cura 5.4. The substrate design included an alignment notch for accurate positioning during subsequent steps. The design and dimensions of the substrate are shown in Figure 5-1 (a). To improve the surface quality, the top layer of the substrate was ironed in-situ immediately after printing. This step significantly reduced surface roughness, as detailed in our earlier study on FDM surface ironing. The FDM printing and ironing settings, listed in Table 5-1, were selected based on the results of chapter 2 to achieve the smoothness necessary for reliable printing of conductive traces and are depicted in Figure 5-1 (b).

Table 5-1. FDM printing parameters

Printing parameter	Value
Nozzle Size	0.4 [mm]
Layer Height	0.2 [mm]
Top/Bottom Layer Thickness	0.8 [mm]
Top Layers	1
Bottom Layers	1
All Patterns	Zig Zag
Top/Bottom Line Direction	0
Ironing Line Spacing	0.06 [mm]
Ironing Flow	65 [%]
Ironing Speed	75 [mm/s]
Infill Density	100 [%]
Flow	100 [%]
Printing Temperature	240 [°C]
Build Plate Temperature	60 [°C]

Following the ironing process, the electrodes were printed using dispense printing. The substrate was removed from the FDM printer bed and placed in a NOVA printer (Voltera, Waterloo, Canada) equipped with 100 μm diameter nozzles (Subrex, Carlsbad, United States). The same dispense printing parameters from chapter 4 were used to print the electrodes. The dispense printing step is illustrated in Figure 5-1 (c). After printing, the electrodes were cured at 100°C for 30 minutes in an oven. While the substrate experienced minor warping in the Z direction during curing, this deformation did not affect the subsequent printing step, and it was corrected in the following steps. Next, the semiconductor layer (PEDOT:PSS) was inkjet printed, as shown in Figure 5-1 (d), also using the same parameters mentioned in chapter 4. Following ink deposition, the ink pattern was cured at 100°C in an oven for 20 minutes. In the last five minutes of this

curing step, a 550 g piece of 3D printing glass bed was placed on the substrate to correct any warping. This flattening step ensured the substrate met the flatness requirement of 0.1 mm for the final FDM printing step, as illustrated in Figure 5-1 (e). The final step involved printing the microfluidic channel. A frame was first printed on the FDM printer to serve as an alignment guide. The flattened device was positioned within the frame, and the fluidic channel was printed on top of the substrate with a height offset of 1.2 mm. The frame size and dimensions are shown in Figure 5-1 (f). The fluidic channel design included a Luer taper inlet and outlet for syringe connections. The completed device is shown in Figure 5-1 (g) and Figure 5-1 (h). Both the frame and the microfluidic channel were printed using the same FDM settings in Table 5-1 without ironing. To prepare the device for sensing applications, 50 μ l of a 100 mM solution of NaCl in water was pushed through the fluidic channel using syringes. Multiple NaCl concentrations, 100 mM, 120 mM, 140 mM, 160 mM, 180 mM, and 200 mM, were used to study the device's sensing capabilities and the effect of ionic concentration on its performance. Ten transistors were printed on the substrate to ensure statistical reliability in performance characterization. The transistor channel design featured a channel width of 5050 ± 15 μ m and a channel length of 250 ± 21 μ m, as measured post-fabrication. These dimensions differed slightly from the original design specifications of 5000 μ m for the width and 300 μ m for the length due to ink spreading during the printing process. The behavior of ink flow and its effect on printed dimensions has been extensively studied in earlier in chapter 3.

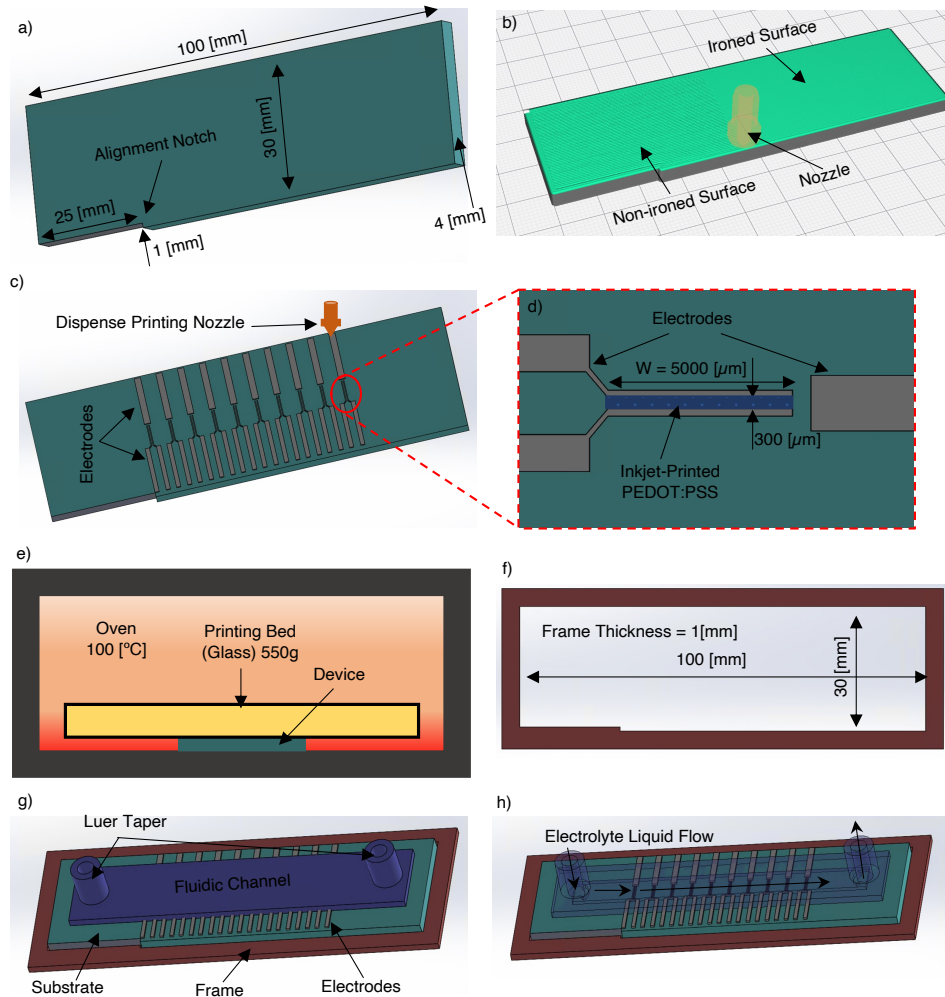


Figure 5-1. Fabrication steps for the OEET embedded into a 3D-printed substrate. (a) The initial substrate design, including an alignment notch, printed using PLA on a Voxelab Aquila C2 FDM printer. (b) In-situ surface ironing of the top layer to reduce roughness, enhancing compatibility with subsequent printing steps. (c) Dispense printing of silver electrodes using the NOVA printer, followed by curing at 100°C for 30 minutes. (d) Inkjet printing of the PEDOT:PSS semiconductor channel in a rectangular pattern using a custom drop-on-demand printer, with subsequent curing at 100°C for 20 minutes. (e) Correction of substrate warping by placing a 550 g glass weight during the final minutes of semiconductor curing. (f) Alignment frame printed to position the device for printing the microfluidic channel with a thickness of 1 mm. (g, h) The final printed OEET integrated with a microfluidic channel, featuring Luer taper inlet and outlet for syringe connection, designed for liquid electrolyte deposition and concentration studies.

5.2.3. Characterization

The dimensions of the transistors and electrodes were evaluated using an optical microscope (Keyence VHX-970F) to ensure precision and assess deviations from the intended design. Electrical measurements were conducted using a probe station equipped with a parameter analyzer (Keithley 4200A) to characterize the transistors' electrical performance. The surface roughness of the PLA substrate after ironing was assessed using an optical profilometer (Bruker, United States). Surface roughness was measured at five different locations near the substrate's center, and the results were averaged. Detailed analysis of the profilometry data, including the methodology for calculating roughness and waviness, is discussed in chapter 2. [112] For this study, the roughness results were used to confirm the effectiveness of the ironing process in producing a smooth substrate suitable for subsequent printing steps. Contact angle measurements were taken using Kruss DSA10 contact angle measurement system. The images were processed using ImageJ software.

5.3. Results and Discussion

The first step in evaluating the suitability of ironed PLA substrates for OECT fabrication is understanding their roughness. The measured average absolute roughness (R_a) of the surface is 847.3 ± 58 nm. The roughness of the surface consists of high and low-frequency roughness.[112] The high-frequency roughness represents the roughness of the surface that is generated from the line spacing of the ironed layer, printing deformities, and dust since this device is not being manufactured in a cleanroom. The measured high-frequency roughness is 575.7 ± 18 nm. The low-frequency roughness represents the waviness of the surface which is generated from the overall printing process. The measured low-frequency roughness is 485.1 ± 59 nm. These roughness values make the surface adequate for printing, and are a major improvement from the absolute roughness values of non-ironed PLA (10 ± 5 μm [112]). Another step to evaluate the suitability of ironed PLA substrates for printing electronics is evaluating their wetting properties. This is achieved using contact angle measurements. Figure 5-2 summarizes the advancing and receding contact angle measurements for deionized (DI) water and PEDOT:PSS droplets on glass, ironed PLA and non-ironed PLA substrates. These measurements provide insight into the influence of surface roughness and material composition on wettability, which is critical for ensuring uniform film deposition. Examples of the contact angle images are shown in Figure 5-3 and Figure 5-4. As expected, the non-ironed PLA substrates exhibited higher advancing and receding contact angles and larger contact angle hysteresis compared to ironed PLA

substrates, which, in turn, is higher than glass for both DI water and PEDOT:PSS. This behavior is attributed to the rough surface of non-ironed PLA compared to ironed PLA, as well as the rougher surface of ironed PLA compared to glass, which increases pinning effects and hysteresis. This highlights the significant reduction in surface roughness achieved through the ironing process.[112] The wetting behavior of PEDOT:PSS droplets on all three substrates closely mirrors that of DI water. This similarity arises from the water-based nature of the PEDOT:PSS dispersion, which governs its interaction with the substrate surfaces. These results demonstrate that ironed PLA substrates, despite their inherent roughness compared to glass, provide adequate wetting for both DI water and PEDOT:PSS.

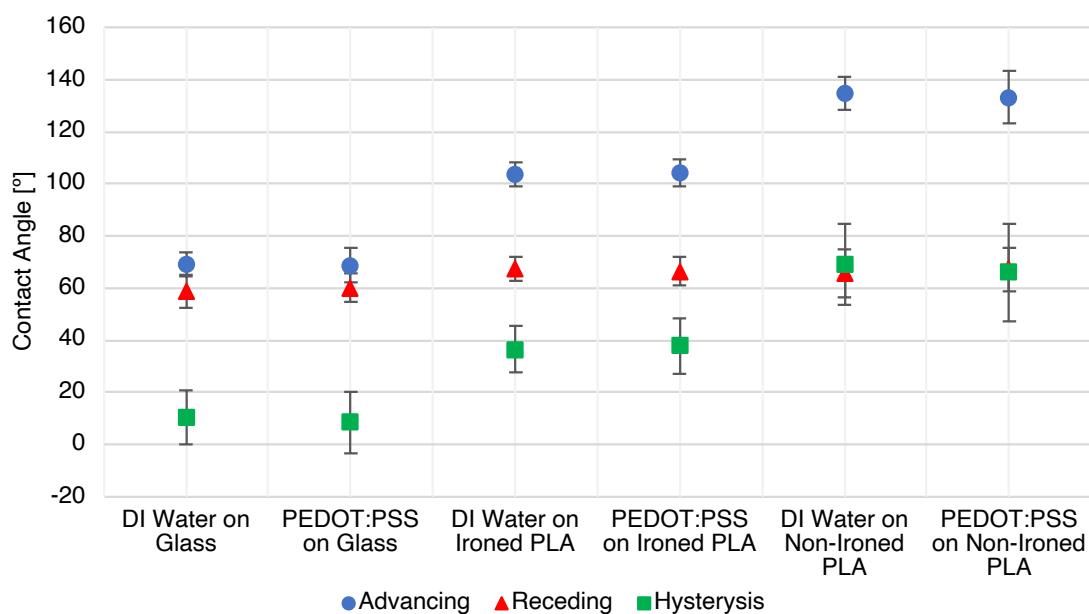


Figure 5-2. Contact angle measurements of advancing and receding droplets of DI water and PEDOT:PSS on both glass and ironed PLA substrates

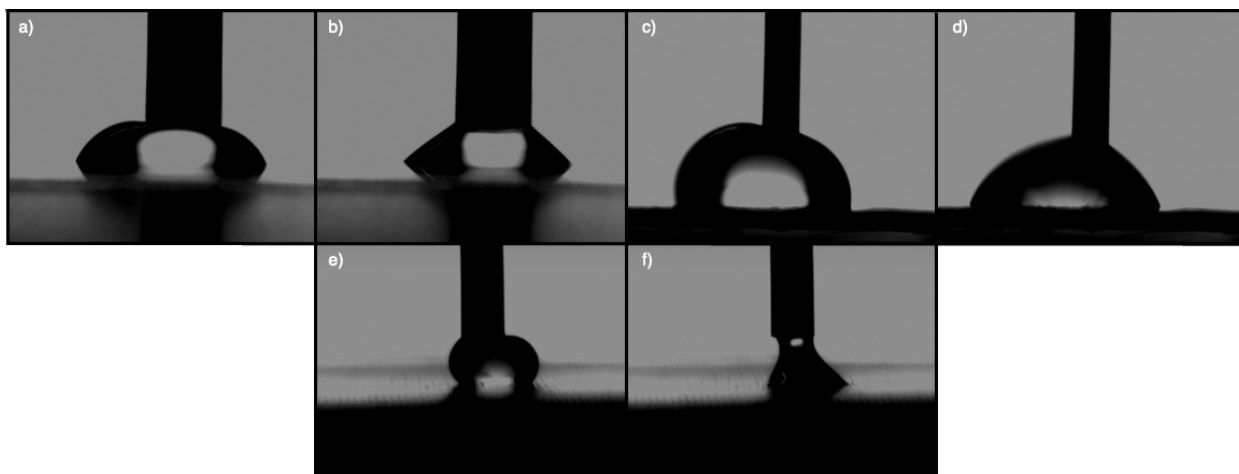


Figure 5-3. Advancing and receding contact angle images of DI water droplets on multiple surfaces. a) Advancing on glass; b) Receding on glass; c) Advancing on ironed PLA surface; d) Receding on ironed PLA surface; e) Advancing on non-ironed PLA surface; f) Receding on non-ironed PLA surface.

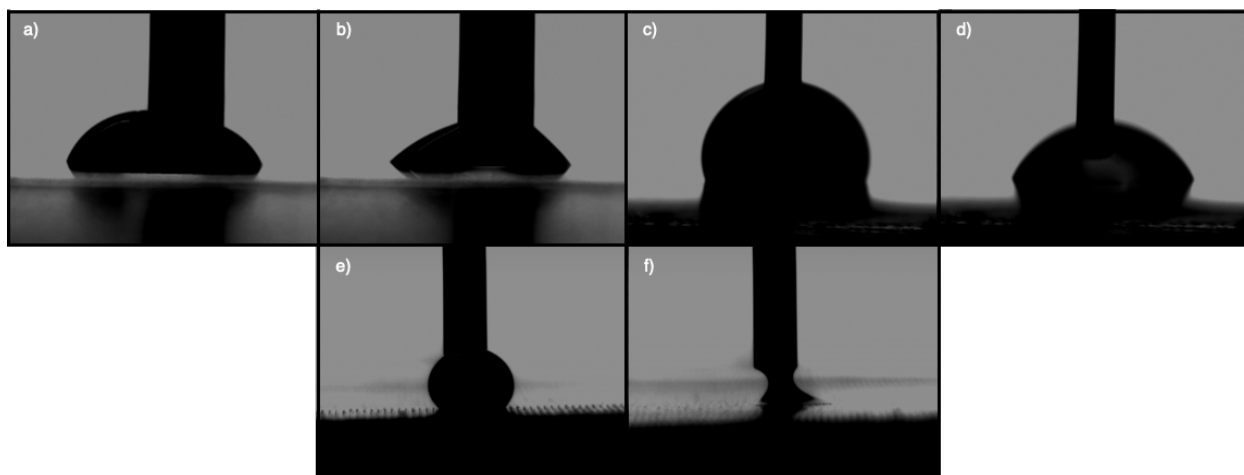


Figure 5-4. Advancing and receding contact angle images of PEDOT:PSS droplets on multiple surfaces. a) Advancing on glass; b) Receding on glass; c) Advancing on ironed PLA surface; d) Receding on ironed PLA surface; e) Advancing on non-ironed PLA surface; f) Receding on non-ironed PLA surface.

Figure 5-5 shows the fabrication design and resulting geometries of the OECT electrodes, showcasing the transition from the initial design to the final manufactured device. This analysis provides critical insights into the fidelity of the dispense and inkjet printing processes on ironed PLA substrates. Figure 5-5 (a) illustrates the electrode design created using EAGLE software. The channel dimensions were specified as $5000 \times 300 \mu\text{m}$. However, as shown in Figure 5-5 (b), the printed electrodes exhibit deviations from these initial design parameters. Post-fabrication measurements of ten transistors revealed a channel width of $5050 \pm 15 \mu\text{m}$ and a channel length of $250 \pm 21 \mu\text{m}$. These differences result from the behavior of the silver ink during deposition and curing, influenced by factors such as ink viscosity, dispense pressure, and surface properties. Small line edge roughness due to the remaining roughness of the ironed FDM printed surface can be observed. The bulge at the tip of the bottom electrode in Figure 5-5 (b) occurs because of the direction the line is printed in with a bulge forming at its start on the right. No bulge forms in a line that is printed starting at the contact pad (top). The toolpath planner of the dispense printer currently does not allow direct control over this direction, but this non-ideality does not strongly affect the OECT device. The behavior of the silver ink has been studied in-depth in previous research.[95] Figure 5-5 (c) provides a profilometric analysis of the printed electrodes and the PEDOT:PSS semiconductor layer deposited on top. The electrode lines exhibit a thickness of $36 \pm 2 \mu\text{m}$ and a width of $251 \pm 17 \mu\text{m}$. The PEDOT:PSS layer, inkjet-printed across the channel and electrode regions, has a measured thickness of $2 \pm 0.7 \mu\text{m}$. Finally, Figure 5-5 (d) shows the fully fabricated OECT device with PEDOT:PSS successfully integrated into the electrode architecture and the whole device embedded in a 3D printed microfluidic channel. The device represents the culmination of the multi-step fabrication process, with each step optimized to ensure smooth integration of functional layers. The combination of dispense printing for electrodes and inkjet printing for the semiconductor channel provides a scalable and precise approach to OECT manufacturing on three-dimensional substrates. These results confirm that the integration of dispense and inkjet printing on ironed PLA substrates produces devices with high geometric and functional fidelity.

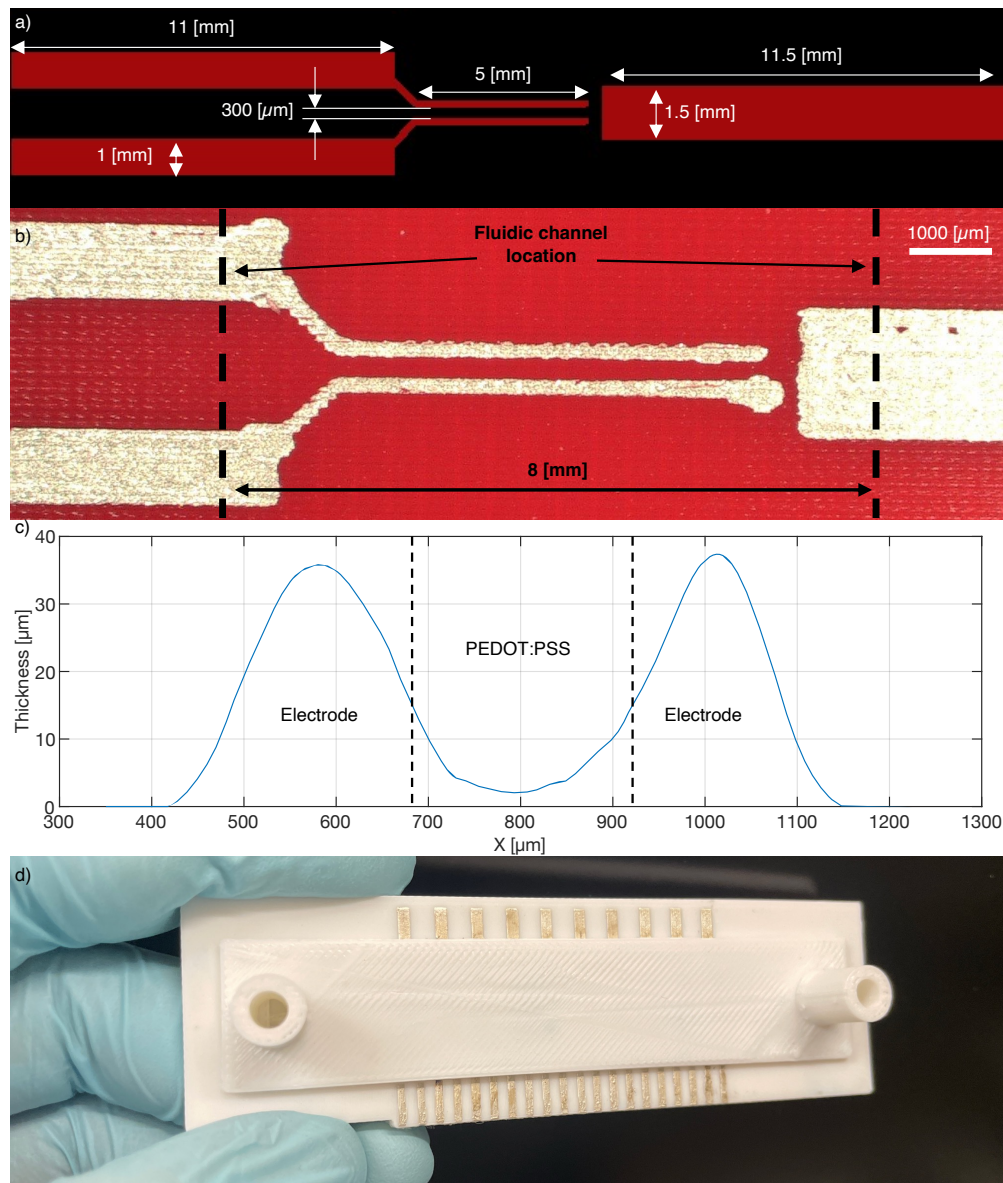


Figure 5-5. Fabrication and dimensional analysis of printed electrodes for organic electrochemical transistors. (a) Electrode design created in EAGLE with a channel length of 300 μm and a channel width of 5000 μm . (b) Optical image of the printed electrodes on ironed PLA substrates, highlighting dimensional deviations post-fabrication. The final channel dimensions measured were 250 ± 21 μm in length and 5050 ± 15 μm in width. (c) Profilometric analysis of the printed electrodes and PEDOT:PSS semiconductor layer, showing electrode thickness of 36 ± 2 μm , electrode width of 251 ± 17 μm , and PEDOT:PSS thickness of 2 ± 0.7 μm . (d) Image of the final OEET device with PEDOT:PSS and microfluidic channel printed onto the electrodes.

The electrical performance of the printed OECTs was evaluated to assess the effectiveness of the fabrication process. Figure 5-6 presents the electrical characterization results (transfer and output characteristics) for a representative transistor with a channel length of 250 μm . These measurements highlight the high transconductance achieved with the dispense printing method. Figure 5-6 (a) shows the transfer characteristic of the OECT, plotting the drain current (I_D) as a function of the gate voltage (V_G) at a constant drain voltage (V_D) of -1 V. The g_m , calculated as the derivative of I_D with respect to V_G , reaches a peak value of 77.7 mS for this representative transistor. This high g_m value demonstrates the excellent electrical performance of the device, enabled by the thick and low-resistance silver electrodes deposited via dispense printing. The output characteristics, depicted in Figure 5-6 (b), illustrate the response of the drain current to varying drain voltages at different gate voltages ($V_G = 1\text{ V}, 0.5\text{ V}, 0\text{ V}, \text{ and } -0.5\text{ V}$). The linear and saturation regions observed in these curves confirm the expected behavior of OECTs, further validating the functionality of the fabricated devices. To ensure statistical reliability, ten transistors were fabricated and characterized. The average peak g_m across all devices was $78.2 \pm 19\text{ mS}$. This value is significantly higher than those reported in similar studies, emphasizing the advantages of the dispense printing process. For example, OECTs fabricated using similar methods but with thinner (10 μm) electrodes achieved g_m values of approximately 30 mS.[161] Additionally, OECTs with thin electrodes fabricated via evaporation or inkjet printing typically exhibit g_m values below 1.2 mS.[82,160] OECTs fabricated with laser-induced graphene electrodes achieved a g_m value of 2.2 mS. [176] OECTs that were fabricated using FDM printed carbon-filled PLA electrodes achieved a g_m value of 0.25 mS.[172] The superior performance of the transistors in this study can be attributed to the low sheet resistance of the electrodes, which is a direct result of their thickness ($36.2 \pm 2\text{ }\mu\text{m}$). The dispense printing process allows for precise deposition of high-viscosity inks, resulting in thick and highly conductive electrodes that are particularly advantageous for OECTs. These findings demonstrate the effectiveness of the dispense printing method for fabricating high-performance transistors, establishing it as a viable approach for scalable manufacturing of OECTs.

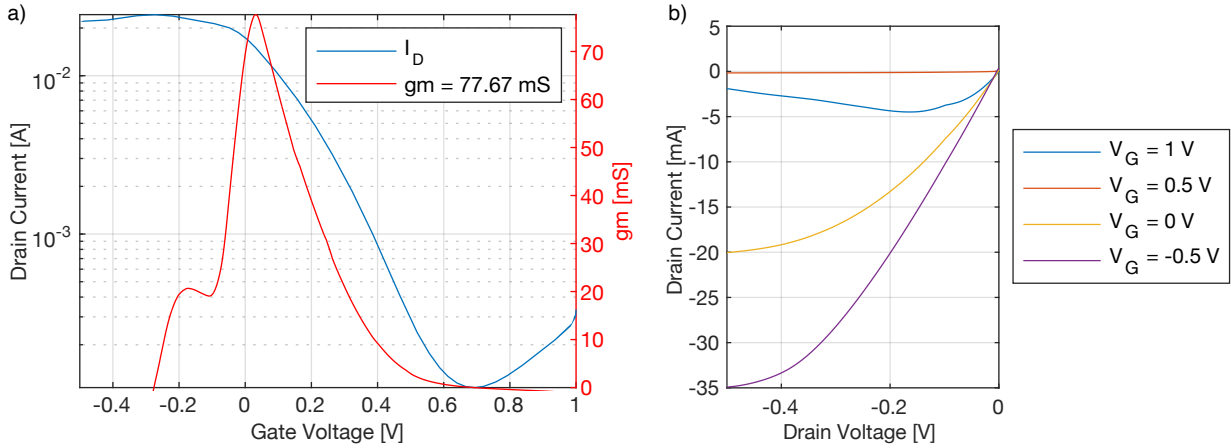


Figure 5-6. Electrical characterization of printed organic electrochemical transistor with channel length 250 μm . (a) Transfer characteristics showing the drain current as a function of gate voltage and the transconductance (g_m), highlighting a peak transconductance of 77.7 mS. The drain voltage (V_D) is -1 V. (b) Output characteristics illustrating the drain current response to varying drain voltage at different gate voltages.

Figure 5-7 illustrates the electrical performance of five OEETs over five consecutive measurement runs, where each run involved flushing the fluidic channel with a fresh volume of electrolyte solution (100 mM NaCl). The g_m and ON/OFF current ratio were measured during each run to evaluate the stability of the devices. In Figure 5-7 (a), the average g_m across all five transistors and measurement runs is depicted with a dashed line. The initial average g_m was 63.6 ± 6.6 mS during Run 1. Across subsequent runs, the average slightly increased, with values of 65 ± 6.7 mS in Run 2, 67.8 ± 7.4 mS in Run 3, 70.2 ± 9.4 mS in Run 4, and 69.1 ± 7.8 mS in Run 5. The transfer characteristics of the transistor that exhibits the most variation (OEET 2) during the five runs are shown in Figure 5-8. An Analysis of Variance (ANOVA) test was performed on the g_m value over the five runs of the five transistors. It returned a p-value considerably higher than 0.05, indicating that there is no significant difference between the runs and demonstrating that the transconductance of the OEETs is stable over multiple measurement cycles, with minimal variation between runs. Figure 5-7 (b) shows the ON/OFF current ratio over the measurement runs. The average ON/OFF current ratio was 341 ± 195 during Run 1, increasing to 353 ± 208 in Run 2. By Run 3, the average reached 385 ± 222 , followed by a slight decrease to 370 ± 213 in Run 4 and 342 ± 194 in Run 5. While the averages showed some fluctuation, the percentage change for individual OEETs remained small, indicating stability. For instance, OEET 2, which exhibited the largest variation, had a maximum change of 9.5%

between Runs 1 and 3, while OECT 4 showed a maximum change of 7.5%. The ANOVA test of the ON/OFF current ratio also yielded a p-value well above 0.05, confirming no significant differences between the runs. This result indicates that the observed variations in averages fall within acceptable limits, demonstrating consistent and stable transistor switching behavior across runs, even with repeated electrolyte replacement. The stability of both g_m and I_{ON}/I_{OFF} across multiple measurements underscores the reliability of the fabricated OECTs. Such consistency is essential for sensors, ensuring accurate and repeatable performance over time. The minimal variations observed demonstrate the suitability of these devices for sensing applications requiring repeated measurements and fluid exchanges without performance degradation. These findings validate the stable electrical characteristics of the OECTs over multiple cycles, highlighting their potential for robust applications in biosensing, environmental monitoring, and other fields demanding high stability and reproducibility.

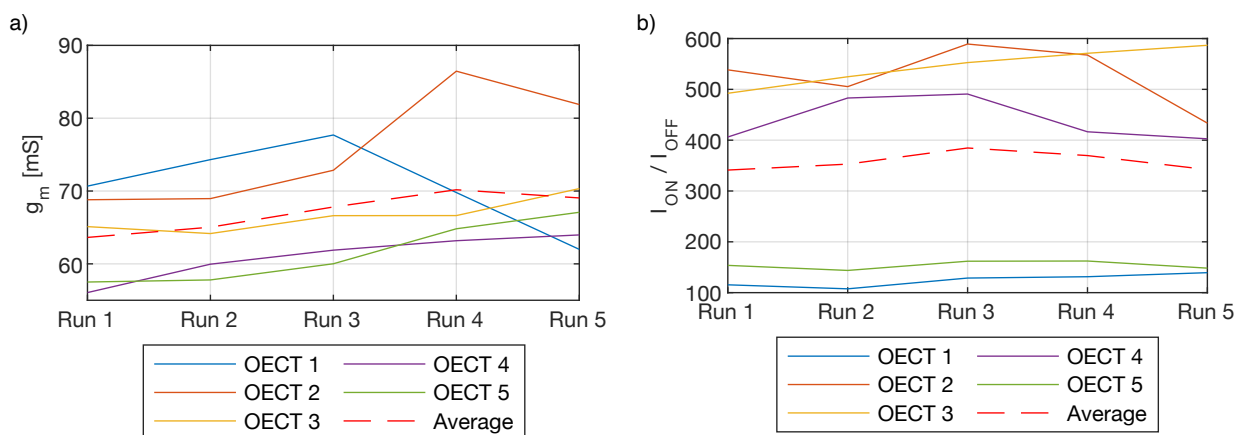


Figure 5-7. The electrical characteristics of the organic electrochemical transistors for multiple measurements (runs). During each run, a new volume of electrolyte liquid with the same concentration (100 mM) is pushed through the fluidic channel. a) The change of transconductance (g_m) during each run for each transistor. b) The change of ON/OFF current ratio (I_{ON}/I_{OFF}) during each run.

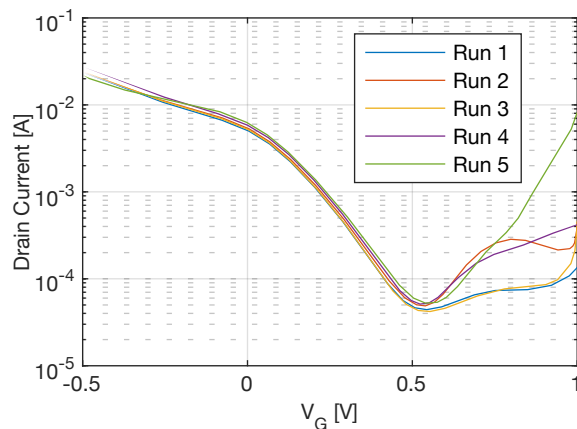


Figure 5-8. Transfer characteristics of the same organic electrochemical transistor for multiple measurements (runs) showing the drain current as a function of gate voltage. During each run, a new volume of electrolyte liquid with the same concentration (100 mM) is pushed through the fluidic channel.

Figure 5-9 demonstrates the dynamic behavior of the OECT as the gate voltage (V_G) is switched from -1 V to 0.6 V. This transition highlights the role of ionic interactions in modulating the channel's conductivity when switching between the saturation and cut-off regimes. When V_G is set to -1 V, the device operates in the saturation regime, where ionic gating leads to high channel conductivity. Switching V_G to 0.6 V transitions the device to the cut-off regime, reducing channel conductivity as ions are expelled from the PEDOT:PSS layer. The sharp and consistent response during this transition underscores the efficiency and reliability of the ionic gating mechanism. These results confirm the OECT's suitability for dynamic sensing applications, where precise and repeatable transitions between operational states are critical.

There is typically a trade-off between the thickness of the organic semiconductor and the switching time of OECTs, as thicker films require more time for ions to penetrate and modulate conductivity. With this in mind, our measured switching time of 2 seconds for a 1.86 μm thick PEDOT:PSS film demonstrates efficient ionic transport. For comparison, Mangoma et al. reported a switching time of 10 seconds and g_m of 0.25 mS for a 2.15 μm thick film, and Nazeri et al. observed a 3 seconds switching time and g_m of 2.2 mS for a thickness of 1.8 μm . [172,176] Unfortunately, most OECT studies do not report switching time, limiting direct comparisons across the literature.

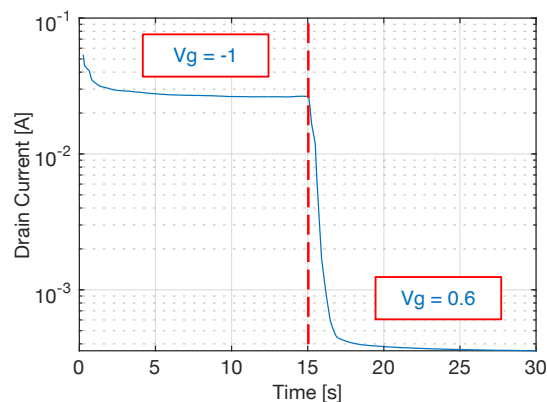


Figure 5-9. The drain current versus time for $V_G = -1\text{V}$ and $V_G = 0.6\text{V}$, representing the role of ions in the OECT when it transitions from the saturation to the cut-off regimes.

Figure 5-10 illustrates the relationship between the concentration of NaCl electrolyte and the drain on-current of the OECT. The measurements were taken at six concentrations ranging from 100 mM to 200 mM, with five replicates for each concentration to ensure statistical reliability. The results show a clear positive correlation between the electrolyte concentration and I_{ON} . As the NaCl concentration increases, the ionic conductivity of the electrolyte improves, facilitating more effective ionic gating of the PEDOT:PSS channel. This enhanced gating increases the channel's conductivity, leading to higher on-current values. This trend demonstrates the OECT's sensitivity to changes in ionic concentration, highlighting its potential for sensing applications where electrolyte concentration is a critical parameter. This behavior further emphasizes the robust performance and reproducibility of the fabricated devices.

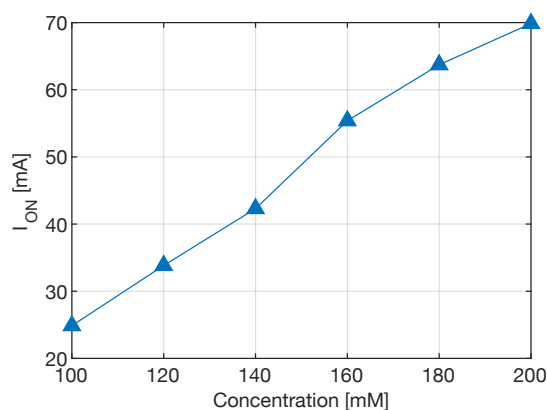


Figure 5-10. The effect of the concentration of electrolytes (NaCl) on the transistor's drain on-current (I_{ON}).

5.4. Comparison of Transistor Performance on Glass and Embedded in 3D Printed Object

A key difference between the transistors in this chapter and chapter 4 is the printed channel length. While the 300 μm design on glass (Chapter 4) resulted in an actual length of $205 \pm 16 \mu\text{m}$, the same design on the ironed 3D-printed surface (Chapter 5) produces a channel length of $250 \pm 21 \mu\text{m}$. This increase is due to the ink spreading and wetting the smooth glass surface more than the rougher 3D printed ironed surface. The average g_m of the 250 μm channel length transistor in this chapter is $78.2 \pm 19 \text{ mS}$, which falls between the 85.6 mS (205 μm) and 84.9 mS (309 μm) transistors from Chapter 4 both in terms of channel length and transconductance. When normalized by channel dimensions (W/L), the 3D-embedded device has a $g_m / (W/L)$ of 3.87 mS, slightly higher than the 205 μm device (3.47 mS) but lower than the 309 μm device (5.19 mS). A difference is also observed in the ON/OFF current ratio. The embedded transistor in Chapter 5 has an ON/OFF ratio of 341 ± 195 , which is comparable to the 309 μm device from Chapter 4 (366.25) but lower than the 205 μm device (507.86). These comparisons highlight the effects of substrate interactions and 3D integration on OEET performance. While the embedded transistors demonstrate strong electrical characteristics, their larger channel dimensions and slight reduction in normalized g_m and ON/OFF current ratio are primarily attributed to the printed pattern rather than degraded device performance. In fact, the electrical performance of the embedded transistors aligns with what would be expected for similar channel lengths on glass, suggesting that the 3D-printed ironed surface did not negatively impact device performance beyond its influence on the geometry of the printed features. Despite these differences, the embedded transistor still exhibits a very high g_m and ON/OFF current ratio compared to the literature discussed in Chapter 4, reinforcing its viability as a sensing transistor.

5.5. Conclusion

This chapter presents a novel approach for integrating OEETs directly into three-dimensional printed objects, demonstrating a significant advancement in the fabrication of functional, embedded electronic devices. By leveraging FDM with in-situ surface ironing, dispense printing for low-resistance silver electrodes, and inkjet printing for high-quality PEDOT:PSS channels, we successfully developed a scalable and fully additive process to create high-performance OEETs. The fabricated transistors exhibited excellent electrical performance, with an average maximum transconductance of 78.2 mS, substantially higher than values reported in the literature for similar devices. This achievement is attributed to the thick, low-sheet-

resistance electrodes produced via dispense printing. The devices also demonstrated remarkable stability and reproducibility across multiple measurement cycles, showcasing their robustness and suitability for real-world applications. Furthermore, the OECTs were utilized as sensors, with their stable performance enabling precise and repeatable measurements of electrolyte concentration. The clear correlation between the drain on-current and ionic concentration highlights the potential of these devices for applications in biosensing, environmental monitoring, and other fields requiring embedded sensing capabilities. By combining different advanced additive manufacturing techniques with scalable materials and processes, this study establishes a new paradigm for embedding functional electronics into 3D-printed structures. This approach not only enhances the versatility of OECTs but also opens the door to a wide range of customizable, application-specific devices, paving the way for innovative developments in bioelectronics, wearable technology, and beyond.

Chapter 6. Conclusion and Future Work

6.1. Conclusions

The primary objective of this thesis was to explore, develop, and demonstrate methodologies for integrating high-performance active electronic elements into 3D-printed objects. Specifically, the work focused on embedding OECTs into additive manufacturing processes, addressing challenges related to material compatibility, fabrication precision, and scalability. By combining advanced printing techniques such as FDM, dispense printing, and inkjet printing, this research successfully achieved seamless integration of OECTs with complex 3D-printed geometries. Among the many accomplishments presented in this thesis, the most significant milestone is the successful development of a scalable process for embedding high-performance OECTs directly within 3D-printed structures. This breakthrough represents a paradigm shift in additive manufacturing and printed electronics, as it bridges the gap between functional device fabrication and three-dimensional geometrical integration. The methods developed in this work not only enhance the versatility of OECTs but also expand their potential applications in bioelectronics, wearables, and environmental sensing.

Chapter 2 details the development and optimization of an ironing technique to address the inherent surface roughness of FDM substrates, a critical limitation for integrating functional electronics into 3D-printed objects. The rough, layered texture of FDM prints often hinders the reliable deposition of conductive traces on top, as it compromises adhesion, uniformity, and electrical performance. To overcome these challenges, this study systematically refined ironing parameters, including temperature, flow, speed, and line spacing, to produce surfaces with significantly reduced roughness. By achieving over 90% reduction in surface roughness, the ironing technique rendered FDM substrates compatible with advanced electronics fabrication. The research further demonstrated that this ironing method is adaptable to various materials, ranging from low-temperature filaments like PLA and PETG to high-temperature polymers such as PSU and PEEK. This versatility makes it a cost-effective and scalable solution for preparing 3D-printed surfaces in diverse applications. Beyond surface quality, the improved substrates enabled the successful integration of conductive traces, laying the groundwork for embedding active electronics in later stages of the research. The advancements presented in this chapter provided a critical foundation for integrating OECTs into 3D-printed geometries, demonstrating the potential of ironing as a transformative step in additive manufacturing workflows.

Chapter 3 focuses on developing and optimizing dispense printing as a critical technique for fabricating thick, low-resistance silver electrodes, which are essential for achieving high-performance OECTs. Disperse printing, an extrusion-based method, was systematically explored for its ability to deposit high-viscosity inks on various substrates with precision and consistency. The research addressed challenges such as uniformity, and line quality. The research identified and studied key parameters, including nozzle height, dispense pressure, ink viscosity, and printing speed, to ensure high-quality conductive traces with low sheet resistance. These optimizations significantly improved the reliability and reproducibility of the printed electrodes, making them suitable for integration with other fabrication steps. The dispense-printed silver electrodes exhibited excellent electrical performance, with significantly lower resistance compared to other fabrication methods, such as evaporation or inkjet printing. The advancements in dispense printing presented in this chapter were pivotal to the overall success of embedding OECTs into 3D-printed objects. The thick, low-resistance electrodes provided by this technique directly contributed to achieving high transconductance in the fabricated OECTs, underscoring the importance of dispense printing in this multi-step fabrication process. This chapter established dispense printing as a scalable and effective solution for integrating high-performance electronics into additive manufacturing workflows, further enhancing the potential for real-world applications.

Chapter 4 focuses on manufacturing high-transconductance OECTs on smooth glass substrates, which served as a benchmark for subsequent integration into 3D-printed objects. This chapter demonstrated the successful combination of inkjet printing for the PEDOT:PSS semiconductor channels and dispense printing for the silver electrodes. The choice of glass as the substrate was critical due to its smoothness, ensuring reliable performance and providing a reference point for evaluating the challenges and successes of integration with 3D-printed surfaces discussed in the following chapter. The work highlighted the complementary strengths of inkjet and dispense printing methods, showcasing their compatibility and effectiveness when used together. Inkjet printing was employed for its precision in depositing thin, uniform layers of PEDOT:PSS, while dispense printing provided thick, low-resistance silver electrodes critical for achieving high transconductance. Together, these techniques resulted in OECTs with exceptional electrical performance, demonstrating high transconductance values compared to those reported in previous studies. This chapter laid the groundwork for the next stage of the research by proving the feasibility of combining these two additive manufacturing techniques. It successfully prepared the OECTs for integration into 3D-printed objects, addressing the technical challenges of adapting high-performance electronics fabrication to non-planar and more complex geometries. The results established a strong foundation for embedding active electronic components into 3D-printed structures, further advancing the goals of this thesis.

Chapter 5 represents the culmination of the thesis, showcasing the successful integration of high-performance OECTs into 3D-printed objects. Building on the foundational work in previous chapters, this chapter demonstrated a fully additive, multi-step fabrication process that combined FDM, dispense printing, and inkjet printing to achieve seamless embedding of active electronic components within three-dimensional geometries. The research tackled the inherent challenges posed by the rough surface textures of FDM-printed substrates, utilizing surface ironing techniques developed in Chapter 2 to achieve smooth surfaces suitable for electronics integration. The dispense printing of thick, low-resistance silver electrodes and the inkjet printing of PEDOT:PSS channels, as established in Chapters 3 and 4, were successfully adapted to these 3D-printed substrates, overcoming material compatibility and process scalability issues. The result was the creation of high-performance OECTs embedded directly into 3D-printed geometries with minimal compromise to their electrical performance. A key achievement highlighted in this chapter was the demonstration of OECTs with high transconductance values (up to 78.2 mS), significantly outperforming other methods of embedded electronics fabrication. The devices also exhibited excellent stability and reproducibility across multiple measurement cycles, validating their suitability for real-world applications. Moreover, the integration extended beyond simple embedding; functional OECTs were incorporated into fluidic channels within the 3D-printed structures, demonstrating the potential for use in biosensing, environmental monitoring, and other advanced applications. This chapter underscores the transformative potential of embedding active electronic components directly into 3D-printed objects, setting a new benchmark for additive manufacturing and printed electronics. By addressing key challenges related to surface roughness, material integration, and process scalability, this work opened up new possibilities for customizable, application-specific devices that combine the structural flexibility of 3D printing with the functional capabilities of active electronics.

This thesis makes significant contributions to the fields of additive manufacturing and printed electronics by pioneering the integration of high-performance OECTs directly into 3D-printed geometries. The developed methodology bridges the gap between functional device fabrication and additive manufacturing, which were traditionally separate domains, by introducing a fully additive, scalable process. Combining techniques such as FDM, surface ironing, dispense printing, and inkjet printing, this work demonstrates a cost-effective and efficient alternative to traditional planar fabrication methods, all while maintaining exceptional device performance. By first establishing a benchmark for high-transconductance OECTs on smooth glass substrates, the research provided a clear foundation for the successful adaptation of these devices to more complex 3D-printed surfaces. This seamless integration of multi-material systems,

including PLA, PEDOT:PSS, and silver inks, establishes a practical template for hybrid electronics fabrication and highlights the versatility and adaptability of the developed processes.

The implications of this work extend far beyond technical innovation, offering transformative opportunities in applications such as bioelectronics, environmental monitoring, and advanced manufacturing. The ability to embed OECTs into 3D-printed objects enables the creation of customized, application-specific devices tailored to ergonomic and functional requirements. In bioelectronics, this opens new possibilities for wearable health monitors and implantable medical devices, while in environmental monitoring, the sensitivity of OECTs to ionic environments provides a robust solution for detecting water quality, chemical concentrations, and pH levels. Furthermore, the demonstrated processes expand the capabilities of additive manufacturing, moving beyond purely structural fabrication to fully embedded, functional devices. This advancement has significant implications for the development of smart materials, IoT systems, and lab-on-a-chip technologies. By addressing long-standing challenges in material compatibility, fabrication precision, and process scalability, this research sets a foundation for a new era of additive manufacturing, where functional electronics are seamlessly integrated into complex, three-dimensional forms.

6.2. Future Work

The studies conducted in this thesis have not only addressed key challenges in integrating OECTs into 3D-printed objects but also raised several new ideas and questions for further exploration, as outlined in this future work section. One important avenue for future research is to expand the scope of this work by incorporating flexible substrates, which would enable new opportunities for wearable and implantable devices. Flexible 3D printable materials, such as thermoplastic polyurethane (TPU) or other stretchable polymers, can be investigated to provide enhanced adaptability for applications requiring conformal electronics. Additionally, preparing and smoothing curved surfaces represents a significant advancement for integrating transistors and electronics into complex geometries. Curved surfaces present unique challenges for achieving uniformity and precision in electronic deposition, but their successful implementation would greatly expand the application range of these devices. Both dispense and inkjet printing already show some capability for working on non-planar surfaces, and further research can optimize their use in such conditions. For instance, tailored printing paths and adjustments of deposition parameters could ensure consistent film formation even on curved or irregular substrates. Exploring these areas would push the boundaries of additive manufacturing, enabling high-performance transistors and

electronic devices to be embedded into previously inaccessible geometries, such as wearable biosensors that conform to human skin or devices integrated into automotive or aerospace structures.

The work presented in this thesis has demonstrated the potential of dispense printing for fabricating high-performance electrodes, but it also highlights gaps in the literature that future research can address. One notable area is the characterization of high-viscosity inks, which remain underexplored compared to their low-viscosity counterparts. Current methods, such as static contact angle measurements, are inadequate for evaluating the behavior of high-viscosity inks during the printing process. Future studies could focus on developing standardized inks with a range of viscosities to systematically investigate their deposition behavior and establish new evaluation techniques. Such research would not only fill a critical knowledge gap but also improve the reproducibility and scalability of dispense printing. Another promising direction is the use of dispense printing for low-viscosity inks, such as PEDOT:PSS, to explore its potential as a replacement for inkjet printing. Simplifying the manufacturing process by reducing reliance on multiple printing techniques could streamline production and make the fabrication of OECTs more efficient. By leveraging the versatility of dispense printing, these studies could also uncover novel applications and further expand the material and design possibilities for printed electronics. These advancements would strengthen the role of dispense printing as a key enabler for scalable, high-performance electronics fabrication.

Another avenue for future exploration involves advancing the material innovations used in OECT fabrication. While this thesis demonstrated the effectiveness of silver electrodes fabricated using dispense printing, the process is inherently compatible with other materials that could potentially enhance device performance. For instance, electrodes made from Ag/AgCl for the gate and gold or copper for other electrodes could be investigated to optimize the electrical and chemical characteristics of OECTs. Additionally, varying the thicknesses of both the electrodes and the semiconductor layers could provide insights into their impact on transconductance. Mapping these relationships could lead to predictive models or design guidelines for optimizing OECT performance. Further research could also explore alternative electrolytes beyond NaCl, which, while effective, is not considered a standard in the literature. A comprehensive study of different electrolytes, including gel-based formulations, could provide valuable data on their impact on device performance and stability. The ability to dispense print gel-based electrolytes would not only improve the in-situ fabrication process but also contribute to creating fully integrated OECT systems. These investigations could significantly broaden the scope of OECT applications, enabling the fabrication of devices tailored to specific operational and environmental requirements.

Furthermore, PLA was chosen as the substrate in this thesis due to its cost-effectiveness and wide availability, along with its ability to achieve low surface roughness values after ironing. However, challenges such as warping during the curing of silver and semiconductor layers highlighted the limitations of PLA for high-temperature processes. Future work could focus on exploring alternative high-temperature materials, such as PEEK and PSU, which not only resist warping but also offer compatibility with advanced electrode fabrication techniques. For example, PEEK and PSU can be used to create laser-induced graphene (LIG), a conductive material that could serve as electrodes for OECTs. Combining LIG electrodes with dispense-printed silver or other materials could unlock new possibilities for improving the performance and scalability of OECTs.

The advancements in multi-toolhead 3D printers present an exciting opportunity for fully in situ fabrication of OECTs and similar devices. Future research could explore how these advanced printers, which combine fused deposition modeling (FDM), dispense printing, inkjet printing, and laser technologies within a heated chamber, could streamline the fabrication process. Such a setup could enable the sequential fabrication of substrates, electrodes, semiconductors, and encapsulation layers, all within a single machine. For example, the FDM toolhead could print and iron the substrate, the dispense printing toolhead could deposit the electrodes, and the inkjet or dispense printing toolhead could apply the semiconductor. A laser toolhead could create additional features, such as LIG electrodes, while the heated chamber would facilitate in situ curing. This approach could also include the automated dispensing of electrolytes, further reducing the need for manual intervention and enabling a fully integrated fabrication process. By leveraging these advancements, it may become possible to fabricate and embed functional OECTs directly within 3D-printed objects in a single, streamlined workflow. This would greatly enhance the scalability and efficiency of the process, opening up new applications in fields such as IoT, bioelectronics, and environmental monitoring. Additionally, such an approach aligns with the future of smart manufacturing, where multi-functional devices can be fabricated in complex geometries with minimal human oversight.

Future work should also focus on the long-term reliability and performance stability of OECTs and similar devices in real-world applications. While the devices fabricated in this thesis demonstrated excellent stability across multiple measurement cycles, further studies are needed to evaluate their performance under diverse environmental conditions, such as varying humidity, temperature, and mechanical stress. Understanding how these factors affect device functionality will be crucial for transitioning from laboratory prototypes to practical, deployable systems. Moreover, the durability of the materials and components, particularly when integrated into complex or flexible 3D-printed structures, must be rigorously tested.

Prolonged exposure to operational environments, such as biosensing applications involving bodily fluids or environmental monitoring in harsh conditions, could lead to performance degradation. Incorporating accelerated aging studies and real-world testing would provide valuable insights into the longevity and reliability of these devices. These efforts will ensure that future iterations of OECTs and similar technologies meet the stringent requirements for industrial and commercial adoption, further solidifying their potential as game-changing innovations in additive manufacturing and printed electronics.

Finally, the scalability and industrial integration of the methodologies developed in this thesis present a compelling direction for future research. While the current processes have demonstrated feasibility and effectiveness at the laboratory scale, further work is needed to adapt these techniques for large-scale manufacturing. Roll-to-roll printing or similar high-throughput fabrication methods could be explored to produce OECTs and other embedded electronics efficiently and at scale. Automating the multi-step fabrication workflow, particularly for integrating FDM, dispense printing, and inkjet printing, would greatly enhance reproducibility and throughput, making the process viable for industrial applications. Additionally, designing and testing prototypes for specific use cases, such as IoT devices, biosensors, or environmental monitors, will be critical for demonstrating the real-world value of these technologies. Collaborating with industry partners to develop application-specific solutions could accelerate the adoption of this approach, ensuring that it meets the demands of commercial and industrial settings. These efforts would pave the way for the widespread use of embedded electronics in custom 3D-printed structures, solidifying their position as a cornerstone of next-generation manufacturing.

REFERENCES

- [1] Suganuma K. Introduction to Printed Electronics. vol. 74. Springer New York; 2014. <https://doi.org/10.1007/978-1-4614-9625-0>.
- [2] Grau G, Cen J, Kang H, Kitsomboonloha R, Scheideler WJ, Subramanian V. Flexible and Printed Electronics Gravure-printed electronics: recent progress in tooling development, understanding of printing physics, and realization of printed devices Gravure-printed electronics: Recent progress in tooling development, understanding . 2016.
- [3] Grau G, Cen J, Kang H, Kitsomboonloha R, Scheideler WJ, Subramanian V. Gravure-printed electronics: Recent progress in tooling development, understanding of printing physics, and realization of printed devices. Flexible and Printed Electronics 2016;1. <https://doi.org/10.1088/2058-8585/1/2/023002>.
- [4] Grau G, Frazier EJ, Subramanian V. Printed unmanned aerial vehicles using paper-based electroactive polymer actuators and organic ion gel transistors. Microsyst Nanoeng 2016;2. <https://doi.org/10.1038/micronano.2016.32>.
- [5] Stoppa M, Chiolerio A. Wearable electronics and smart textiles: A critical review. Sensors (Switzerland) 2014;14:11957–92. <https://doi.org/10.3390/s140711957>.
- [6] Lee J, Kwon H, Seo J, Shin S, Koo JH, Pang C, Son S, Kim JH, Jang YH, Kim DE, Lee T. Conductive fiber-based ultrasensitive textile pressure sensor for wearable electronics. Advanced Materials 2015;27:2433–9. <https://doi.org/10.1002/adma.201500009>.
- [7] Whittow WG, Chauraya A, Vardaxoglou JC, Li Y, Torah R, Yang K, Beeby S, Tudor J. Inkjet-printed microstrip patch antennas realized on textile for wearable applications. IEEE Antennas Wirel Propag Lett 2014;13:71–4. <https://doi.org/10.1109/LAWP.2013.2295942>.
- [8] Jost K, Stenger D, Perez CR, McDonough JK, Lian K, Gogotsi Y, Dion G. Knitted and screen printed carbon-fiber supercapacitors for applications in wearable electronics. Energy Environ Sci 2013;6:2698–705. <https://doi.org/10.1039/c3ee40515j>.
- [9] Kim Y, Lim T, Kim CH, Yeo CS, Seo K, Kim SM, Kim J, Park SY, Ju S, Yoon MH. Organic electrochemical transistor-based channel dimension-independent single-strand wearable sweat sensors. NPG Asia Mater 2018;10:1086–95. <https://doi.org/10.1038/S41427-018-0097-3>.

- [10] Carey T, Cacovich S, Divitini G, Ren J, Mansouri A, Kim JM, Wang C, Ducati C, Sordan R, Torrisi F. Fully inkjet-printed two-dimensional material field-effect heterojunctions for wearable and textile electronics. *Nat Commun* 2017;8. <https://doi.org/10.1038/s41467-017-01210-2>.
- [11] Li Y, Torah R, Beeby S, Tudor J. An all-inkjet printed flexible capacitor on a textile using a new poly(4-vinylphenol) dielectric ink for wearable applications. *Proceedings of IEEE Sensors, IEEE*; 2012, p. 1–4. <https://doi.org/10.1109/ICSENS.2012.6411117>.
- [12] Ostfeld AE, Deckman I, Gaikwad AM, Lochner CM, Arias AC. Screen printed passive components for flexible power electronics. *Sci Rep* 2015;5. <https://doi.org/10.1038/srep15959>.
- [13] Tan HW, Tran T, Chua CK. A review of printed passive electronic components through fully additive manufacturing methods. *Virtual Phys Prototyp* 2016;11:271–88. <https://doi.org/10.1080/17452759.2016.1217586>.
- [14] Idris MK, Sarwar B, Rehman Y, Imeci T. Rectangular shaped microstrip patch antenna with multiple slits and slots. 2017 25th Signal Processing and Communications Applications Conference, SIU 2017, IEEE; 2017, p. 1–4. <https://doi.org/10.1109/SIU.2017.7960256>.
- [15] Hee Joon Jung B, Jin Shin Y, Jung Park Y, Cheol Yoon S, Hoon Choi D, Park C, Jung HJ, Shin YJ, Park YJ, Park C, Yoon SC, Choi DH. Ultrathin, Organic, Semiconductor/Polymer Blends by Scanning Corona-Discharge Coating for High-Performance Organic Thin-Film Transistors. *Adv Funct Mater* 2010;20:2903–10. <https://doi.org/10.1002/ADFM.201000032>.
- [16] Feng L, Tang W, Zhao J, Cui Q, Jiang C, Guo X. All-solution-processed low-voltage organic thin-film transistor inverter on plastic substrate. *IEEE Trans Electron Devices* 2014;61:1175–80. <https://doi.org/10.1109/TED.2014.2303992>.
- [17] Kim W, Kwon J, Lee Y, Baek S, Jung S, Kim W, Lee Y, Baek S, Jung S, Kwon J. Phase-Separated, Printed Organic Thin-Film Transistor-Based Nonvolatile Memory with Enhanced Data Retention. *Adv Mater Technol* 2020;5:2000228. <https://doi.org/10.1002/ADMT.202000228>.
- [18] Wang C, Lee WY, Nakajima R, Mei J, Kim DH, Bao Z. Thiol-ene cross-linked polymer gate dielectrics for low-voltage organic thin-film transistors. *Chemistry of Materials*

2013;25:4806–12.

https://doi.org/10.1021/CM403203K/SUPPL_FILE/CM403203K_SI_001.PDF.

- [19] Huang Y, Sun J, Zhang J, Wang S, Huang H, Zhang J, Yan D, Gao Y, Yang J. Controllable thin-film morphology and structure for 2,7-dioctyl[1] benzothieno[3,2-b][1]benzothiophene (C8BTBT) based organic field-effect transistors 2016. <https://doi.org/10.1016/j.orgel.2016.05.019>.
- [20] Fukuda K, Takeda Y, Yoshimura Y, Shiwaoku R, Truc Tran L, Sekine T, Mizukami M, Kumaki D, Tokito S. ARTICLE Fully-printed high-performance organic thin-film transistors and circuitry on one-micron-thick polymer films. *Nature* 2014. <https://doi.org/10.1038/ncomms5147>.
- [21] Fukuda K, Takeda Y, Kobayashi Y, Shimizu M, Sekine T, Kumaki D, Kurihara M, Sakamoto M, Tokito S. Patterning method for silver nanoparticle electrodes in fully solution-processed organic thin-film transistors using selectively treated hydrophilic and hydrophobic surfaces. *Jpn J Appl Phys* 2013;52:05DB05. <https://doi.org/10.7567/JJAP.52.05DB05>.
- [22] Hamaguchi A, Negishi T, Kimura Y, Ikeda Y, Takimiya K, Bisri SZ, Iwasa Y, Shiro T, Hamaguchi A, Negishi T, Kimura Y, Ikeda Y, Shiro T, Takimiya K, Bisri SZ, Iwasa Y. Single-Crystal-Like Organic Thin-Film Transistors Fabricated from Dinaphtho[2,3-b :2',3'-f]thieno[3,2-b]thiophene (DNTT) Precursor-Polystyrene Blends 2015. <https://doi.org/10.1002/adma.201502413>.
- [23] Rajput P, Singh VK. Characterization of organic thin film transistors n.d. <https://doi.org/10.1016/j.matpr.2021.04.541>.
- [24] Natali D, Fumagalli L, Sampietro M. Modeling of organic thin film transistors: Effect of contact resistances. *J Appl Phys* 2007;101. <https://doi.org/10.1063/1.2402349/917455>.
- [25] Kumar B, Kaushik BK, Negi YS. Organic thin film transistors: Structures, models, materials, fabrication, and applications: A review. *Polymer Reviews* 2014;54:33–111. <https://doi.org/10.1080/15583724.2013.848455>.
- [26] Park SK, Jackson TN, Anthony JE, Mourey DA. High mobility solution processed 6,13-bis(triisopropyl-silyl)ethynyl pentacene organic thin film transistors. *Appl Phys Lett* 2007;91:063514. <https://doi.org/10.1063/1.2768934>.

- [27] Pei K, Chen M, Zhou Z, Li H, Kwok P, Chan L. Overestimation of Carrier Mobility in Organic Thin Film Transistors Due to Unaccounted Fringe Currents 2019. <https://doi.org/10.1021/acsaelm.8b00097>.
- [28] Madec MB, Smith PJ, Malandraki A, Wang N, Korvink JG, Yeates SG. Enhanced reproducibility of inkjet printed organic thin film transistors based on solution processable polymer-small molecule blends. *J Mater Chem* 2010;20:9155–60. <https://doi.org/10.1039/C0JM01614D/>.
- [29] Soeda J, Okamoto T, Mitsui C, Takeya J. Stable growth of large-area single crystalline thin films from an organic semiconductor/polymer blend solution for high-mobility organic field-effect transistors 2016. <https://doi.org/10.1016/j.orgel.2016.09.006>.
- [30] Shen T, Zhou H, Xin J, Fan Q, Yang Z, Wang J, Mei T, Wang X, Wang N, Li J. Controllable microstructure of polymer-small molecule blend thin films for high-performance organic field-effect transistors 2019. <https://doi.org/10.1016/j.apsusc.2019.143822>.
- [31] Yuan Y, Giri G, Ayzner AL, Zoombelt AP, Mannsfeld SCB, Chen J, Nordlund D, Toney MF, Huang J, Bao Z. Ultra-high mobility transparent organic thin film transistors grown by an off-centre spin-coating method. *Nat Commun* 2014. <https://doi.org/10.1038/ncomms4005>.
- [32] Lin Z, Guo X, Zhou L, Zhang C, Chang J, Wu J, Zhang J. Solution-processed high performance organic thin film transistors enabled by roll-to-roll slot die coating technique. *Org Electron* 2018;54:80–8. <https://doi.org/10.1016/J.ORGEL.2017.12.030>.
- [33] Milan GF, Grau N. Gravure-printed electronics: Devices, technology development and design. 2016.
- [34] Stempien Z, Rybicki E, Rybicki T, Lesnikowski J. Inkjet-printing deposition of silver electro-conductive layers on textile substrates at low sintering temperature by using an aqueous silver ions-containing ink for textronic applications. *Sens Actuators B Chem* 2016;224:714–25. <https://doi.org/10.1016/j.snb.2015.10.074>.
- [35] Naderi P, Grau G. Organic thin-film transistors with inkjet-printed electrodes on hydrophobic Teflon-AF gate dielectric with reversible surface properties. *Org Electron* 2022;108. <https://doi.org/10.1016/j.orgel.2022.106612>.

- [36] James DT, Kjellander BKC, Smaal WTT, Gelinck GH, Combe C, McCulloch I, Wilson R, Burroughes JH, Bradley DDC, Kim JS. Thin-film morphology of inkjet-printed single-droplet organic transistors using polarized Raman spectroscopy: Effect of blending TIPS-pentacene with insulating polymer. *ACS Nano* 2011;5:9824–35. https://doi.org/10.1021/NN203397M/SUPPL_FILE/NN203397M_SI_001.PDF.
- [37] Rao CH, Avinash K, Varaprasad BKSVL, Goel S. A Review on Printed Electronics with Digital 3D Printing: Fabrication Techniques, Materials, Challenges and Future Opportunities. *Journal of Electronic Materials* 2022 51:6 2022;51:2747–65. <https://doi.org/10.1007/S11664-022-09579-7>.
- [38] Yang H, Leow WR, Chen X. 3D Printing of Flexible Electronic Devices. *Small Methods* 2018;2:1700259. <https://doi.org/10.1002/SMTD.201700259>.
- [39] Saengchairat N, Tran T, Chua CK. A review: additive manufacturing for active electronic components. <Http://DxDoiOrg/101080/1745275920161253181> 2016;12:31–46. <https://doi.org/10.1080/17452759.2016.1253181>.
- [40] Chang JS, Facchetti AF, Reuss R. A Circuits and Systems Perspective of Organic/Printed Electronics: Review, Challenges, and Contemporary and Emerging Design Approaches. *IEEE J Emerg Sel Top Circuits Syst* 2017;7:7–26. <https://doi.org/10.1109/JETCAS.2017.2673863>.
- [41] Kleemann H, Krechan K, Fischer A, Leo K. A Review of Vertical Organic Transistors. *Adv Funct Mater* 2020;30. <https://doi.org/10.1002/ADFM.201907113>.
- [42] Castro HF, Sowade E, Rocha JG, Alpuim P, Machado AV, Baumann RR, Lanceros-Méndez S. Degradation of all-inkjet-printed organic thin-film transistors with TIPS-pentacene under processes applied in textile manufacturing. *Org Electron* 2015;22:12–9. <https://doi.org/10.1016/j.orgel.2015.03.028>.
- [43] Rosker ES, Sandhu R, Hester J, Goorsky MS, Tice J. Printable Materials for the Realization of High Performance RF Components: Challenges and Opportunities. *Int J Antennas Propag* 2018;2018:9359528. <https://doi.org/10.1155/2018/9359528>.

- [44] Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Compos B Eng* 2018;143:172–96. <https://doi.org/10.1016/J.COMPOSITESB.2018.02.012>.
- [45] Charbonneau M, Locatelli D, Lombard S, Serbutoviez C, Tournon L, Torricelli F, Abdinia S, Cantatore E, Fattori M. A large-area gravure printed process for P-type organic thin-film transistors on plastic substrates. *European Solid-State Device Research Conference* 2018;2018-September:70–3. <https://doi.org/10.1109/ESSDERC.2018.8486895>.
- [46] Grau G, Subramanian V. Fully High-Speed Gravure Printed, Low-Variability, High-Performance Organic Polymer Transistors with Sub-5 V Operation. *Adv Electron Mater* 2016;2. <https://doi.org/10.1002/AELM.201500328>.
- [47] AlChamaa W, Khraiche M. High Performance Fully Inkjet-Printed Organic Electrochemical Transistor (OECT) Biosensor. *J Electrochem Soc* 2022;169:087518. <https://doi.org/10.1149/1945-7111/AC88FA>.
- [48] Heinrich F, Genco T, Lammering R. On the mechanical behavior of a composite stiffener with inkjet-printed electronics. *9th European Workshop on Structural Health Monitoring, EWSHM 2018*, 2018.
- [49] Naderi P, Sheuten BR, Amirfazli A, Grau G. Inkjet printing on hydrophobic surfaces: Controlled pattern formation using sequential drying. *Journal of Chemical Physics* 2023;159:24712. <https://doi.org/10.1063/5.0149663/2902200>.
- [50] Chen CT, Hung TY. Morphology and deposit of picoliter droplet tracks generated by inkjet printing. *Journal of Micromechanics and Microengineering* 2016;26. <https://doi.org/10.1088/0960-1317/26/11/115005>.
- [51] Lee SH, Shin KY, Hwang JY, Kang KT, Kang HS. Silver inkjet printing with control of surface energy and substrate temperature. *Journal of Micromechanics and Microengineering* 2008;18:075014. <https://doi.org/10.1088/0960-1317/18/7/075014>.
- [52] Zhang Y, Zhang L, Zhou C. Review of chemical vapor deposition of graphene and related applications. *Acc Chem Res* 2013;46:2329–39. https://doi.org/10.1021/AR300203N/ASSET/IMAGES/MEDIUM/AR-2012-00203N_0002.GIF.

- [53] Carlsson JO, Martin PM. Chemical Vapor Deposition. Handbook of Deposition Technologies for Films and Coatings: Science, Applications and Technology 2010;314–63. <https://doi.org/10.1016/B978-0-8155-2031-3.00007-7>.
- [54] He T, Wang Z, Zhong F, Fang H, Wang P, Hu W. Etching Techniques in 2D Materials. Adv Mater Technol 2019;4:1900064. <https://doi.org/10.1002/ADMT.201900064>.
- [55] Pearton SJ, Norton DP. Dry Etching of Electronic Oxides, Polymers, and Semiconductors. Plasma Processes and Polymers 2005;2:16–37. <https://doi.org/10.1002/PPAP.200400035>.
- [56] He B, Yang Y, Yuen MF, Chen XF, Lee CS, Zhang WJ. Vertical nanostructure arrays by plasma etching for applications in biology, energy, and electronics. Nano Today 2013;8:265–89. <https://doi.org/10.1016/J.NANTOD.2013.04.008>.
- [57] Ferro C, Grassi R, Seclì C, Maggiore P. Additive Manufacturing Offers New Opportunities in UAV Research. Procedia CIRP, 2016. <https://doi.org/10.1016/j.procir.2015.12.104>.
- [58] Perez KB, Williams CB. Combining additive manufacturing and direct write for integrated electronics - A review. 24th International SFF Symposium - An Additive Manufacturing Conference, SFF 2013, 2013, p. 962–79.
- [59] Yang Y, Song X, Li X, Chen Z, Zhou C, Zhou Q, Chen Y. Recent Progress in Biomimetic Additive Manufacturing Technology: From Materials to Functional Structures. Advanced Materials 2018;30:1706539. <https://doi.org/10.1002/ADMA.201706539>.
- [60] Zhang X, Ge T, Chang JS. Fully-Additive Printed Electronics: Transistor model, process variation and fundamental circuit designs. Org Electron 2015;26:371–9. <https://doi.org/10.1016/j.orgel.2015.07.058>.
- [61] Espera AH, Dizon JRC, Chen Q, Advincula RC. 3D-printing and advanced manufacturing for electronics. Progress in Additive Manufacturing 2019;4:245–67. <https://doi.org/10.1007/S40964-019-00077-7/FIGURES/25>.
- [62] Espera AH, Dizon JRC, Chen Q, Advincula RC. 3D-printing and advanced manufacturing for electronics. Progress in Additive Manufacturing 2019;4:245–67. <https://doi.org/10.1007/S40964-019-00077-7/METRICS>.
- [63] and DS, Subramanian V. Inkjet-Printed Line Morphologies and Temperature Control of the Coffee Ring Effect 2008. <https://doi.org/10.1021/LA7026847>.

- [64] Kang H, Kitsomboonloha R, Ulmer K, Stecker L, Grau G, Jang J, Subramanian V. Megahertz-class printed high mobility organic thin-film transistors and inverters on plastic using attoliter-scale high-speed gravure-printed sub-5 μ m gate electrodes 2014. <https://doi.org/10.1016/j.orgel.2014.10.005>.
- [65] Sibinski M, Jakubowska M, Sloma M. Flexible temperature sensors on fibers. *Sensors* 2010;10:7934–46. <https://doi.org/10.3390/s100907934>.
- [66] Sun J, Sun R, Jia P, Ma M, Song Y. Fabricating flexible conductive structures by printing techniques and printable conductive materials. *J Mater Chem C Mater* 2022;10:9441–64. <https://doi.org/10.1039/D2TC01168A>.
- [67] Vertuccio L, De Santis F, Pantani R, Lafdi K, Guadagno L. Effective de-icing skin using graphene-based flexible heater. *Compos B Eng* 2019;162:600–10. <https://doi.org/10.1016/j.compositesb.2019.01.045>.
- [68] Khan S, Lorenzelli L, Dahiya RS. Technologies for printing sensors and electronics over large flexible substrates: A review. *IEEE Sens J* 2015;15:3164–85. <https://doi.org/10.1109/JSEN.2014.2375203>.
- [69] Shin SR, Farzad R, Tamayol A, Manoharan V, Mostafalu P, Zhang YS, Akbari M, Jung SM, Kim D, Comotto M, Annabi N, Al-Hazmi FE, Dokmeci MR, Khademhosseini A. A Bioactive Carbon Nanotube-Based Ink for Printing 2D and 3D Flexible Electronics. *Advanced Materials* 2016;28:3280–9. <https://doi.org/10.1002/adma.201506420>.
- [70] Park H, Yoo S, Yi MH, Kim YH, Jung S. Flexible and stable organic field-effect transistors using low-temperature solution-processed polyimide gate dielectrics. *Org Electron* 2019;68:70–5. <https://doi.org/10.1016/J.ORGEL.2019.01.043>.
- [71] Bharti D, Raghuwanshi V, Varun I, Mahato AK, Tiwari SP. High Performance and Electro-Mechanical Stability in Small Molecule: Polymer Blend Flexible Organic Field-Effect Transistors. *IEEE Electron Device Letters* 2016;37:1215–8. <https://doi.org/10.1109/LED.2016.2592943>.
- [72] Onojima N, Mori Y, Ozawa T, Sugai T, Akiyama N, Obata S. Flexible organic field-effect transistors based on 6,13-bis(triisopropylsilyl)ethynyl pentacene/polystyrene blend film

- prepared by electrostatic spray deposition. *Jpn J Appl Phys* 2020;59:SDDA13. <https://doi.org/10.7567/1347-4065/AB5C7A>.
- [73] Mizukami M, Cho S Il, Watanabe K, Abiko M, Suzuri Y, Tokito S, Kido J. Flexible Organic Light-Emitting Diode Displays Driven by Inkjet-Printed High-Mobility Organic Thin-Film Transistors. *IEEE Electron Device Letters* 2018;39:39–42. <https://doi.org/10.1109/LED.2017.2776296>.
- [74] Schouten M, Wolterink G, Dijkshoorn A, Kosmas D, Stramigioli S, Krijnen G. A Review of Extrusion-Based 3D Printing for the Fabrication of Electro- And Biomechanical Sensors. *IEEE Sens J* 2021;21:12900–12. <https://doi.org/10.1109/JSEN.2020.3042436>.
- [75] Subramanian V, Cen J, De La Fuente Vornbrock A, Grau G, Kang H, Kitsomboonloha R, Soltman D, Tseng HY. High-speed printing of transistors: From inks to devices. *Proceedings of the IEEE* 2015;103:567–82. <https://doi.org/10.1109/JPROC.2015.2408321>.
- [76] Hassan K, Nine MJ, Tung TT, Stanley N, Yap PL, Rastin H, Yu L, Losic D. Functional inks and extrusion-based 3D printing of 2D materials: a review of current research and applications. *Nanoscale* 2020;12:19007–42. <https://doi.org/10.1039/D0NR04933F>.
- [77] Augustin T, Grunert D, Langner HH, Haverkamp V, Fiedler B. Online monitoring of surface cracks and delaminations in carbon fiber/epoxy composites using silver nanoparticle based ink. *Advanced Manufacturing: Polymer & Composites Science* 2017;3:110–9. <https://doi.org/10.1080/20550340.2017.1362508>.
- [78] Araki T, Nogi M, Suganuma K, Kogure M, Kirihaara O. Printable and stretchable conductive wirings comprising silver flakes and elastomers. *IEEE Electron Device Letters* 2011;32:1424–6. <https://doi.org/10.1109/LED.2011.2161663>.
- [79] Rahman MS, Grau G. Direct writing of stretchable metal flake conductors: improved stretchability and conductivity by combining differently sintered materials. *Flexible and Printed Electronics* 2020;5:025005. <https://doi.org/10.1088/2058-8585/AB8F22>.
- [80] Joo SJ, Yu MH, Jeon EB, Kim HS. In situ fabrication of copper electrodes on carbon-fiber-reinforced polymer (CFRP) for damage monitoring by printing and flash light sintering. *Compos Sci Technol* 2017;142:189–97. <https://doi.org/10.1016/J.COMPSCITECH.2017.02.011>.

- [81] White HS, Kittlesen GP, Wrighton MS. Chemical Derivatization of an Array of Three Gold Microelectrodes with Polypyrrole: Fabrication of a Molecule-Based Transistor. *J Am Chem Soc* 1984;106:5375–7. <https://doi.org/10.1021/JA00330A070>.
- [82] Demuru S, Huang CH, Parvez K, Worsley R, Mattana G, Piro B, Noël V, Casiraghi C, Briand D. All-Inkjet-Printed Graphene-Gated Organic Electrochemical Transistors on Polymeric Foil as Highly Sensitive Enzymatic Biosensors. *ACS Appl Nano Mater* 2022;5:1664–73. <https://doi.org/10.1021/ACSANM.1C04434>.
- [83] Luo S, Wang Y, Wang G, Wang K, Wang Z, Zhang C, Wang B, Luo Y, Li L, Liu T. CNT Enabled Co-braided Smart Fabrics: A New Route for Non-invasive, Highly Sensitive & large-area Monitoring of Composites. *Sci Rep* 2017;7:1–10. <https://doi.org/10.1038/srep44056>.
- [84] Wang Y, Huang X, Li T, Li L, Guo X, Jiang P. Polymer-Based Gate Dielectrics for Organic Field-Effect Transistors 2019. <https://doi.org/10.1021/acs.chemmater.8b03904>.
- [85] Li J, Tang W, Wang Q, Sun W, Zhang Q, Guo X, Wang X, Yan F. Solution-processable organic and hybrid gate dielectrics for printed electronics. *Materials Science and Engineering R: Reports* 2018;127:1–36. <https://doi.org/10.1016/J.MSER.2018.02.004>.
- [86] Feng L, Tang W, Xu X, Cui Q, Guo X. Ultralow-voltage solution-processed organic transistors with small gate dielectric capacitance. *IEEE Electron Device Letters* 2013;34:129–31. <https://doi.org/10.1109/LED.2012.2227236>.
- [87] Facchetti A, Yoon MH, Marks TJ. Gate dielectrics for organic field-effect transistors: New opportunities for organic electronics. *Advanced Materials* 2005;17:1705–25. <https://doi.org/10.1002/ADMA.200500517>.
- [88] Hempel F, Law JKY, Nguyen TC, Lanche R, Susloparova A, Vu XT, Ingebrandt S. PEDOT:PSS organic electrochemical transistors for electrical cell-substrate impedance sensing down to single cells. *Biosens Bioelectron* 2021;180:113101. <https://doi.org/10.1016/J.BIOS.2021.113101>.
- [89] Hempel F, Law JKY, Nguyen TC, Munief W, Lu X, Pachauri V, Susloparova A, Vu XT, Ingebrandt S. PEDOT:PSS organic electrochemical transistor arrays for extracellular electrophysiological sensing of cardiac cells. *Biosens Bioelectron* 2017;93:132–8. <https://doi.org/10.1016/J.BIOS.2016.09.047>.

- [90] Tang K, Miao W, Guo S. Crosslinked PEDOT:PSS Organic Electrochemical Transistors on Interdigitated Electrodes with Improved Stability. *ACS Appl Polym Mater* 2021;3:1436–44. https://doi.org/10.1021/ACSAPM.0C01292/SUPPL_FILE/AP0C01292_SI_001.PDF.
- [91] Xu G, Jarjes ZA, Desprez V, Kilmartin PA, Travas-Sejdic J. Sensitive, selective, disposable electrochemical dopamine sensor based on PEDOT-modified laser scribed graphene 2018. <https://doi.org/10.1016/j.bios.2018.02.031>.
- [92] Jain S, Surya SG, Suggiseti PK, Gupta A, Ramgopal Rao V. Sensitivity Improvement of Medical Dosimeters Using Solution Processed TIPS-Pentacene FETs. *IEEE Sens J* 2019;19:4428–34. <https://doi.org/10.1109/JSEN.2019.2901810>.
- [93] Raghuwanshi V, Bharti D, Varun I, Mahato AK, Tiwari SP. Performance enhancement in mechanically stable flexible organic-field effect transistors with TIPS-pentacene:polymer blend. *Org Electron* 2016;34:284–8. <https://doi.org/10.1016/J.ORGEL.2016.04.039>.
- [94] Raghuwanshi V, Bharti D, Mahato AK, Varun I, Tiwari SP. Effect of TIPS-Pentacene:Polystyrene Blend Ratio on Electrical Performance and Stability of Solution Processed Organic Field-Effect Transistors. 2018 4th IEEE International Conference on Emerging Electronics, ICEE 2018 2018. <https://doi.org/10.1109/ICEE44586.2018.8937941>.
- [95] Idris MK, Grau G. Dispense Printing of Silver Flake Inks on Hydrophilic and Hydrophobic Surfaces. *Adv Eng Mater* 2024. <https://doi.org/10.1002/ADEM.202401302>.
- [96] Cook A, Parekh DP, Ladd C, Kotwal G, Panich L, Durstock M, Dickey MD, Tabor CE. Shear-Driven Direct-Write Printing of Room-Temperature Gallium-Based Liquid Metal Alloys. *Adv Eng Mater* 2019;21:1900400. <https://doi.org/10.1002/ADEM.201900400>.
- [97] Greener Y, Middleman S. Blade-coating of a viscoelastic fluid. *Polym Eng Sci* 1974;14:791–6. <https://doi.org/10.1002/PEN.760141110>.
- [98] Lee SH, Choi MH, Han H, Choo DJ, Jang J, Kwon SK. High-performance thin-film transistor with 6,13-bis(triisopropylsilylethynyl) pentacene by inkjet printing 2008. <https://doi.org/10.1016/j.orgel.2008.05.002>.
- [99] Tang W, Feng L, Zhao J, Cui Q, Chen S, Guo X. Inkjet printed fine silver electrodes for all-solution-processed low-voltage organic thin film transistors. *J Mater Chem C Mater* 2014;2:1995–2000. <https://doi.org/10.1039/C3TC32134G>.

- [100] Berteau-Rainville M, Tamayo A, Leydecker T, Pezeshki A, Salzmann I, Mas-Torrent M, Orgiu E. Low activation energy field-effect transistors fabricated by bar-assisted meniscus shearing. *Appl Phys Lett* 2021;119:103301. <https://doi.org/10.1063/5.0059735>.
- [101] Umeda T, Kumaki D, Tokito S. Surface-energy-dependent field-effect mobilities up to 1 cm²/V s for polymer thin-film transistor. *J Appl Phys* 2009;105:024516. <https://doi.org/10.1063/1.3072669>.
- [102] Sprang N, Theirich D, Engemann J. Surface modification of fluoropolymers by microwave plasmas: FTIR investigations. *Surf Coat Technol* 1998;98:865–71. [https://doi.org/10.1016/S0257-8972\(97\)00362-9](https://doi.org/10.1016/S0257-8972(97)00362-9).
- [103] Duineveld PC. The stability of ink-jet printed lines of liquid with zero receding contact angle on a homogeneous substrate. *J Fluid Mech* 2003;477:175–200. <https://doi.org/10.1017/S0022112002003117>.
- [104] Jiang C. All-Inkjet Printed Organic Thin-Film Transistors with and without Photo-Sensitivity to Visible Lights. *Crystals* 2020, Vol 10, Page 727 2020;10:727. <https://doi.org/10.3390/CRYST10090727>.
- [105] Tokarska M, Frydrysiak M, Zięba J. Electrical properties of flat textile material as inhomogeneous and anisotropic structure. *Journal of Materials Science: Materials in Electronics* 2013;24:5061–8. <https://doi.org/10.1007/s10854-013-1524-4>.
- [106] Qiu J, Idris MK, Grau G, Melenka GW. STRUCTURAL HEALTH MONITORING THROUGH ELECTROLUMINESCENT STRAIN SENSING CARBON FIBER REINFORCED POLYMER. n.d.
- [107] Idris MK, Qiu J, Melenka GW, Grau G. Printing electronics directly onto carbon fiber composites: Unmanned Aerial Vehicle (UAV) wings with integrated heater for de-icing. *Engineering Research Express* 2020;2:025022. <https://doi.org/10.1088/2631-8695/AB8E24>.
- [108] Qiu J, Idris MK, Grau G, Melenka GW. Fabrication of electroluminescent carbon fiber composite for damage visualization. *Manuf Lett* 2020;24:56–60. <https://doi.org/10.1016/j.mfglet.2020.03.010>.
- [109] Idris MK, Qiu J, Melenka GW, Grau G. Smart Carbon Fiber Sheets for 2D Structural Health Monitoring of Composites, Phoenix, AZ: MRS Spring 2019; 2019.

- [110] Zanini S, Barni R, Pergola R Della, Riccardi C. Modification of the PTFE wettability by oxygen plasma treatments: influence of the operating parameters and investigation of the ageing behaviour. *J Phys D Appl Phys* 2014;47:325202. <https://doi.org/10.1088/0022-3727/47/32/325202>.
- [111] Kwon K-S, Rahman MK, Phung TH, Hoath SD, Jeong S, Kim JS. Review of digital printing technologies for electronic materials. *Flexible and Printed Electronics* 2020;5:043003. <https://doi.org/10.1088/2058-8585/ABC8CA>.
- [112] Neuhaus B, Idris MK, Naderi P, El-Hajj Y, Grau G. Low-Roughness 3D-Printed Surfaces by Ironing for the Integration with Printed Electronics. *Adv Eng Mater* 2024;26:2301711. <https://doi.org/10.1002/ADEM.202301711>.
- [113] Sardinha M, Vicente CMS, Frutuoso N, Leite M, Ribeiro R, Reis L. Effect of the ironing process on ABS parts produced by FDM. *Material Design & Processing Communications* 2021;3:e151. <https://doi.org/10.1002/MDP2.151>.
- [114] Butt J, Bhaskar R, Mohaghegh V. Investigating the Effects of Ironing Parameters on the Dimensional Accuracy, Surface Roughness, and Hardness of FFF-Printed Thermoplastics. *Journal of Composites Science* 2022, Vol 6, Page 121 2022;6:121. <https://doi.org/10.3390/JCS6050121>.
- [115] Tan HW, Tran T, Chua CK. A review of printed passive electronic components through fully additive manufacturing methods. *Virtual Phys Prototyp* 2016;11:271–88. <https://doi.org/10.1080/17452759.2016.1217586>.
- [116] Mohammed MG, Kramer R. All-Printed Flexible and Stretchable Electronics. *Advanced Materials* 2017;29. <https://doi.org/10.1002/adma.201604965>.
- [117] Sun J, Zhou W, Yan L, Huang D, Lin L. Extrusion-based food printing for digitalized food design and nutrition control. *J Food Eng* 2018;220:1–11. <https://doi.org/10.1016/j.jfoodeng.2017.02.028>.
- [118] Pidcock GC, In Het Panhuis M. Extrusion printing of flexible electrically conducting carbon nanotube networks. *Adv Funct Mater* 2012;22:4790–800. <https://doi.org/10.1002/adfm.201200724>.

- [119] Suikkola J, Björninen T, Mosallaei M, Kankkunen T, Iso-Ketola P, Ukkonen L, Vanhala J, Mäntysalo M. Screen-Printing Fabrication and Characterization of Stretchable Electronics. *Sci Rep* 2016;6. <https://doi.org/10.1038/srep25784>.
- [120] Kazani I, Hertleer C, de Mey G, Schwarz A, Guxho G, van Langenhove L. Electrical conductive textiles obtained by screen printing. *Fibres and Textiles in Eastern Europe* 2012;90:57–63.
- [121] Kim K, Hong J, Hahm SG, Rho Y, An TK, Se Il, Kim H, Park CE. Facile and Microcontrolled Blade Coating of Organic Semiconductor Blends for Uniaxial Crystal Alignment and Reliable Flexible Organic Field-Effect Transistors 2019. <https://doi.org/10.1021/acsami.8b21130>.
- [122] Liu C, Li Y, Minari T, Takimiya K, Tsukagoshi K. Forming semiconductor/dielectric double layers by one-step spin-coating for enhancing the performance of organic field-effect transistors 2012. <https://doi.org/10.1016/j.orgel.2012.03.025>.
- [123] Calvert P, Lin TL, Martin H. Extrusion Freeform Fabrication of Chopped-Fibre Reinforced Composites. *High Perform Polym* 1997;9:449–56. <https://doi.org/10.1088/0954-0083/9/4/008>.
- [124] Idris MK, Naderi P, Melenka GW, Grau G. Damage location sensing in carbon fiber composites using extrusion printed electronics. *Functional Composites and Structures* 2021;3:045001. <https://doi.org/10.1088/2631-6331/AC3731>.
- [125] Heikkinen ITS, Kauppinen C, Liu Z, Asikainen SM, Spoljaric S, Seppälä J V, Savin H, Pearce JM. Chemical compatibility of fused filament fabrication-based 3-D printed components with solutions commonly used in semiconductor wet processing 2019. <https://doi.org/10.1016/j.addma.2018.07.015>.
- [126] Jerkovic I, Koncar V, Grancaric A. New Textile Sensors for In Situ Structural Health Monitoring of Textile Reinforced Thermoplastic Composites Based on the Conductive Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate) Polymer Complex. *Sensors* 2017;17:2297. <https://doi.org/10.3390/s17102297>.
- [127] Qiu J, Wang G, Min J, Barreno-Avila AF, Monar-Naranjo M, Barreno-Avila M. Fusion deposition modeling (FDM) 3D printing parameters correlation: An analysis of different

- polymers surface roughness. *IOP Conf Ser Mater Sci Eng* 2021;1173:012071. <https://doi.org/10.1088/1757-899X/1173/1/012071>.
- [128] Torricelli F, Alessandri I, Macchia E, Vassalini I, Maddaloni M, Torsi L. Green Materials and Technologies for Sustainable Organic Transistors. *Adv Mater Technol* 2022;7. <https://doi.org/10.1002/ADMT.202100445>.
- [129] Matsui H, Takeda Y, Tokito S. Flexible and printed organic transistors: From materials to integrated circuits. *Org Electron* 2019;75:105432. <https://doi.org/10.1016/J.ORGEL.2019.105432>.
- [130] Yongsang Kim, Hyejung Kim, Hoi-Jun Yoo. Electrical Characterization of Screen-Printed Circuits on the Fabric. *IEEE Transactions on Advanced Packaging* 2010;33:196–205. <https://doi.org/10.1109/TADVP.2009.2034536>.
- [131] Kitsomboonloha R, Kang H, Grau G, Scheideler W, Subramanian V. MHz-Range Fully Printed High-Performance Thin-Film Transistors by Using High-Resolution Gravure-Printed Lines. *Adv Electron Mater* 2015;1. <https://doi.org/10.1002/AELM.201500155>.
- [132] Ho CC, Evans JW, Wright PK. Direct write dispenser printing of a zinc microbattery with an ionic liquid gel electrolyte. *Journal of Micromechanics and Microengineering* 2010;20. <https://doi.org/10.1088/0960-1317/20/10/104009>.
- [133] Guo N, Leu MC. Additive manufacturing: Technology, applications and research needs. *Frontiers of Mechanical Engineering* 2013;8:215–43. <https://doi.org/10.1007/s11465-013-0248-8>.
- [134] Kruth JP, Leu MC, Nakagawa T. Progress in additive manufacturing and rapid prototyping. *CIRP Ann Manuf Technol* 1998;47:525–40. [https://doi.org/10.1016/S0007-8506\(07\)63240-5](https://doi.org/10.1016/S0007-8506(07)63240-5).
- [135] Qiu J, Idris MK, Grau G, Melenka GW. Electroluminescent strain sensing on carbon fiber reinforced polymer. *Compos B Eng* 2022;238. <https://doi.org/10.1016/j.compositesb.2022.109893>.
- [136] Bai H, Yang Y, Voyles RM, Nawrocki RA. A no-hysteresis TIPS–pentacene:polystyrene blend-based organic field effect transistor by extruded direct ink writing and the application

- in a resistive load inverter circuit. *J Mater Chem C Mater* 2022;10:10973–80. <https://doi.org/10.1039/D2TC00948J>.
- [137] Yoon Y, Kim S, Kim D, Kauh SK, Lee J. Four Degrees-of-Freedom Direct Writing of Liquid Metal Patterns on Uneven Surfaces. *Adv Mater Technol* 2019;4:1800379. <https://doi.org/10.1002/ADMT.201800379>.
- [138] Lu BH, Lan HB, Liu HZ. Additive manufacturing frontier: 3D printing electronics. *Opto-Electronic Advances* 2018;1:1–10. <https://doi.org/10.29026/oea.2018.170004>.
- [139] Ota H, Emaminejad S, Gao Y, Zhao A, Wu E, Challa S, Chen K, Fahad HM, Jha AK, Kiriya D, Gao W, Shiraki H, Morioka K, Ferguson AR, Healy KE, Davis RW, Javey A. Application of 3D Printing for Smart Objects with Embedded Electronic Sensors and Systems. *Adv Mater Technol* 2016;1. <https://doi.org/10.1002/admt.201600013>.
- [140] Espera AH, Dizon JRC, Chen Q, Advincula RC. 3D-printing and advanced manufacturing for electronics. *Progress in Additive Manufacturing* 2019;4:245–67. <https://doi.org/10.1007/s40964-019-00077-7>.
- [141] MacDonald E, Wicker R. Multiprocess 3D printing for increasing component functionality. *Science (1979)* 2016;353. <https://doi.org/10.1126/science.aaf2093>.
- [142] Dezaki ML, Mohd Ariffin MKA. The effects of combined infill patterns on mechanical properties in fdm process. *Polymers (Basel)* 2020;12:1–20. <https://doi.org/10.3390/polym12122792>.
- [143] Akhoundi B, Behraves AH. Effect of Filling Pattern on the Tensile and Flexural Mechanical Properties of FDM 3D Printed Products n.d. <https://doi.org/10.1007/s11340-018-00467-y>.
- [144] Wałpuski B, Słoma M. Accelerated Testing and Reliability of FDM-Based Structural Electronics 2022. <https://doi.org/10.3390/app12031110>.
- [145] Sehhat MH, Mahdianikhotbesara A, Yadegari F. Impact of temperature and material variation on mechanical properties of parts fabricated with fused deposition modeling (FDM) additive manufacturing. *International Journal of Advanced Manufacturing Technology* 2022;120:4791–801. <https://doi.org/10.1007/S00170-022-09043-0/METRICS>.
- [146] Drumright RE, Gruber PR, Henton DE. Polylactic Acid Technology n.d. <https://doi.org/10.1002/1521-4095>.

- [147] Moore JD. Acrylonitrile-butadiene-styrene (ABS) - a review. *Composites* 1973;4:118–30. [https://doi.org/10.1016/0010-4361\(73\)90585-5](https://doi.org/10.1016/0010-4361(73)90585-5).
- [148] Calignano F, Lorusso M, Roppolo I, Minetola P. Investigation of the Mechanical Properties of a Carbon Fibre-Reinforced Nylon Filament for 3D Printing. *Machines* 2020, Vol 8, Page 52 2020;8:52. <https://doi.org/10.3390/MACHINES8030052>.
- [149] Qi HJ, Boyce MC. Stress–strain behavior of thermoplastic polyurethanes. *Mechanics of Materials* 2005;37:817–39. <https://doi.org/10.1016/J.MECHMAT.2004.08.001>.
- [150] Dolzyk G, Jung S. Tensile and Fatigue Analysis of 3D-Printed Polyethylene Terephthalate Glycol. *Journal of Failure Analysis and Prevention* 2019;19:511–8. <https://doi.org/10.1007/S11668-019-00631-Z/FIGURES/7>.
- [151] Duran C, Subbian V, Giovanetti MT, Simkins JR, Beyette FR. Experimental desktop 3D printing using dual extrusion and water-soluble polyvinyl alcohol. *Rapid Prototyp J* 2015;21:528–34. <https://doi.org/10.1108/RPJ-09-2014-0117/FULL/PDF>.
- [152] Miao Z, Seo J, Hickner MA. Solvent-cast 3D printing of polysulfone and polyaniline composites. *Polymer (Guildf)* 2018;152:18–24. <https://doi.org/10.1016/J.POLYMER.2018.05.055>.
- [153] Chueca de Bruijn A, Gómez-Gras G, Pérez MA, Esposito Corcione C, Santagata A. A Comparative Analysis of Chemical, Thermal, and Mechanical Post-Process of Fused Filament Fabricated Polyetherimide Parts for Surface Quality Enhancement. *Materials* 2021, Vol 14, Page 5880 2021;14:5880. <https://doi.org/10.3390/MA14195880>.
- [154] Zanjanijam AR, Major I, Lyons JG, Lafont U, Devine DM. Fused Filament Fabrication of PEEK: A Review of Process-Structure-Property Relationships. *Polymers* 2020, Vol 12, Page 1665 2020;12:1665. <https://doi.org/10.3390/POLYM12081665>.
- [155] Espalin D, Muse DW, MacDonald E, Wicker RB. 3D Printing multifunctionality: Structures with electronics. *International Journal of Advanced Manufacturing Technology* 2014;72:963–78. <https://doi.org/10.1007/S00170-014-5717-7/METRICS>.
- [156] Griffiths ER, Leigh SJ. Hybrid additive manufacture: Surface finishing methods for improving conductivity of inkjet printed tracks on non-planar substrates fabricated using

- p fused deposition modeling.
- Sens Actuators A Phys*
- 2022;333:113235.
- <https://doi.org/10.1016/J.SNA.2021.113235>
- .
- [157] Ferro LMM, Merces L, Camargo DHS de, Bufon CCB. Organic Electrochemical Transistors: Ultrahigh-Gain Organic Electrochemical Transistor Chemosensors Based on Self-Curled Nanomembranes (*Adv. Mater.* 29/2021). *Advanced Materials* 2021;33:2170223. <https://doi.org/10.1002/ADMA.202170223>.
- [158] Han S, Polyravas AG, Wustoni S, Inal S, Malliaras GG. Integration of Organic Electrochemical Transistors with Implantable Probes. *Adv Mater Technol* 2021;6. <https://doi.org/10.1002/admt.202100763>.
- [159] Battistoni S, Peruzzi C, Verna A, Marasso SL, Cocuzza M, Erokhin V, Iannotta S. Synaptic response in organic electrochemical transistor gated by a graphene electrode. *Flexible and Printed Electronics* 2019;4. <https://doi.org/10.1088/2058-8585/AB4DCE>.
- [160] Yeung SY, Veronica A, Li Y, Hsing IM. High-Performance Internal Ion-Gated Organic Electrochemical Transistors for High-Frequency Bioimpedance Analysis. *Adv Mater Technol* 2023;8:2201116. <https://doi.org/10.1002/ADMT.202201116>.
- [161] Fan J, Montemagno C, Gupta M. 3D printed high transconductance organic electrochemical transistors on flexible substrates. *Org Electron* 2019;73:122–9. <https://doi.org/10.1016/J.ORGEL.2019.06.012>.
- [162] Granelli R, Alessandri I, Gkoupidenis P, Vassalini I, Kovács-Vajna ZM, Blom PWM, Torricelli F, Granelli R, Alessandri I, Vassalini I, Kovács-Vajna ZM, Torricelli F, Gkoupidenis P, Blom PWM. High-Performance Bioelectronic Circuits Integrated on Biodegradable and Compostable Substrates with Fully Printed Mask-Less Organic Electrochemical Transistors. *Small* 2022;18:2108077. <https://doi.org/10.1002/SMLL.202108077>.
- [163] Travaglini L, Micolich AP, Cazorla C, Zeglio E, Lauto A, Mawad D. Single-Material OECT-Based Flexible Complementary Circuits Featuring Polyaniline in Both Conducting Channels. *Adv Funct Mater* 2021;31:2007205. <https://doi.org/10.1002/ADFM.202007205>.

- [164] Kawamura R, Michinobu T. PEDOT:PSS versus Polyaniline: A Comparative Study of Conducting Polymers for Organic Electrochemical Transistors. *Polymers (Basel)* 2023;15:4657. <https://doi.org/10.3390/POLYM15244657/S1>.
- [165] Mello HJNPD, Faleiros MC, Mulato M. Electrochemically activated polyaniline based ambipolar organic electrochemical transistor. *Electrochemical Science Advances* 2022;2:e2100176. <https://doi.org/10.1002/ELSA.202100176>.
- [166] Kim JH, Ahmad Z, Kim Y, Kim W, Ahn H, Lee JS, Yoon MH. Decoupling Critical Parameters in Large-Range Crystallinity-Controlled Polypyrrole-Based High-Performance Organic Electrochemical Transistors. *Chemistry of Materials* 2020;32:8606–18. https://doi.org/10.1021/ACS.CHEMMATER.0C02936/SUPPL_FILE/CM0C02936_SI_001.PDF.
- [167] Tang K, Turner C, Case L, Mehrehjedy A, He X, Miao W, Guo S. Organic Electrochemical Transistor with Molecularly Imprinted Polymer-Modified Gate for the Real-Time Selective Detection of Dopamine. *ACS Appl Polym Mater* 2022;4:2337–45. https://doi.org/10.1021/ACSAPM.1C01563/SUPPL_FILE/AP1C01563_SI_001.PDF.
- [168] Fayez M, Morsi KM, Sabry MN. OTFTs compact models: Analysis, comparison, and insights. *IET Circuits, Devices and Systems* 2017;11:409–20. <https://doi.org/10.1049/IET-CDS.2016.0439>.
- [169] Shur MS, Slade HC, Jacunski MD, Owusu AA, Ytterdal T. SPICE Models for Amorphous Silicon and Polysilicon Thin Film Transistors. *J Electrochem Soc* 1997;144:2833–9. <https://doi.org/10.1149/1.1837903>.
- [170] Hamilton R, Smith J, Ogier S, Heeney M, Anthony JE, McCulloch I, Veres J, Bradley DDC, Anthopoulos TD. High-performance polymer-small molecule blend organic transistors. *Advanced Materials* 2009;21:1166–71. <https://doi.org/10.1002/ADMA.200801725>.
- [171] Bittle EG, Basham JI, Jackson TN, Jurchescu OD, Gundlach DJ. Mobility overestimation due to gated contacts in organic field-effect transistors. *Nature Communications* 2016 7:1 2016;7:1–7. <https://doi.org/10.1038/ncomms10908>.

- [172] Mangoma TN, Yamamoto S, Malliaras GG, Daly R. Hybrid 3D/Inkjet-Printed Organic Neuromorphic Transistors. *Adv Mater Technol* 2022;7. <https://doi.org/10.1002/admt.202000798>.
- [173] Ji W, Wu D, Tang W, Xi X, Su Y, Guo X, Liu R. Carbonized silk fabric-based flexible organic electrochemical transistors for highly sensitive and selective dopamine detection. *Sens Actuators B Chem* 2020;304. <https://doi.org/10.1016/J.SNB.2019.127414>.
- [174] Liang Y, Brings F, Maybeck V, Ingebrandt S, Wolfrum B, Pich A, Offenhäusser A, Mayer D. Tuning Channel Architecture of Interdigitated Organic Electrochemical Transistors for Recording the Action Potentials of Electrogenic Cells. *Adv Funct Mater* 2019;29:1902085. <https://doi.org/10.1002/ADFM.201902085>.
- [175] M J, Khurshid F, Akhil M, Rathes Kannan R, Ramesh A, Nagarajan S, Hofmann M, Sterlin Leo Hudson M. Highly sensitive organic electrochemical transistor for detection of stress-induced cation leakage from plant cells. *Biosens Bioelectron X* 2022;12:100251. <https://doi.org/10.1016/J.BIOSX.2022.100251>.
- [176] Nazeri M, Ghalamboran M, Grau G. Laser-Induced Graphene Electrodes for Organic Electrochemical Transistors (OECTs). *Adv Mater Technol* 2023;8. <https://doi.org/10.1002/ADMT.202300188>.
- [177] Espalin D, Muse DW, Macdonald E, Wicker RB, Muse DW, Macdonald E, Espalin D, Wicker RB, Keck WM. 3D Printing multifunctionality: structures with electronics. *Int J Adv Manuf Technol* 2014;72:963–78. <https://doi.org/10.1007/s00170-014-5717-7>.
- [178] Wei Tan H, Ying Clarrisa Choong Y, Nan Kuo C, Yee Low H, Kai Chua C. 3D printed electronics: Processes, materials and future trends 2022. <https://doi.org/10.1016/j.pmatsci.2022.100945>.
- [179] Gao W, Pumera M. 3D Printed Nanocarbon Frameworks for Li-Ion Battery Cathodes. *Adv Funct Mater* 2021;31:2007285. <https://doi.org/10.1002/ADFM.202007285>.
- [180] Spinelli G, Lamberti P, Tucci V, Ivanova R, Tabakova S, Ivanov E, Kotsilkova R, Cimmino S, Di Maio R, Silvestre C. Rheological and electrical behaviour of nanocarbon/poly(lactic) acid for 3D printing applications. *Compos B Eng* 2019;167:467–76. <https://doi.org/10.1016/J.COMPOSITESB.2019.03.021>.

- [181] Mufti AA. Structural health monitoring of innovative Canadian civil engineering structures. *Struct Health Monit* 2002;1:89–103. <https://doi.org/10.1177/147592170200100106>.
- [182] Ihn J-B, Chang F-K. Pitch-catch Active Sensing Methods in Structural Health Monitoring for Aircraft Structures. *Structural Health Monitoring: An International Journal* 2008;7:5–19. <https://doi.org/10.1177/1475921707081979>.
- [183] Balageas Daniel, Fritzen C-Peter, Güemes Alfredo, Wiley InterScience (Online service). *Structural health monitoring*. ISTE; 2006.
- [184] Giurgiutiu V, Zagrai A, Jing Bao J. Piezoelectric Wafer Embedded Active Sensors for Aging Aircraft Structural Health Monitoring. vol. 1. Sage PublicationsSage CA: Thousand Oaks, CA; 2002. <https://doi.org/10.1177/147592170200100104>.
- [185] Zhao D, Liu T, Zhang M, Liang R, Wang B. Fabrication and characterization of aerosol-jet printed strain sensors for multifunctional composite structures. *Smart Mater Struct* 2012;21. <https://doi.org/10.1088/0964-1726/21/11/115008>.
- [186] Ibrahim Y, Melenka GW, Kempers R. Fabrication and tensile testing of 3D printed continuous wire polymer composites. *Rapid Prototyp J* 2018;24:1131–41. <https://doi.org/10.1108/RPJ-11-2017-0222/FULL/PDF>.
- [187] Ibrahim Y, Melenka GW, Kempers R. Additive manufacturing of Continuous Wire Polymer Composites. *Manuf Lett* 2018;16:49–51. <https://doi.org/10.1016/J.MFGLET.2018.04.001>.
- [188] Ibrahim Y, Melenka GW, Kempers R. Additive manufacturing of Continuous Wire Polymer Composites. *Manuf Lett* 2018;16:49–51. <https://doi.org/10.1016/J.MFGLET.2018.04.001>.
- [189] Melenka GW, Cheung BKO, Schofield JS, Dawson MR, Carey JP. Evaluation and prediction of the tensile properties of continuous fiber-reinforced 3D printed structures. *Compos Struct* 2016;153:866–75. <https://doi.org/10.1016/J.COMPSTRUCT.2016.07.018>.
- [190] Peng Z, Lin J, Ye R, Samuel ELG, Tour JM. Flexible and stackable laser-induced graphene supercapacitors. *ACS Appl Mater Interfaces* 2015;7:3414–9. https://doi.org/10.1021/AM509065D/SUPPL_FILE/AM509065D_SI_001.PDF.
- [191] Khan Y, Thielens A, Muin S, Ting J, Baumbauer C, Arias AC. A New Frontier of Printed Electronics: Flexible Hybrid Electronics. *Advanced Materials* 2019:1905279. <https://doi.org/10.1002/adma.201905279>.

- [192] Camargo JC, Machado ÁR, Almeida EC, Silva EFMS. Mechanical properties of PLA-graphene filament for FDM 3D printing. *International Journal of Advanced Manufacturing Technology* 2019;103:2423–43. <https://doi.org/10.1007/S00170-019-03532-5/METRICS>.
- [193] Li Q, Wu T, Zhao W, Ji J, Wang G. Laser-Induced Corrugated Graphene Films for Integrated Multimodal Sensors. *ACS Appl Mater Interfaces* 2021;13:37433–44. <https://doi.org/10.1021/acsami.1c12686>.
- [194] Hanemann T, Klein A, Baumgärtner S, Jung J, Wilhelm D, Antusch S. Material Extrusion 3D Printing of PEEK-Based Composites. *Polymers (Basel)* 2023;15. <https://doi.org/10.3390/polym15163412>.
- [195] Butt J, Bhaskar R, Mohaghegh V. Investigating the Effects of Ironing Parameters on the Dimensional Accuracy, Surface Roughness, and Hardness of FFF-Printed Thermoplastics. *Journal of Composites Science* 2022;6. <https://doi.org/10.3390/jcs6050121>.
- [196] Kim DH, Ryu SS, Shin D, Shin JH, Jeong JJ, Kim HJ, Chang HS. The fabrication of front electrodes of Si solar cell by dispensing printing. *Materials Science and Engineering: B* 2012;177:217–22. <https://doi.org/10.1016/J.MSEB.2011.12.027>.
- [197] Temiño I, Del Pozo FG, Ajayakumar MR, Galindo S, Puigdollers J, Mas-Torrent M. A Rapid, Low-Cost, and Scalable Technique for Printing State-of-the-Art Organic Field-Effect Transistors. *Adv Mater Technol* 2016;1. <https://doi.org/10.1002/ADMT.201600090>.
- [198] Marková A, Stříteský S, Weiter M, Vala M. Serial Resistance Effect on Organic Electrochemical Transistors' Transconductance. *IEEE Sens J* 2023;23:19417–23. <https://doi.org/10.1109/JSEN.2023.3296939>.
- [199] Paterson AF, Faber H, Savva A, Nikiforidis G, Gedda M, Hidalgo TC, Chen X, McCulloch I, Anthopoulos TD, Inal S. On the Role of Contact Resistance and Electrode Modification in Organic Electrochemical Transistors. *Advanced Materials* 2019;31. <https://doi.org/10.1002/ADMA.201902291>.
- [200] Shiwaku R, Matsui H, Hayasaka K, Takeda Y, Fukuda T, Kumaki D, Tokito S, Shiwaku R, Matsui H, Hayasaka K, Takeda Y, Kumaki D, Tokito S. Printed Organic Inverter Circuits with Ultralow Operating Voltages. *Adv Electron Mater* 2017;3:1600557. <https://doi.org/10.1002/aelm.201600557>.

- [201] Kjellander BKC, Smaal WTT, Myny K, Genoe J, Dehaene W, Heremans P, Gelinck GH. Optimized circuit design for flexible 8-bit RFID transponders with active layer of ink-jet printed small molecule semiconductors. *Org Electron* 2013;14:768–74. <https://doi.org/10.1016/J.ORGEL.2012.12.027>.

APPENDICES

Appendix A. Advanced FDM Surface Results

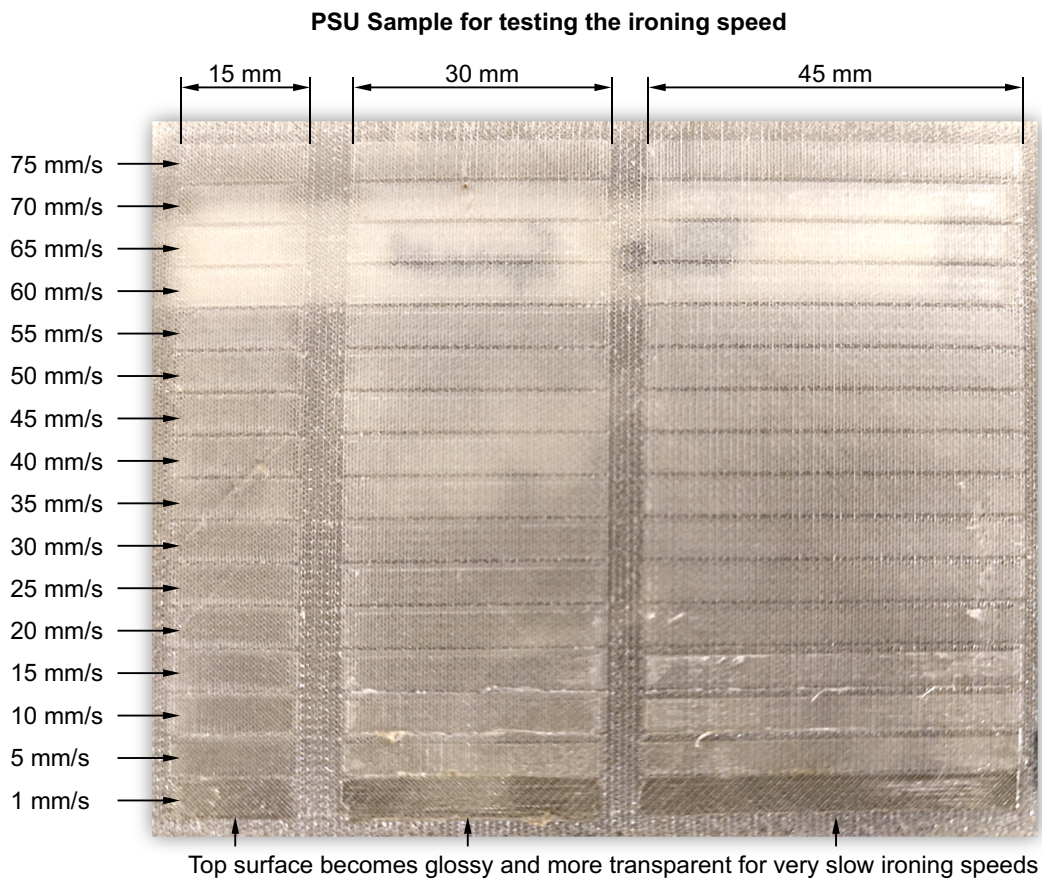


Figure 6-1. Printed PSU sample to analyze the effect of ironing speed on surface roughness. Only when the ironing speed is set to 1 mm/s does the surface structure change and become very shiny, but also wavy compared to the other matt and smooth ironed surfaces.

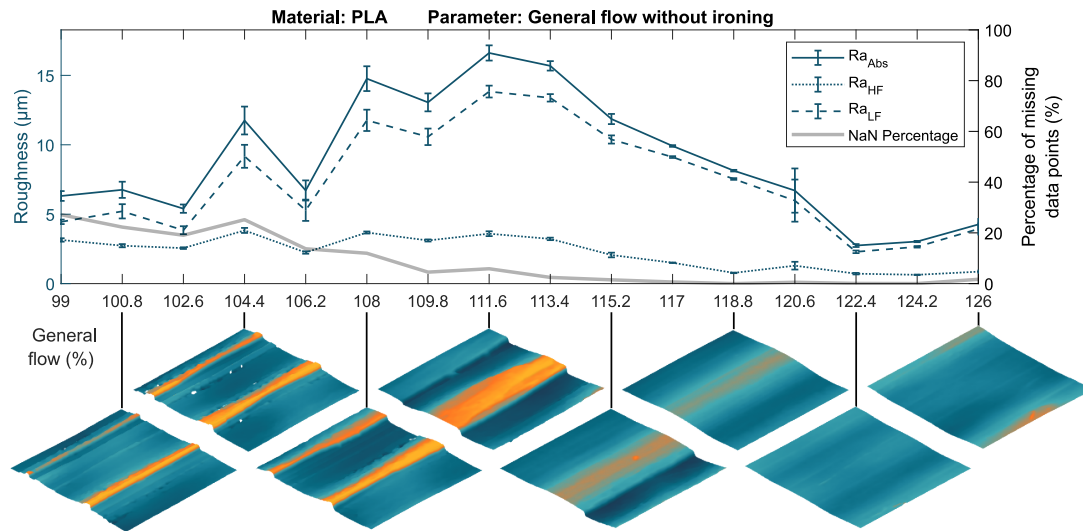


Figure 6-2. Effect of the overall flow without ironing on roughness for PLA.

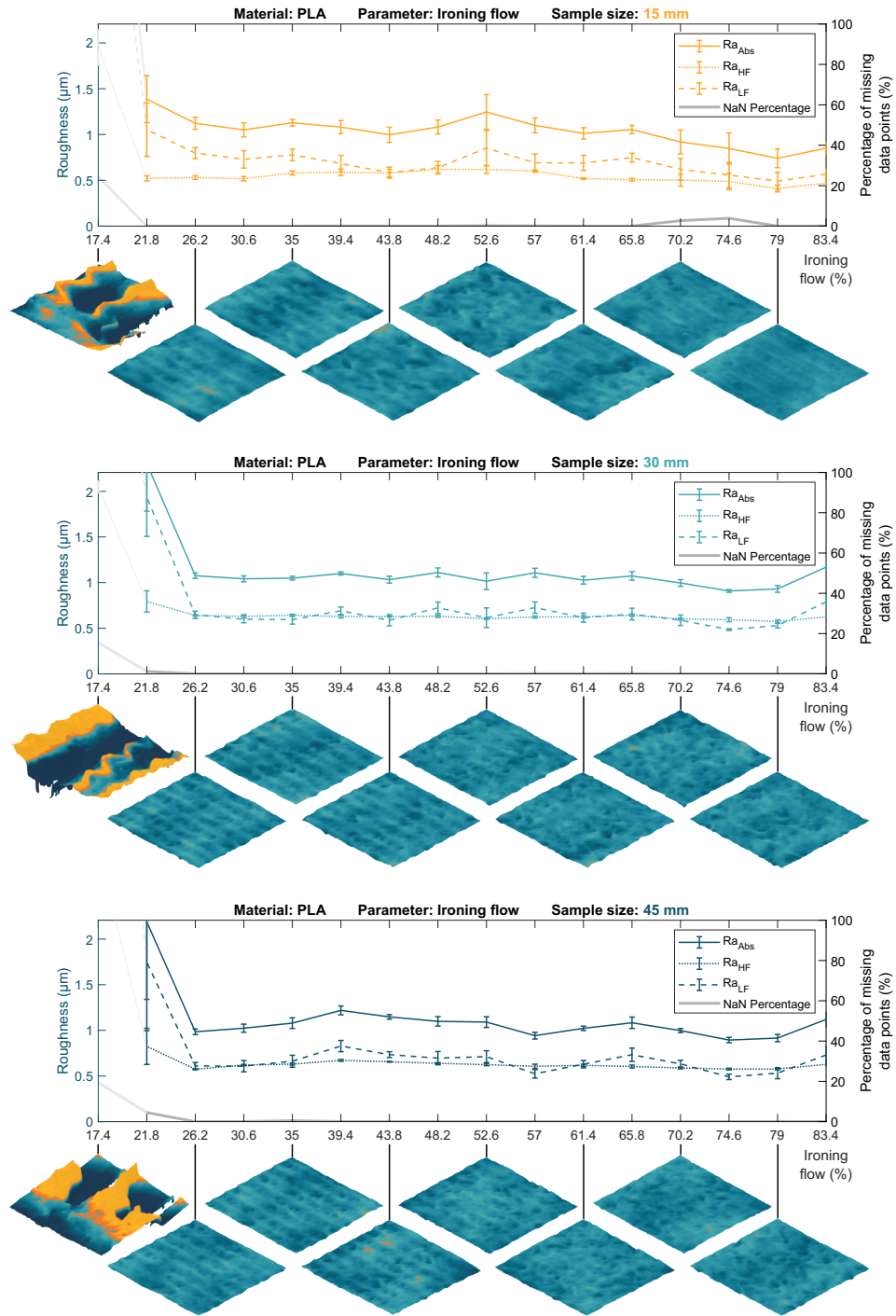


Figure 6-3. Effect of the ironing flow on roughness for PLA. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

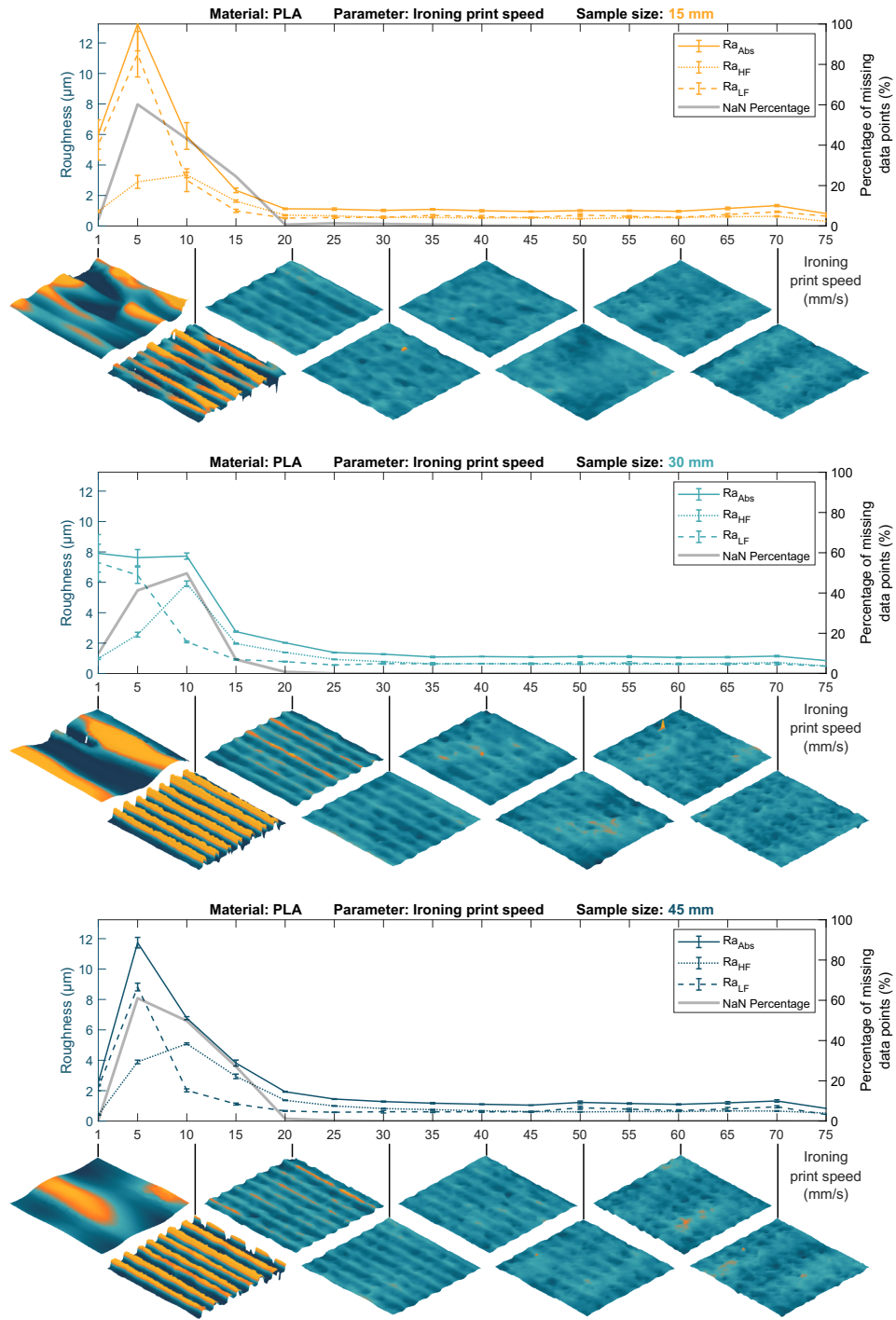


Figure 6-4. Effect of the ironing speed on roughness for PLA. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

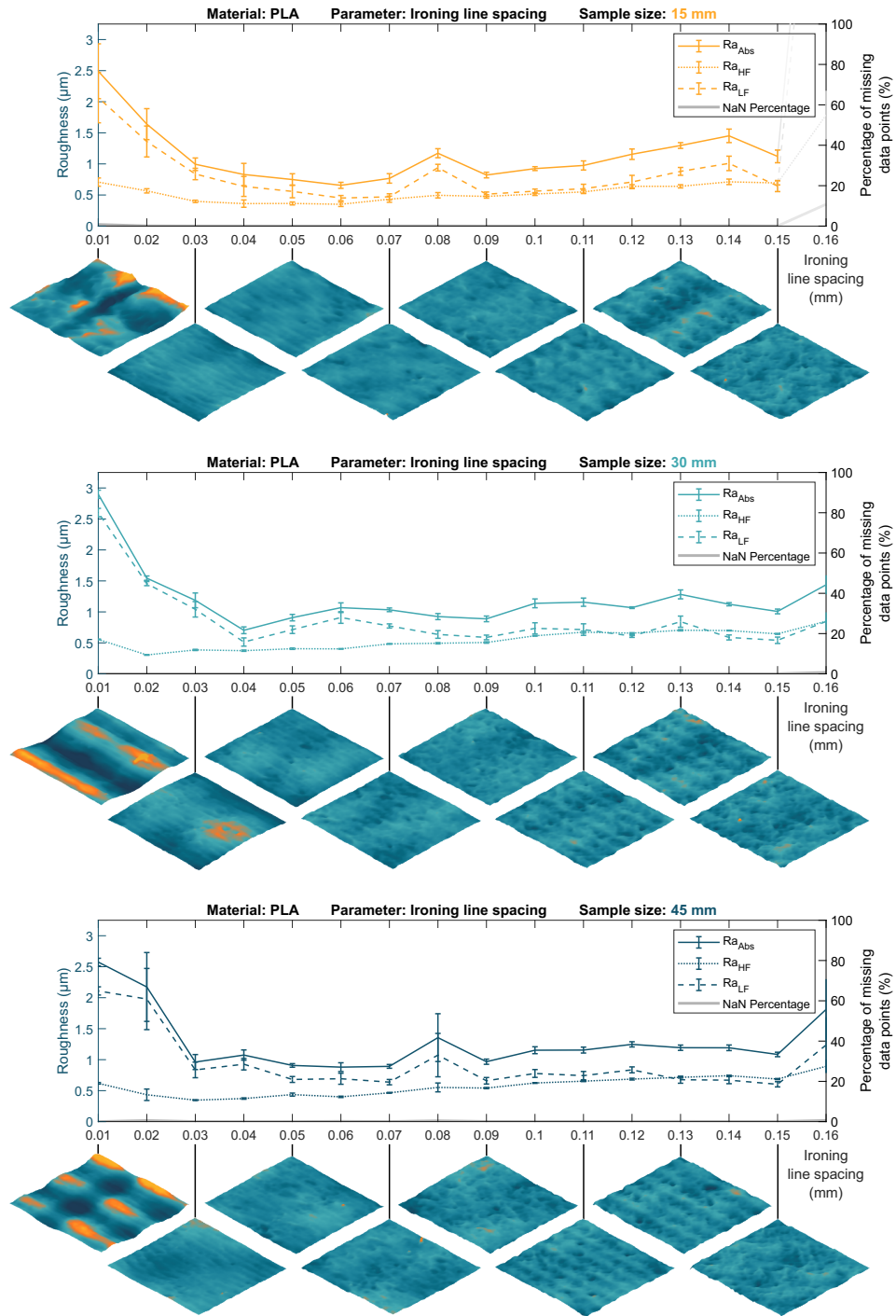


Figure 6-5. Effect of the ironing line spacing on roughness for PLA. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

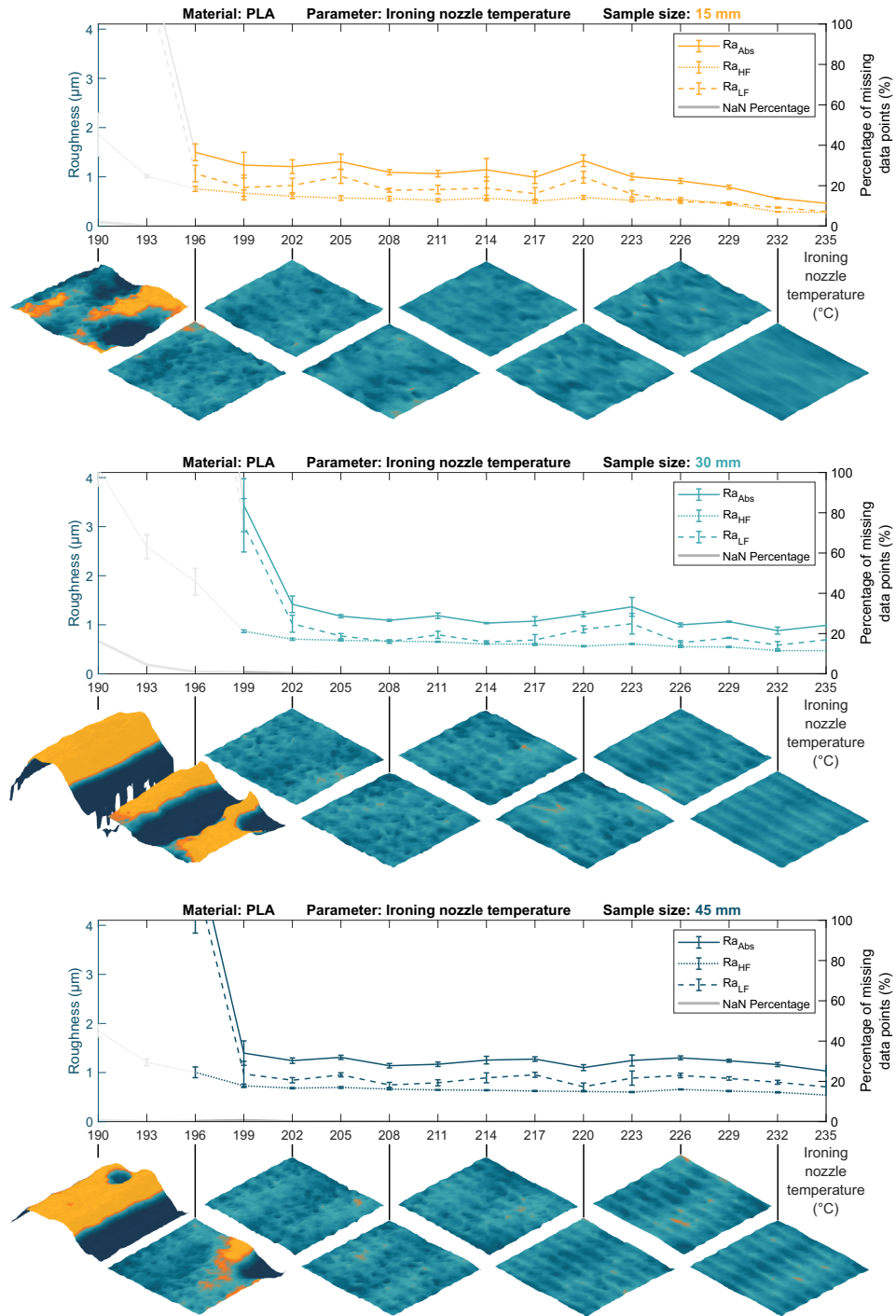


Figure 6-6. Effect of the ironing temperature on roughness for PLA. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

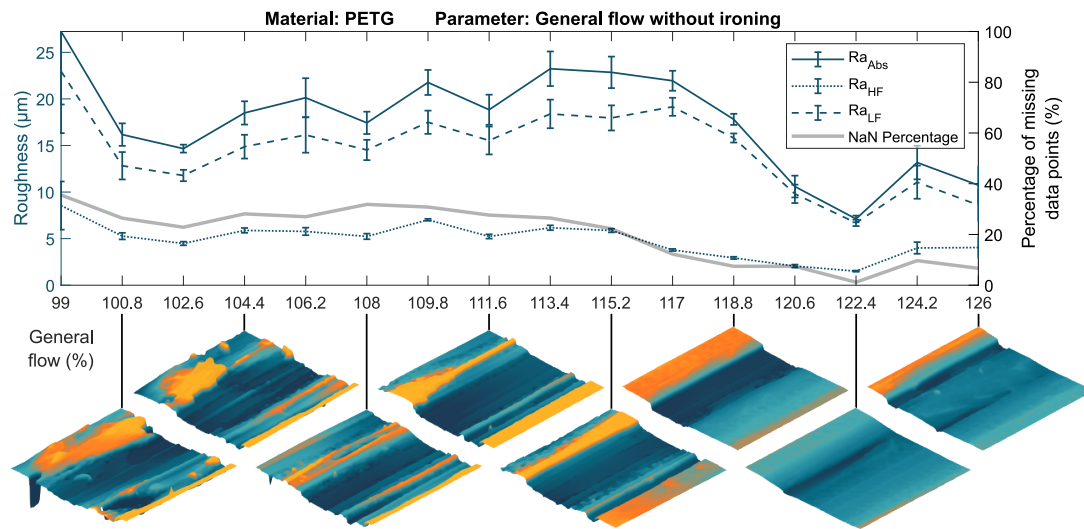


Figure 6-7. Effect of the overall flow without ironing on roughness for PETG.

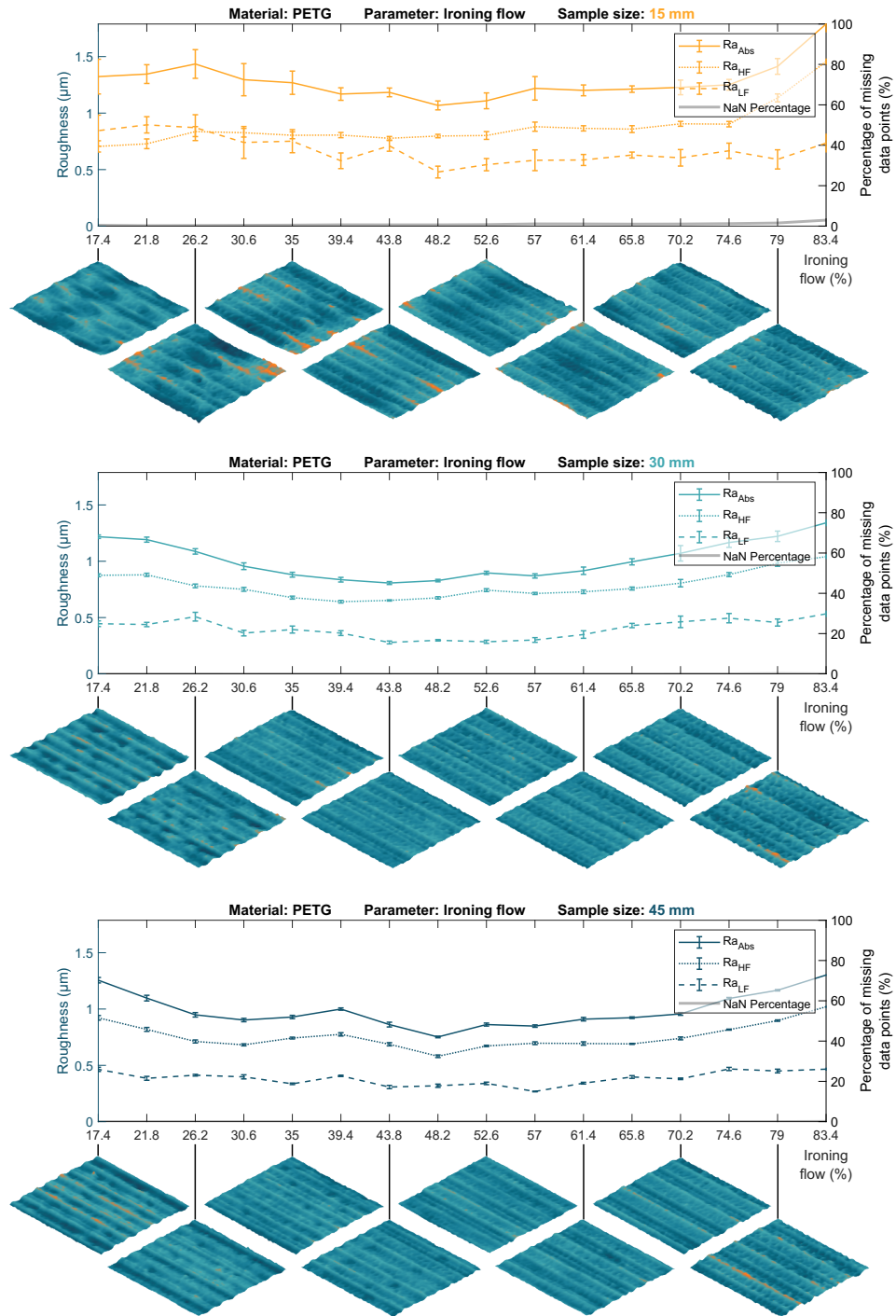


Figure 6-8. Effect of the ironing flow on roughness for PETG. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

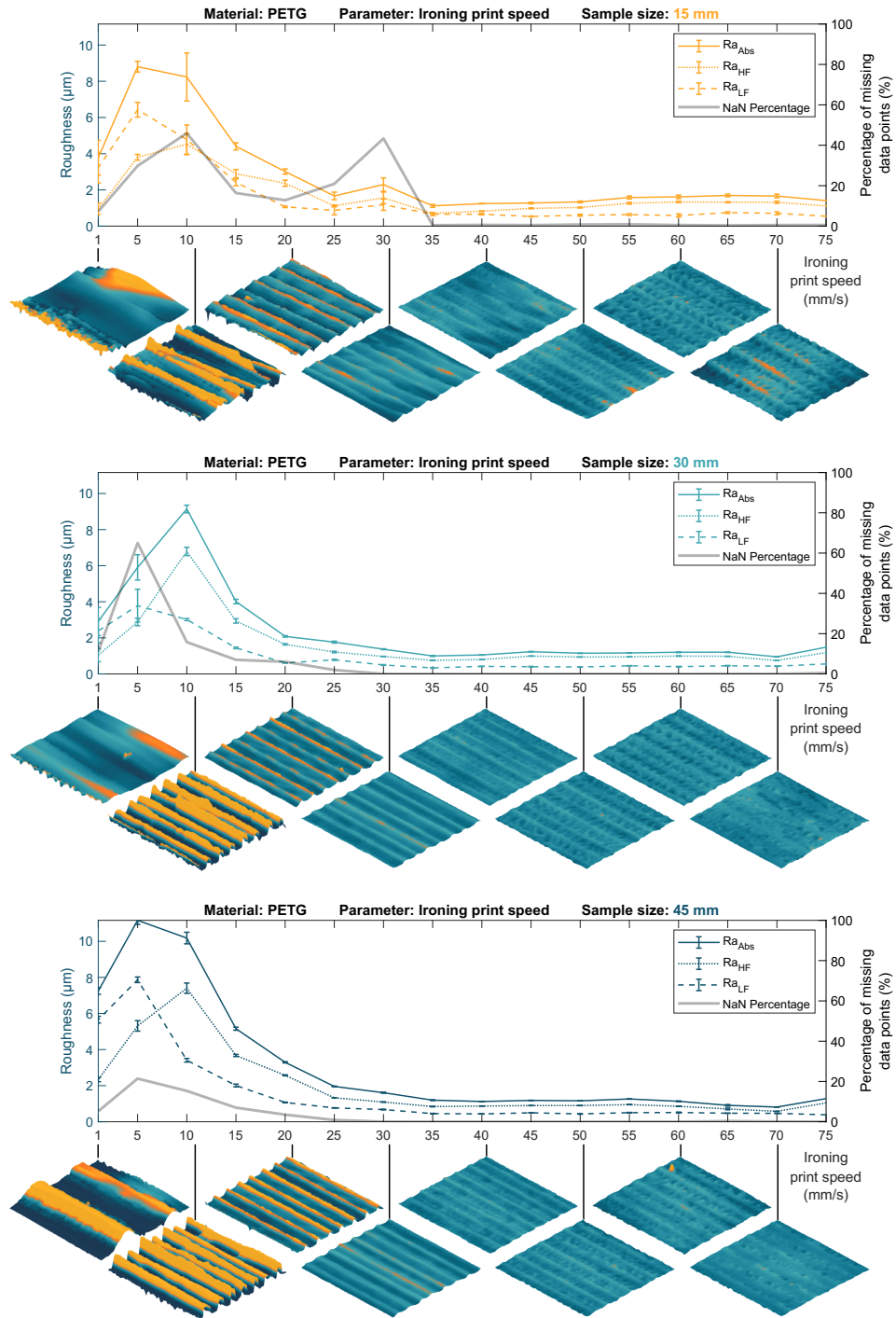


Figure 6-9. Effect of the ironing speed on roughness for PETG. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

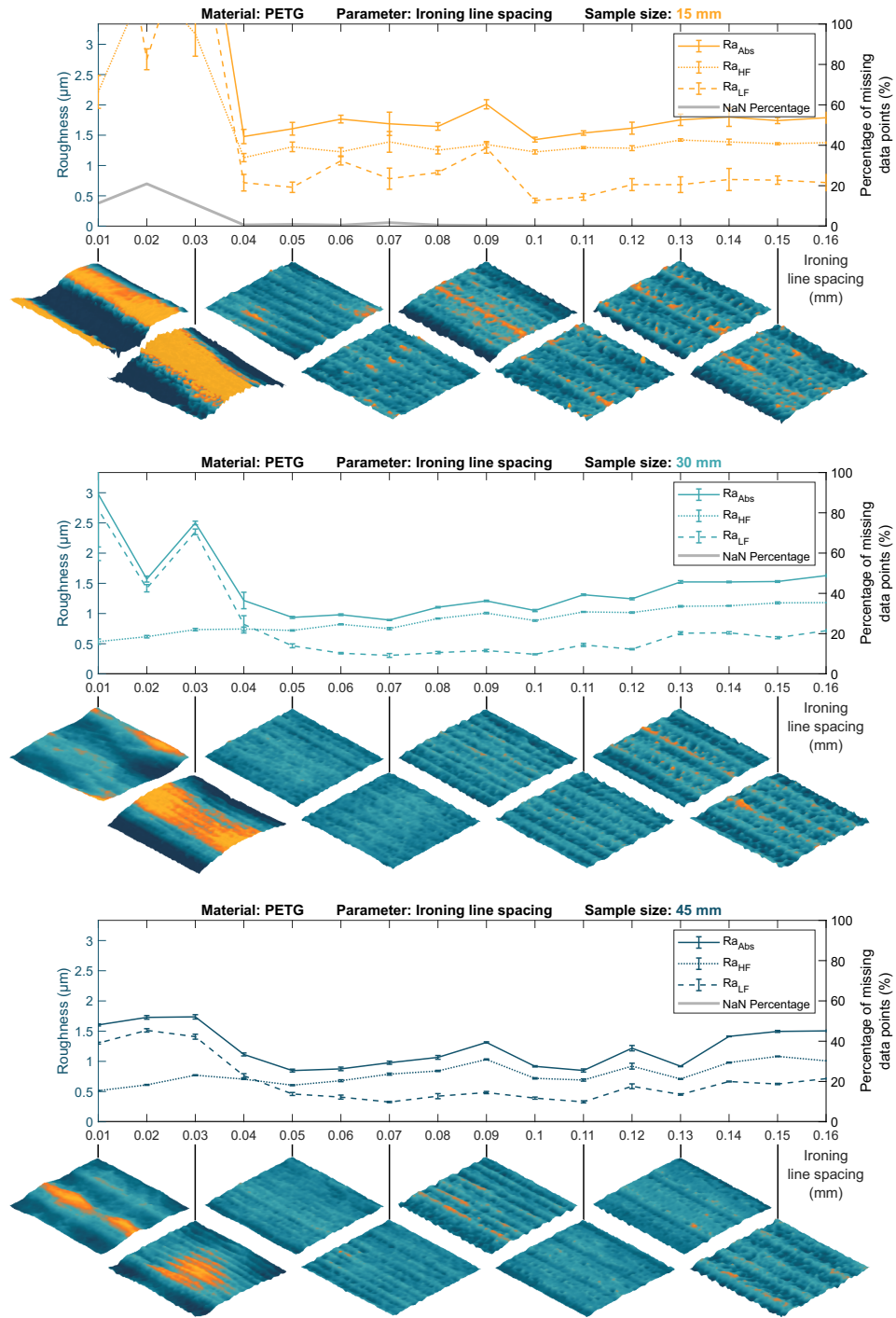


Figure 6-10. Effect of the ironing line spacing on roughness for PETG. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

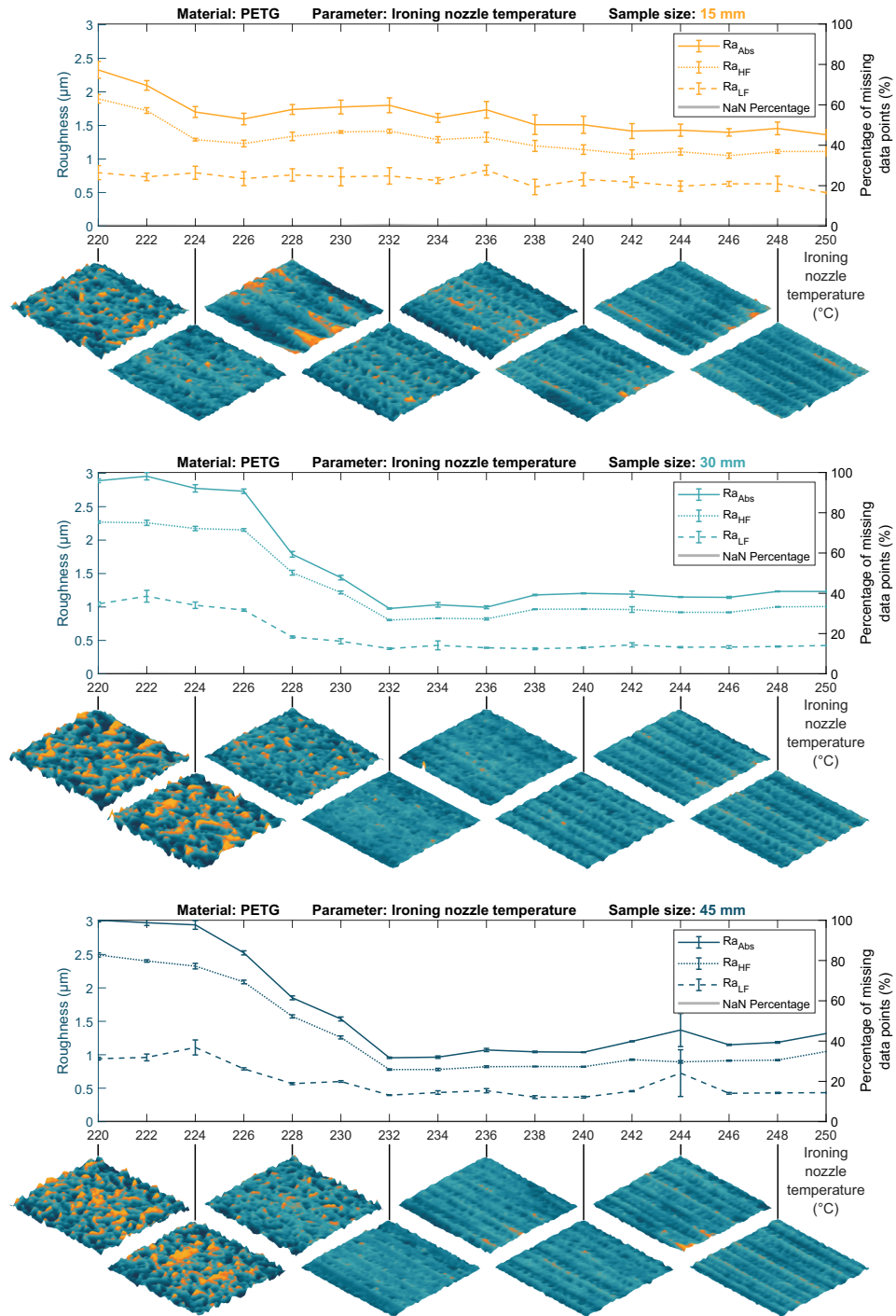


Figure 6-11. Effect of the ironing temperature on roughness for PETG. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

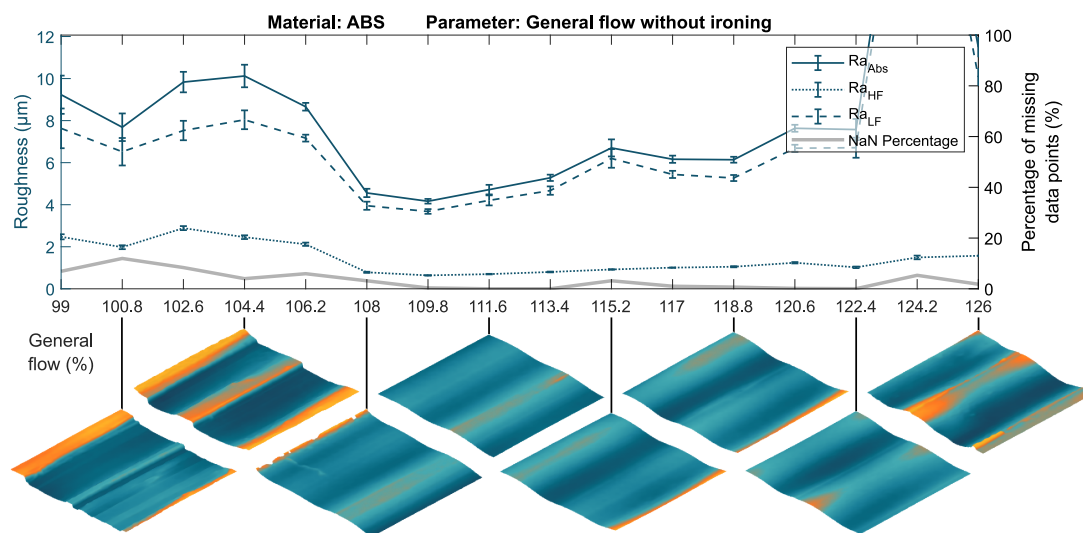


Figure 6-12. Effect of the overall flow without ironing on roughness for ABS.

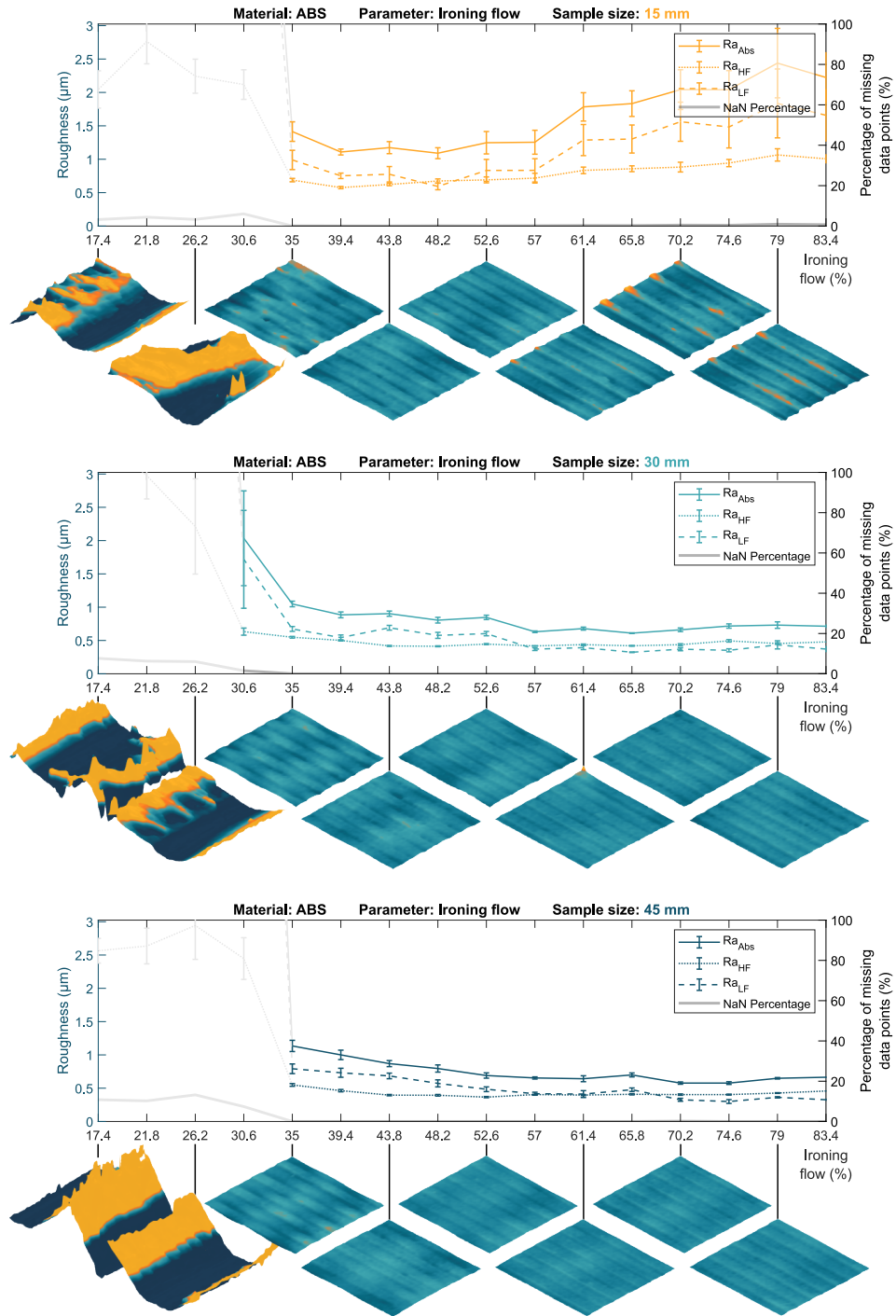


Figure 6-13. Effect of the ironing flow on roughness for ABS. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

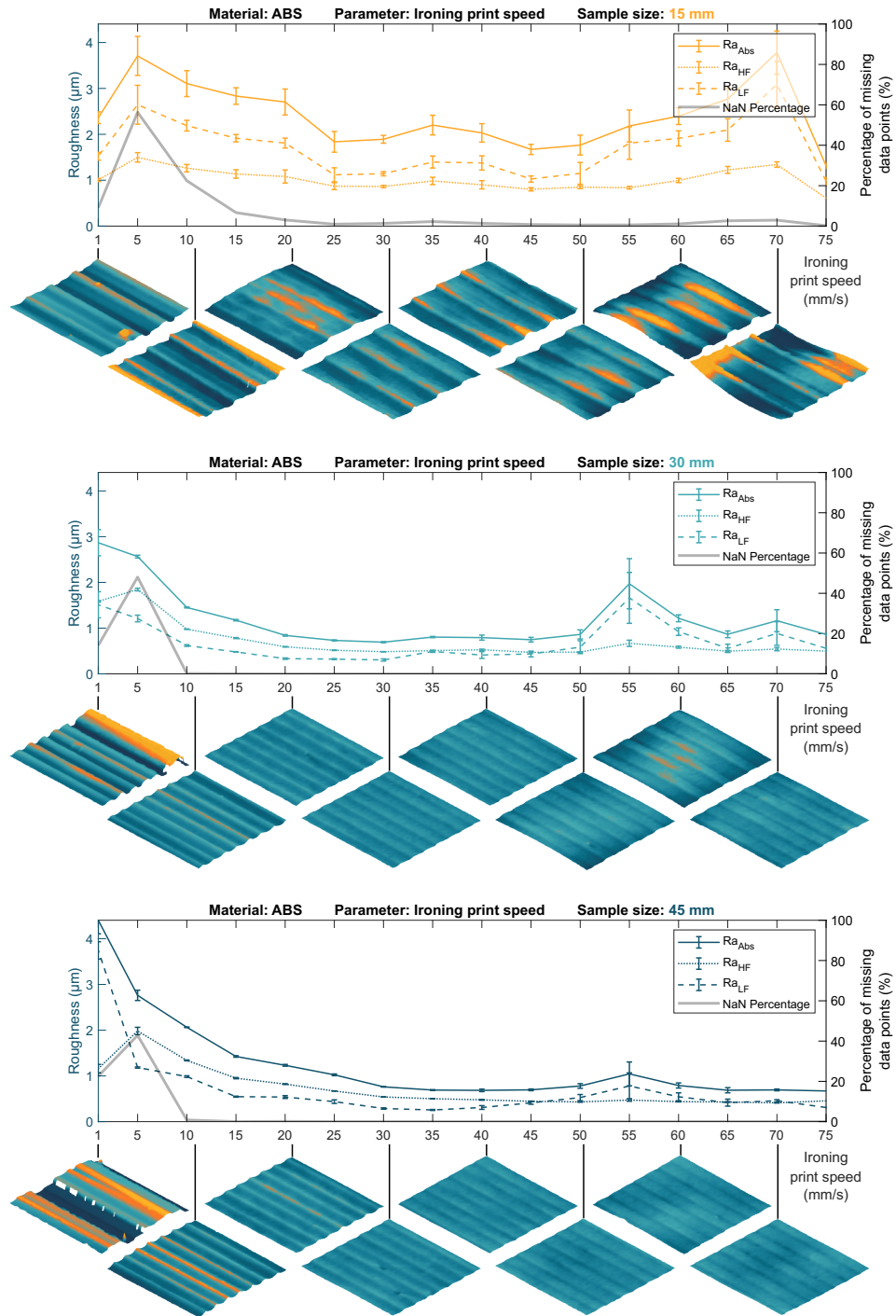


Figure 6-14. Effect of the ironing speed on roughness for ABS. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

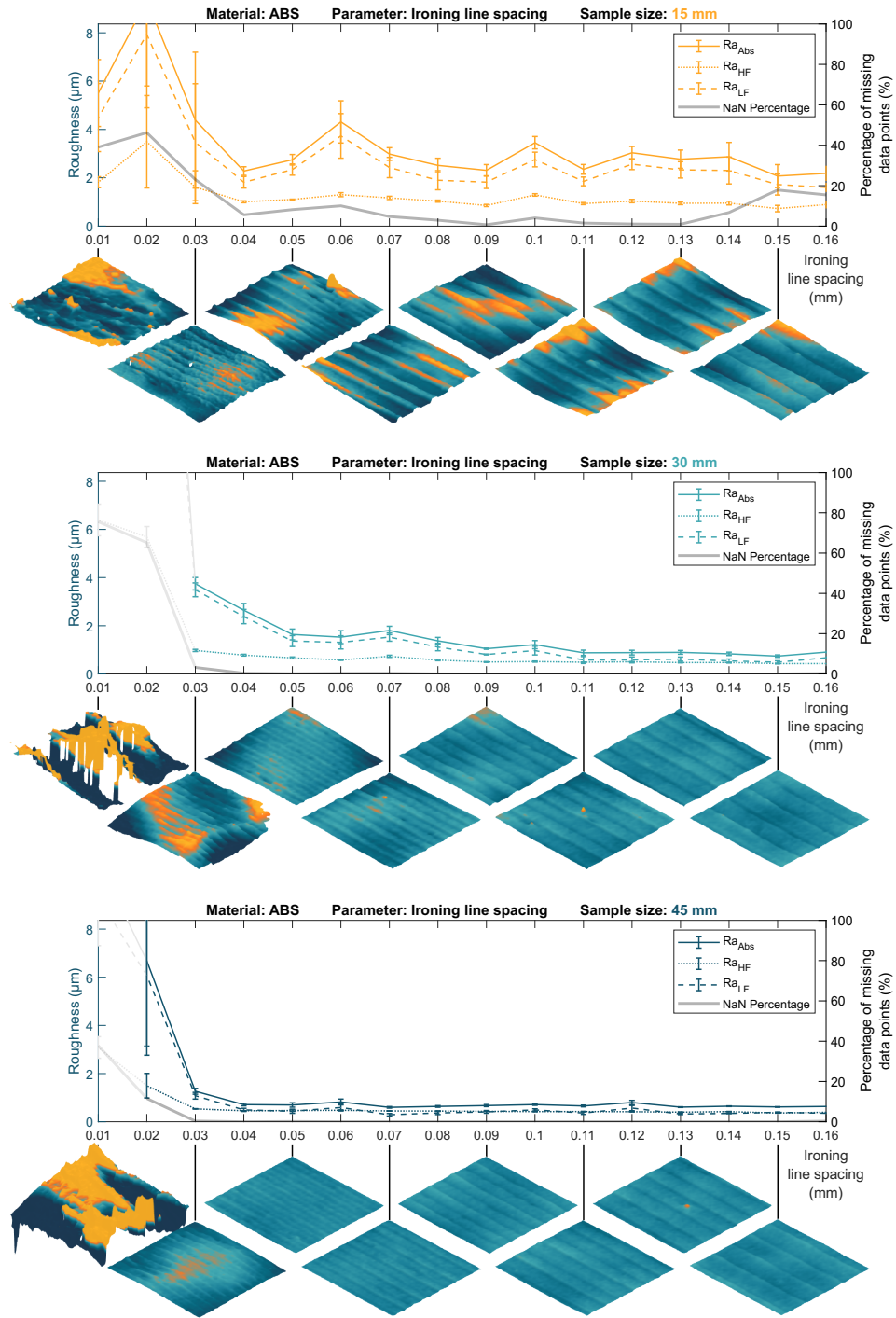


Figure 6-15. Effect of the ironing line spacing on roughness for ABS. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

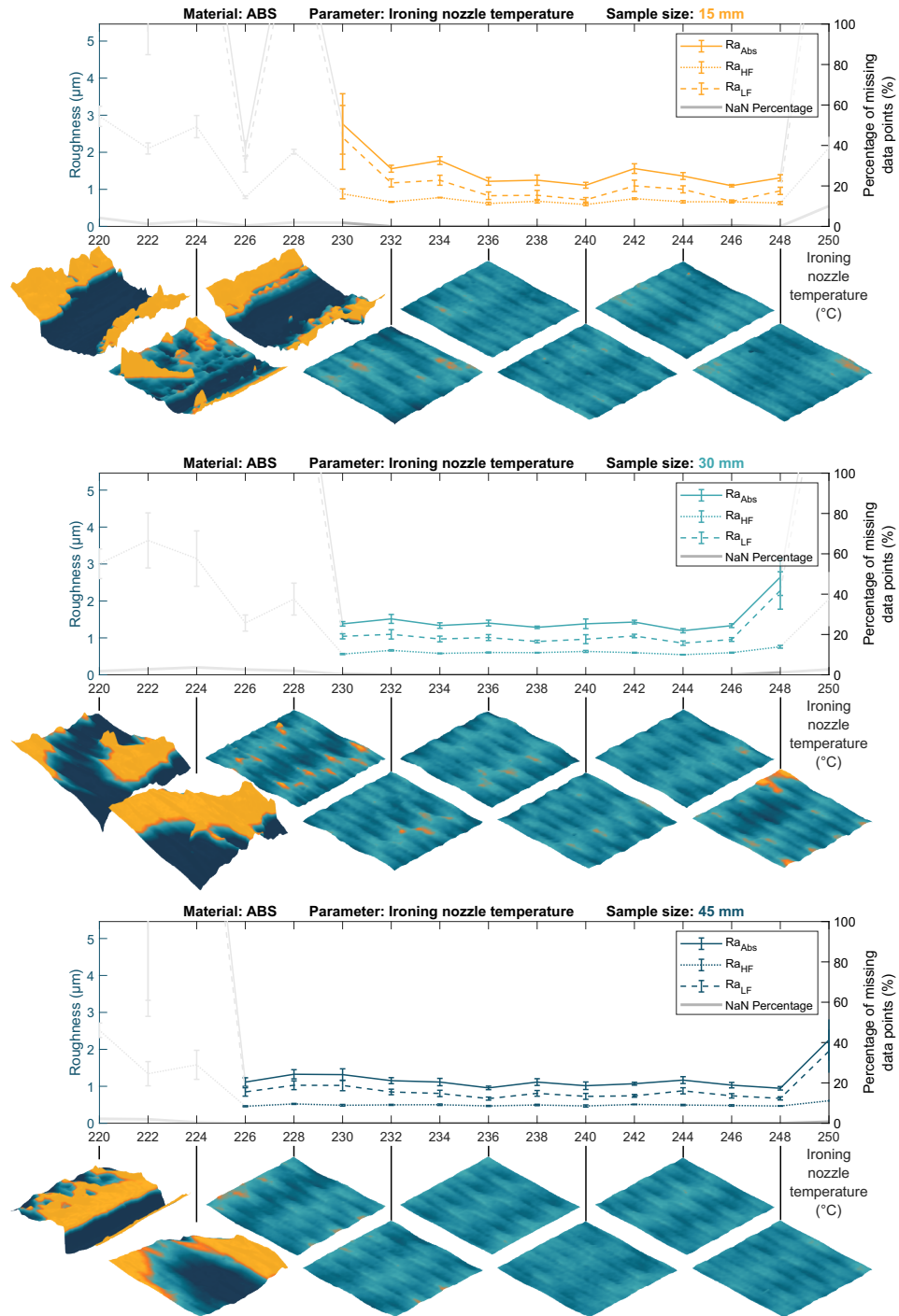


Figure 6-16. Effect of the ironing temperature on roughness for ABS. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

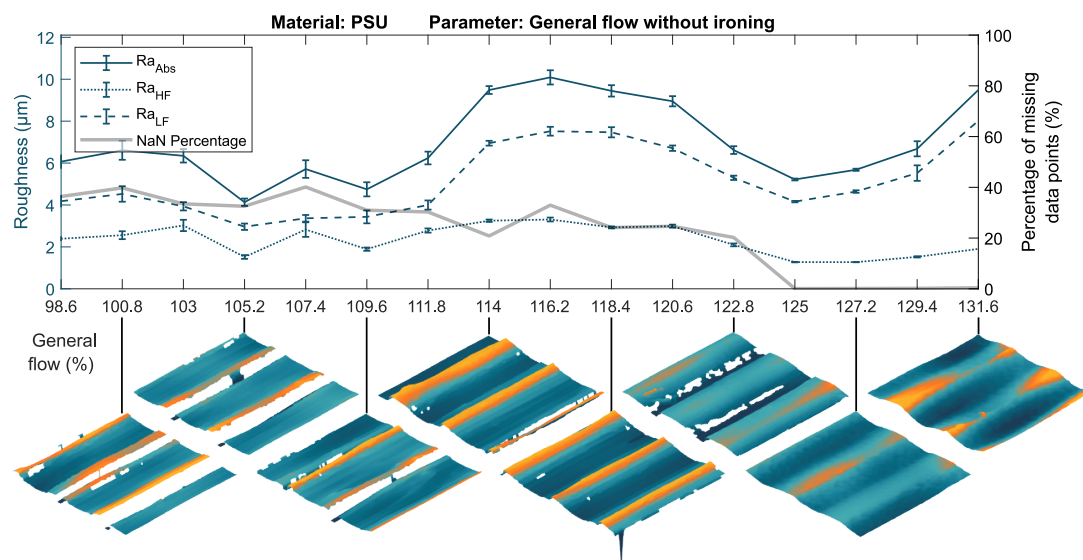


Figure 6-17. Effect of the overall flow without ironing on roughness for PSU.

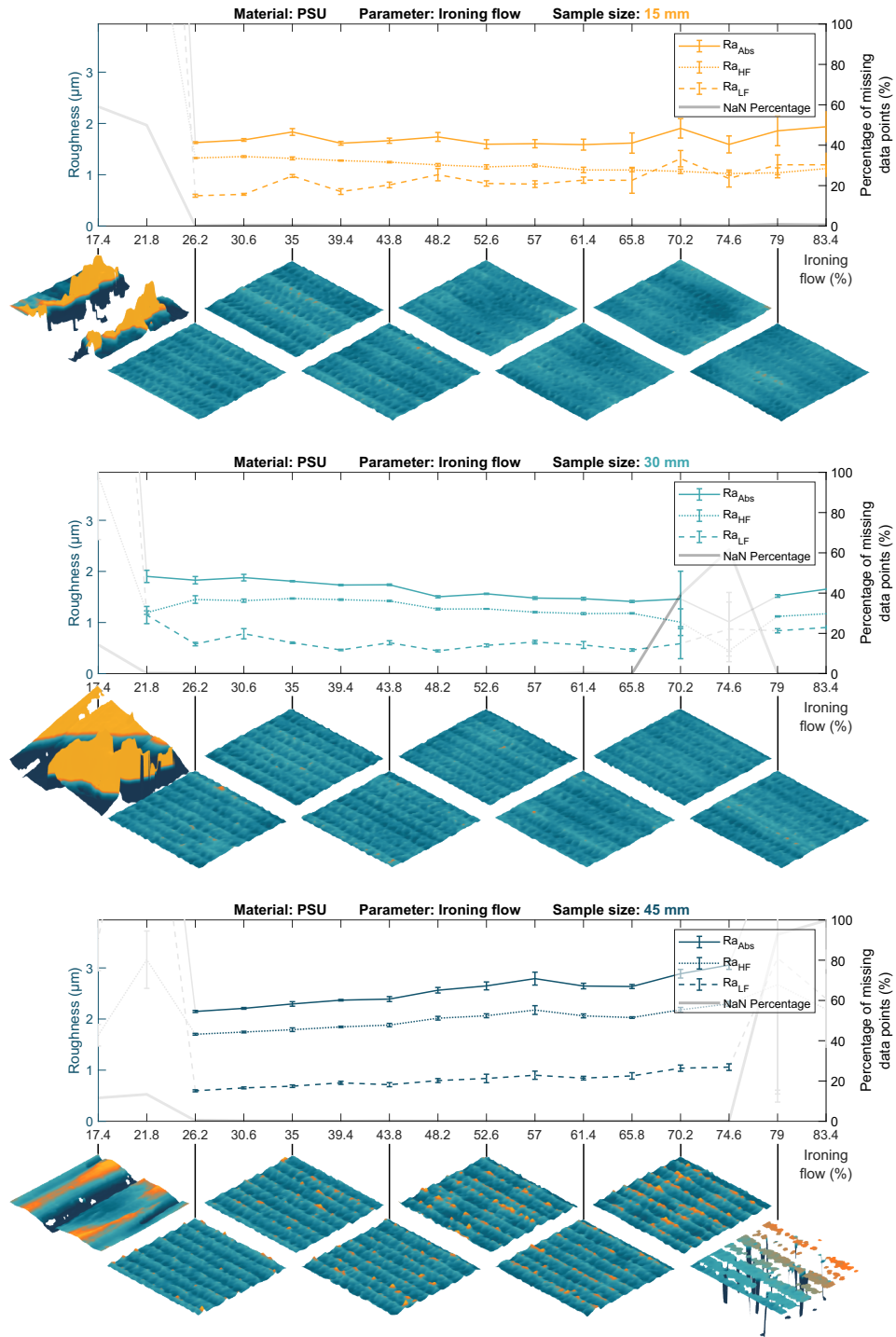


Figure 6-18. Effect of the ironing flow on roughness for PSU. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

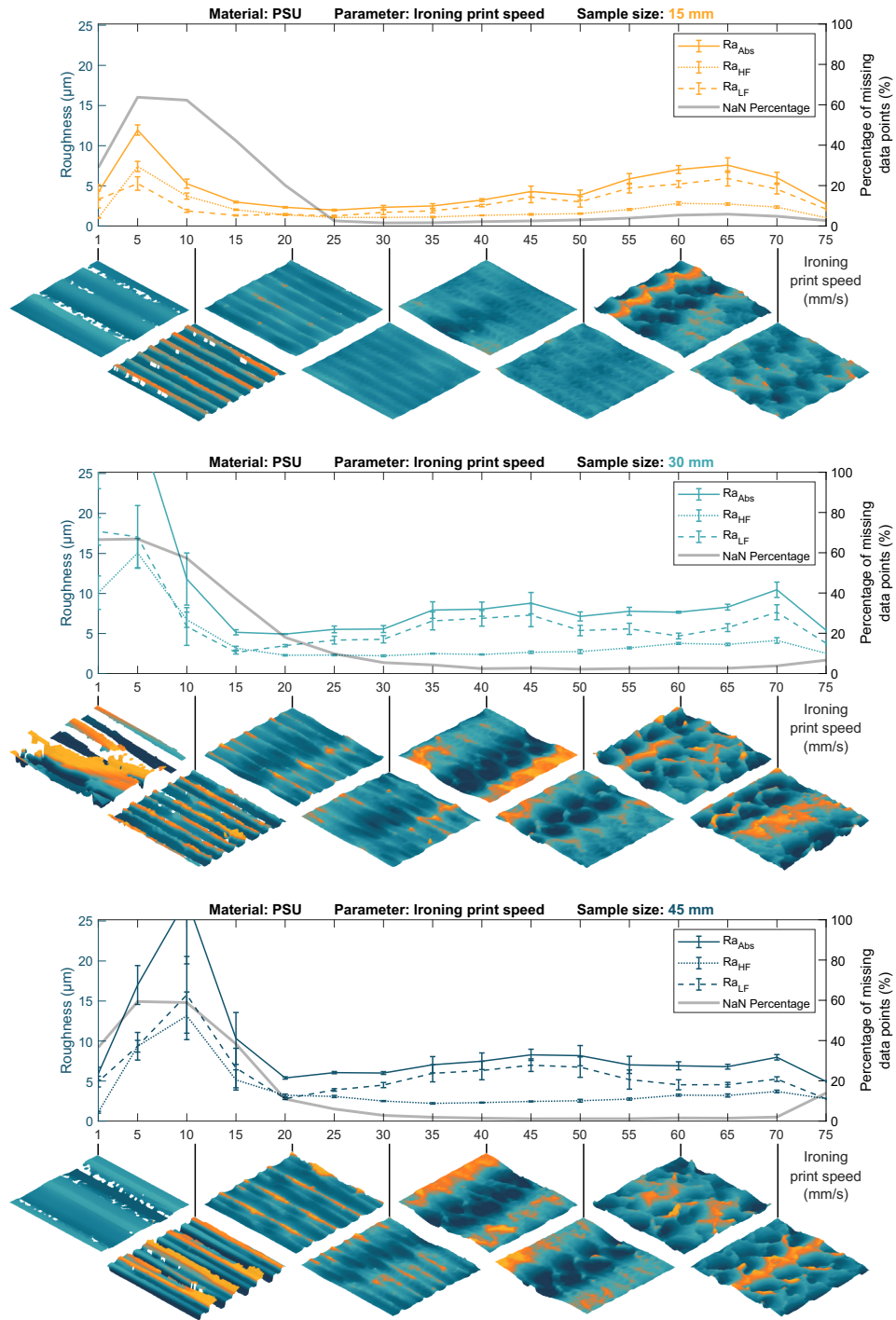


Figure 6-19. Effect of the ironing speed on roughness for PSU. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

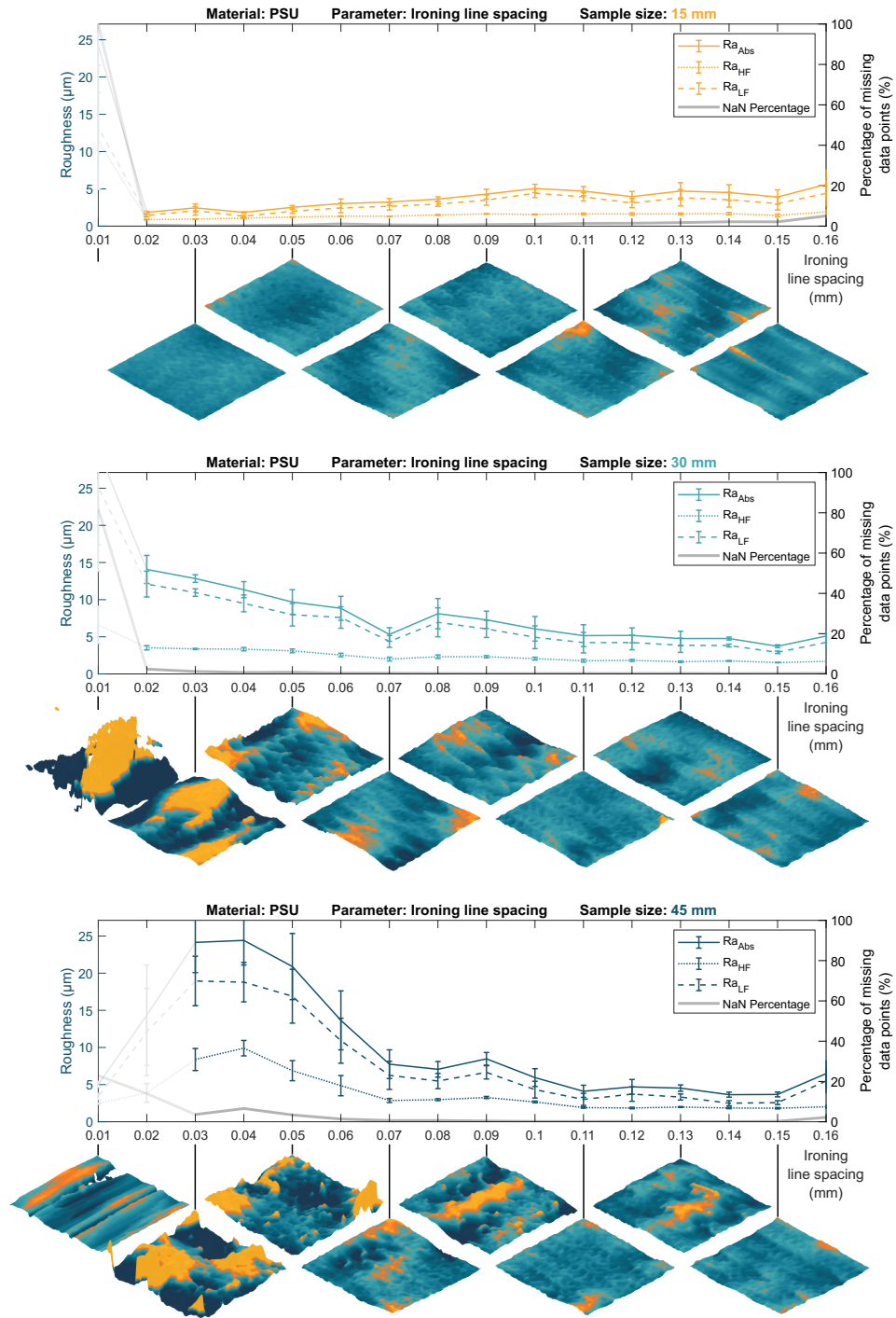


Figure 6-20. Effect of the ironing line spacing on roughness for PSU. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

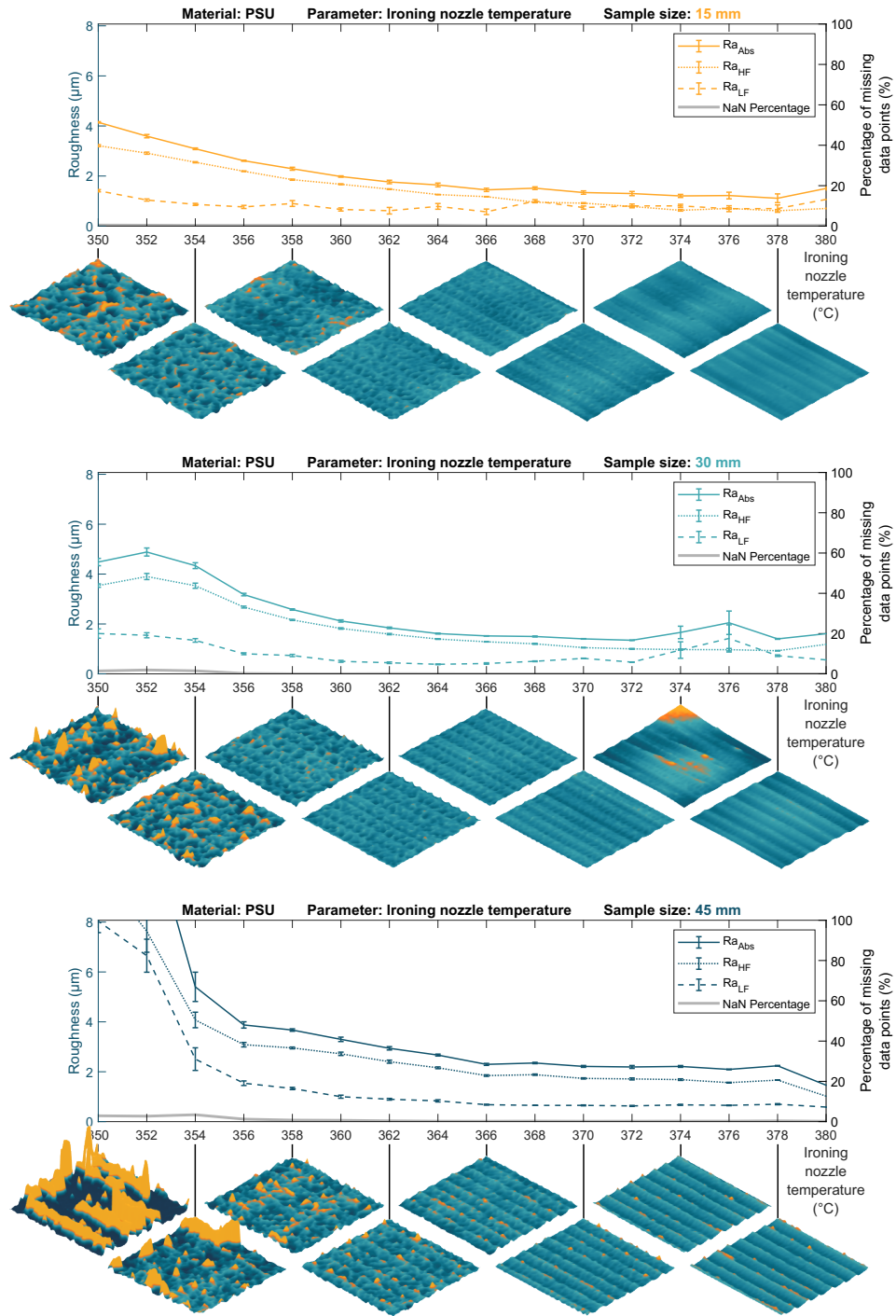


Figure 6-21. Effect of the ironing temperature on roughness for PSU. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

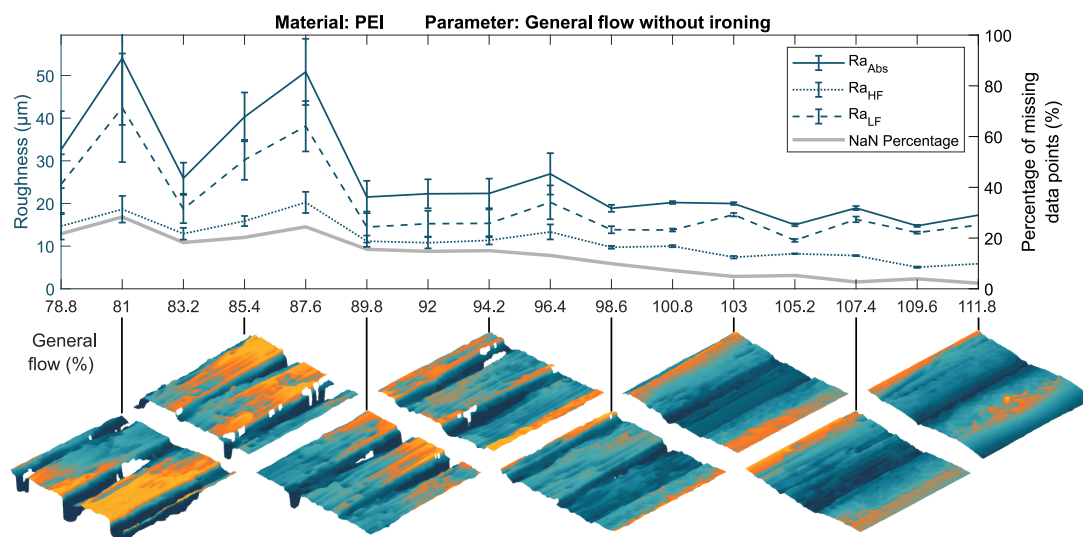


Figure 6-22. Effect of the overall flow without ironing on roughness for PEI.

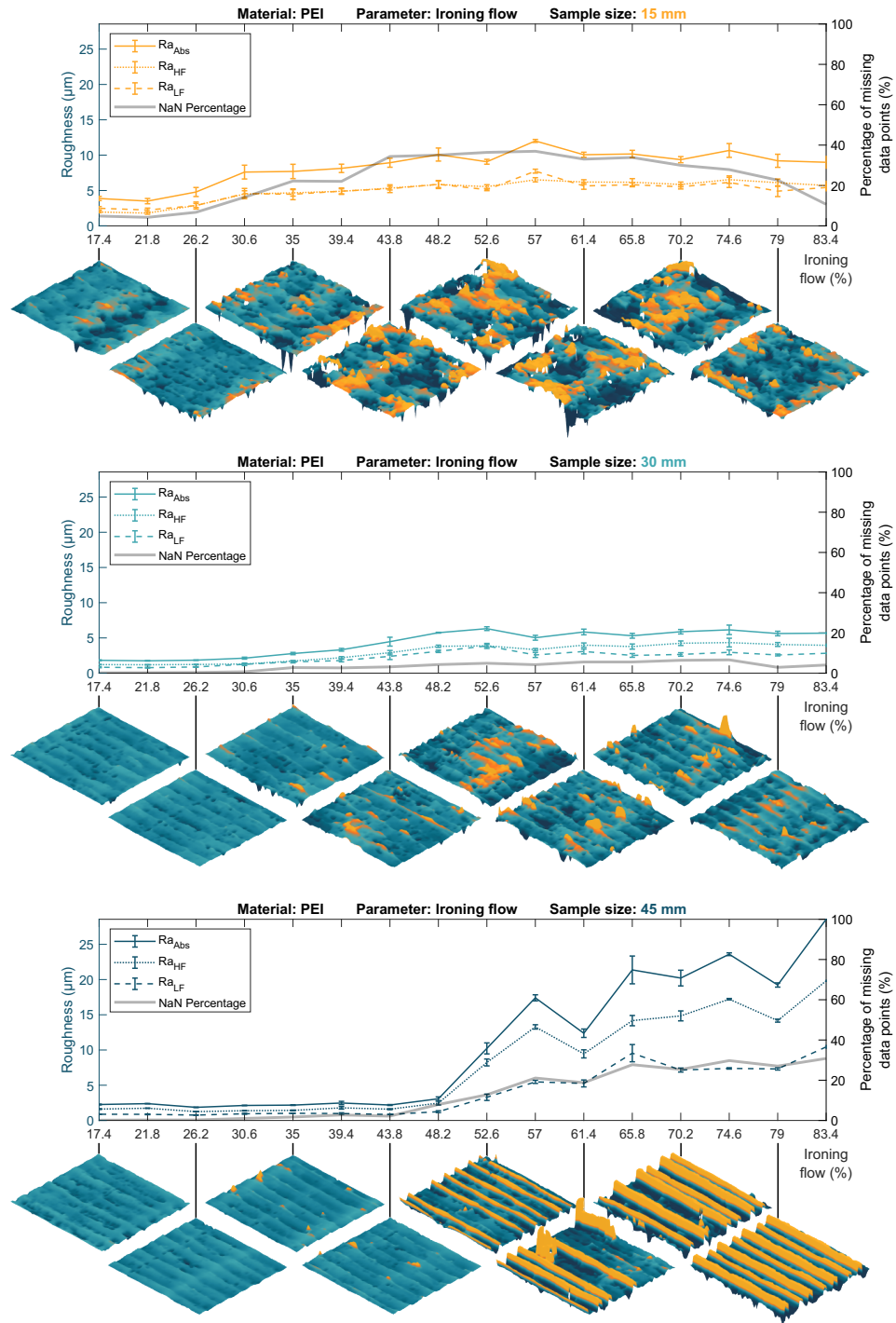


Figure 6-23. Effect of the ironing flow on roughness for PEI. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

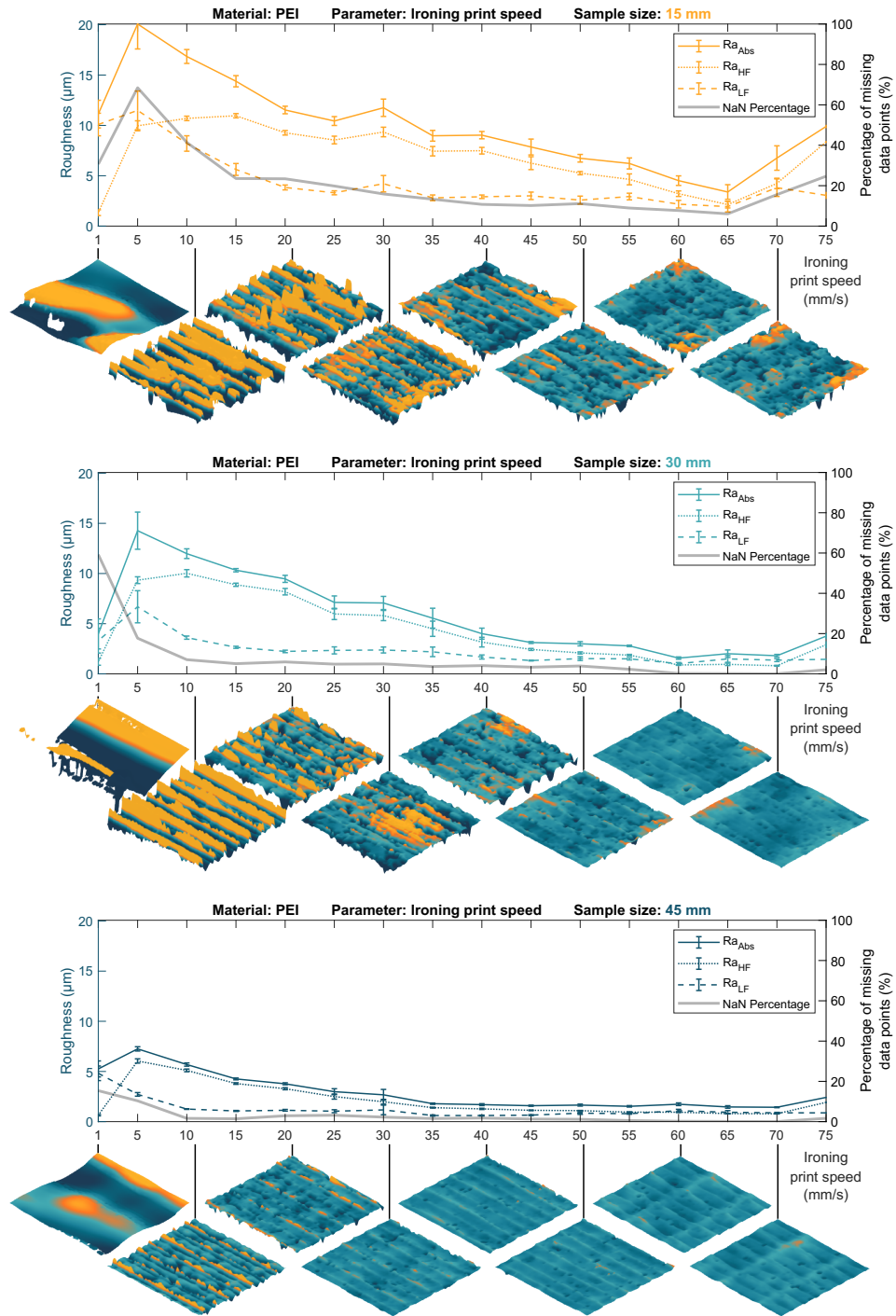


Figure 6-24. Effect of the ironing speed on roughness for PEI. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

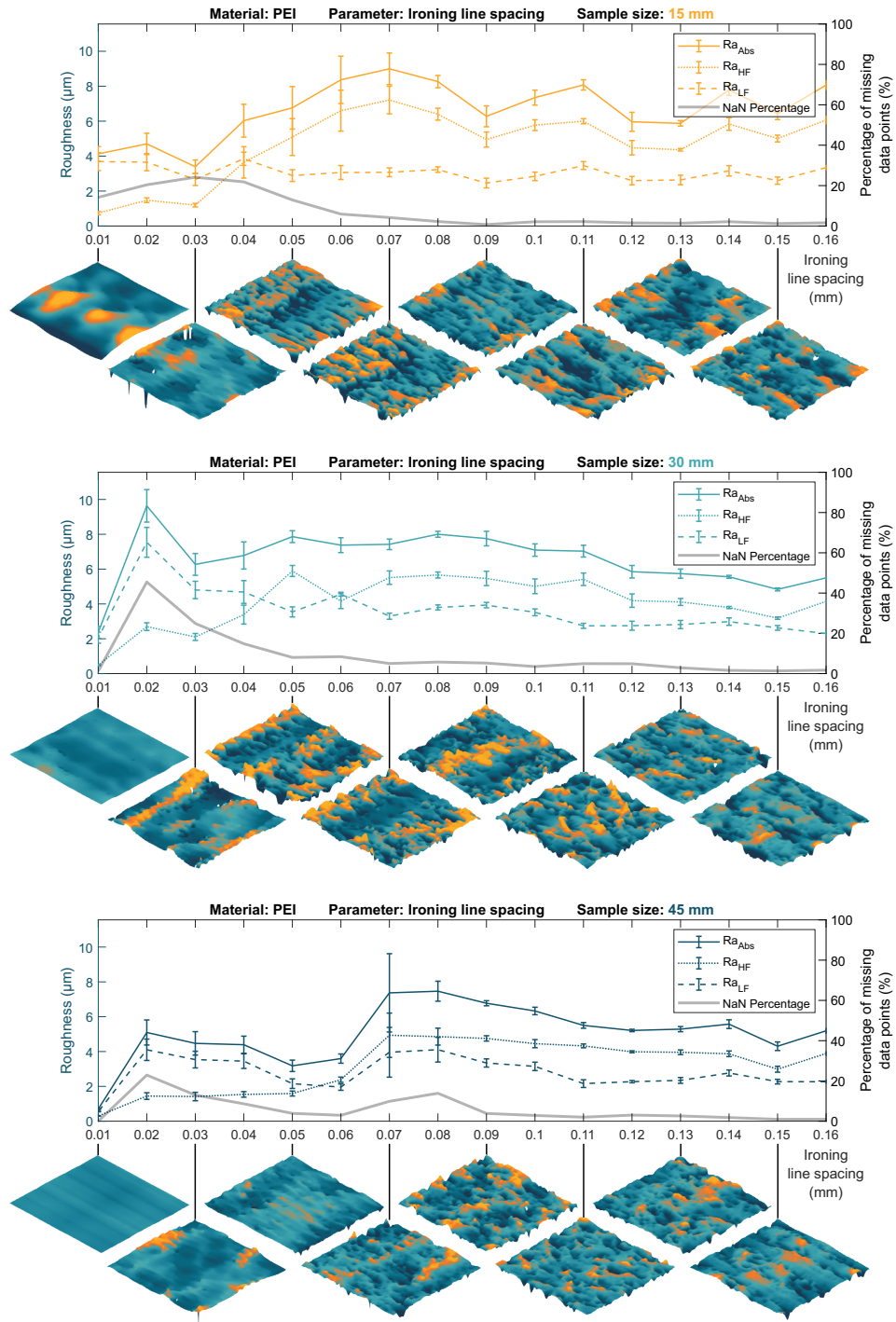


Figure 6-25. Effect of the ironing line spacing on roughness for PEI. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

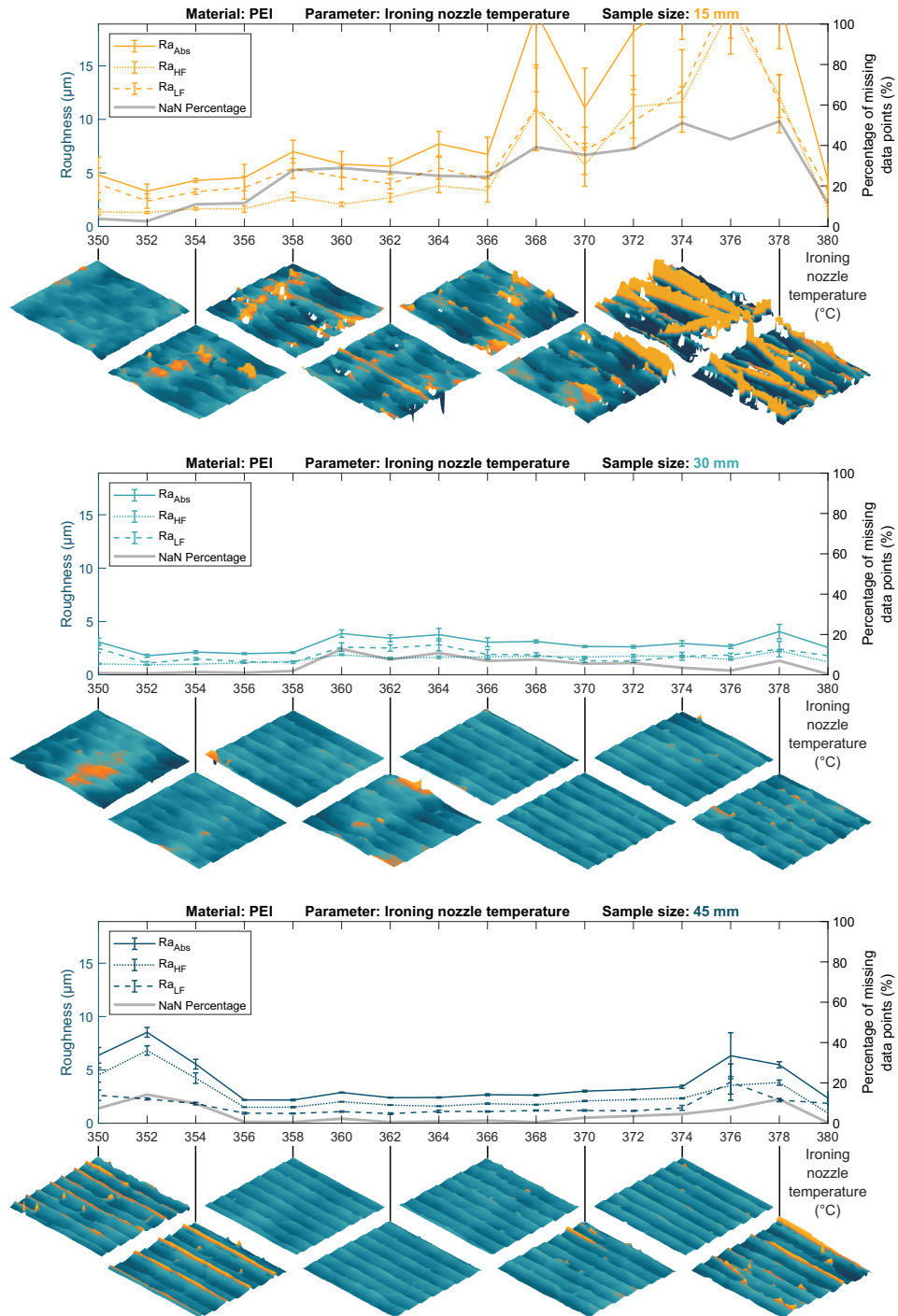


Figure 6-26. Effect of the ironing temperature on roughness for PEI. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

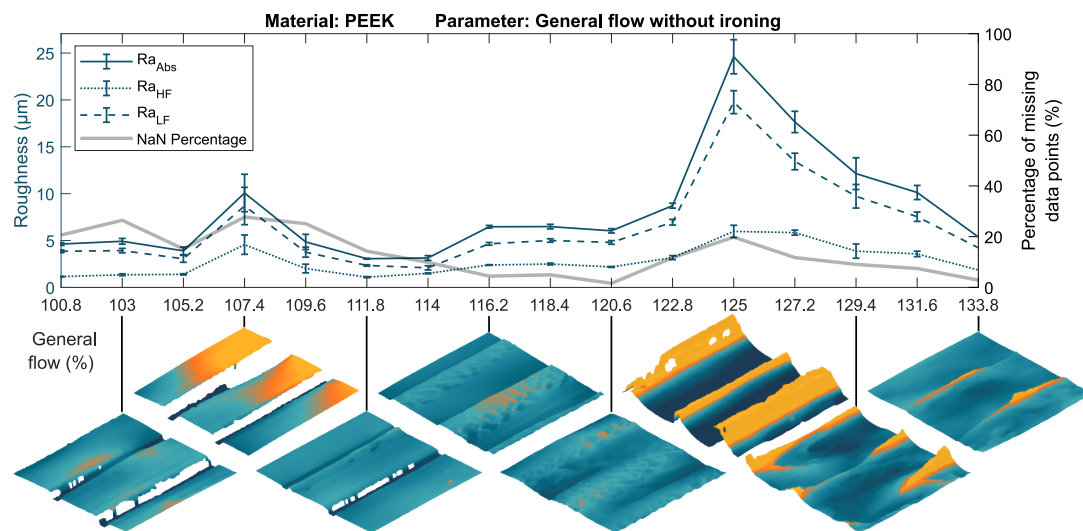


Figure 6-27. Effect of the overall flow without ironing on roughness for PEEK.

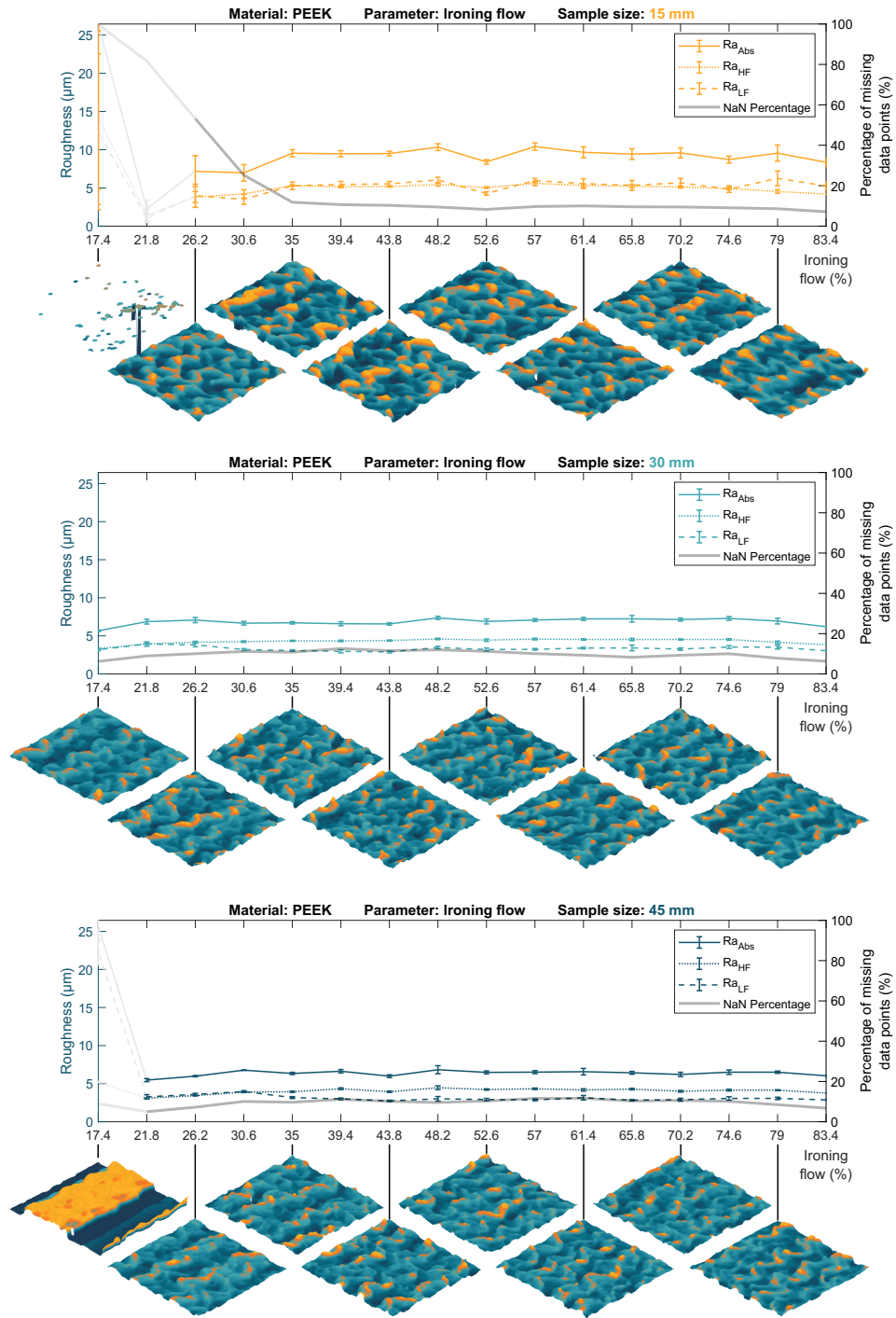


Figure 6-28. Effect of the ironing flow on roughness for PEEK. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

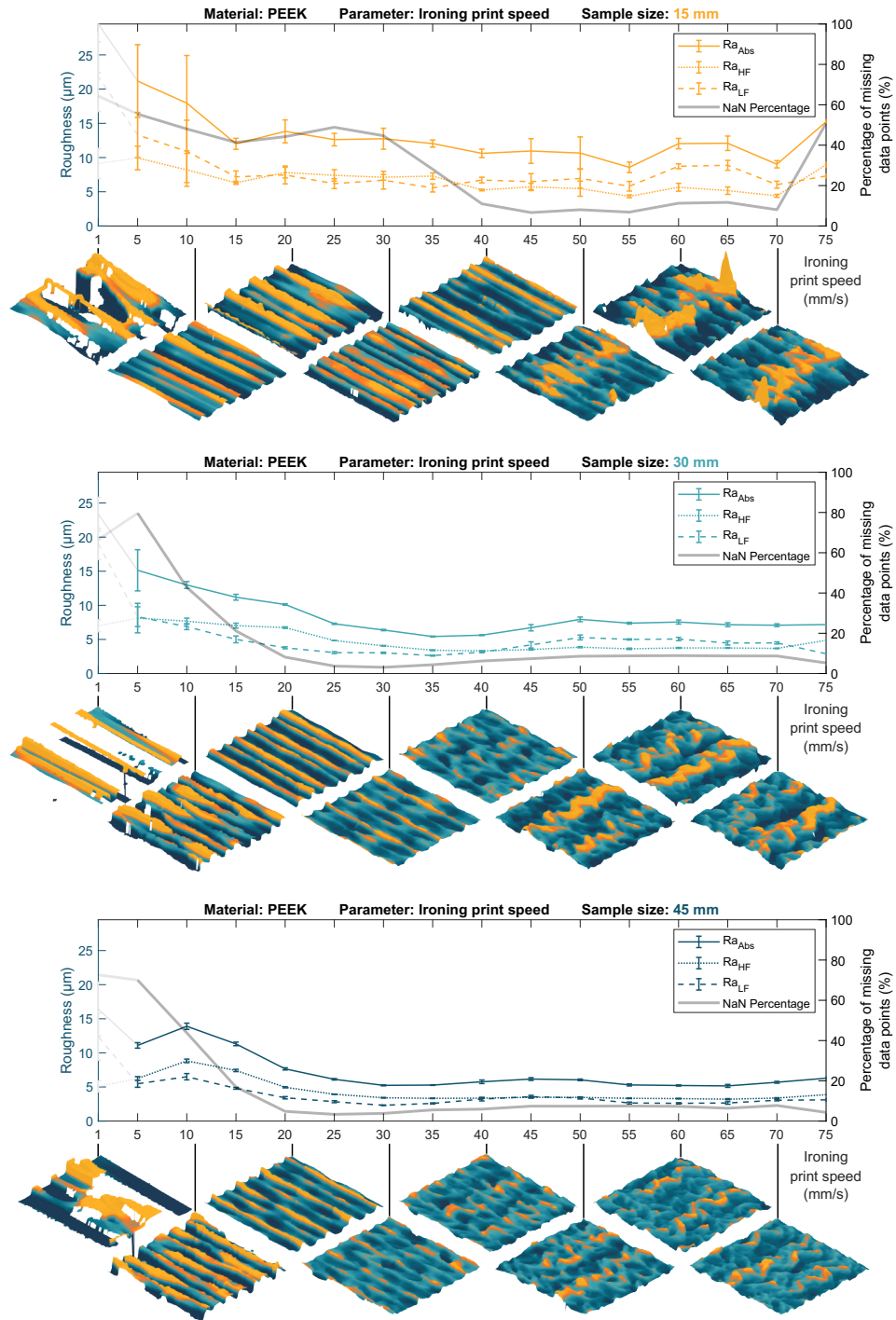


Figure 6-29. Effect of the ironing speed on roughness for PEEK. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

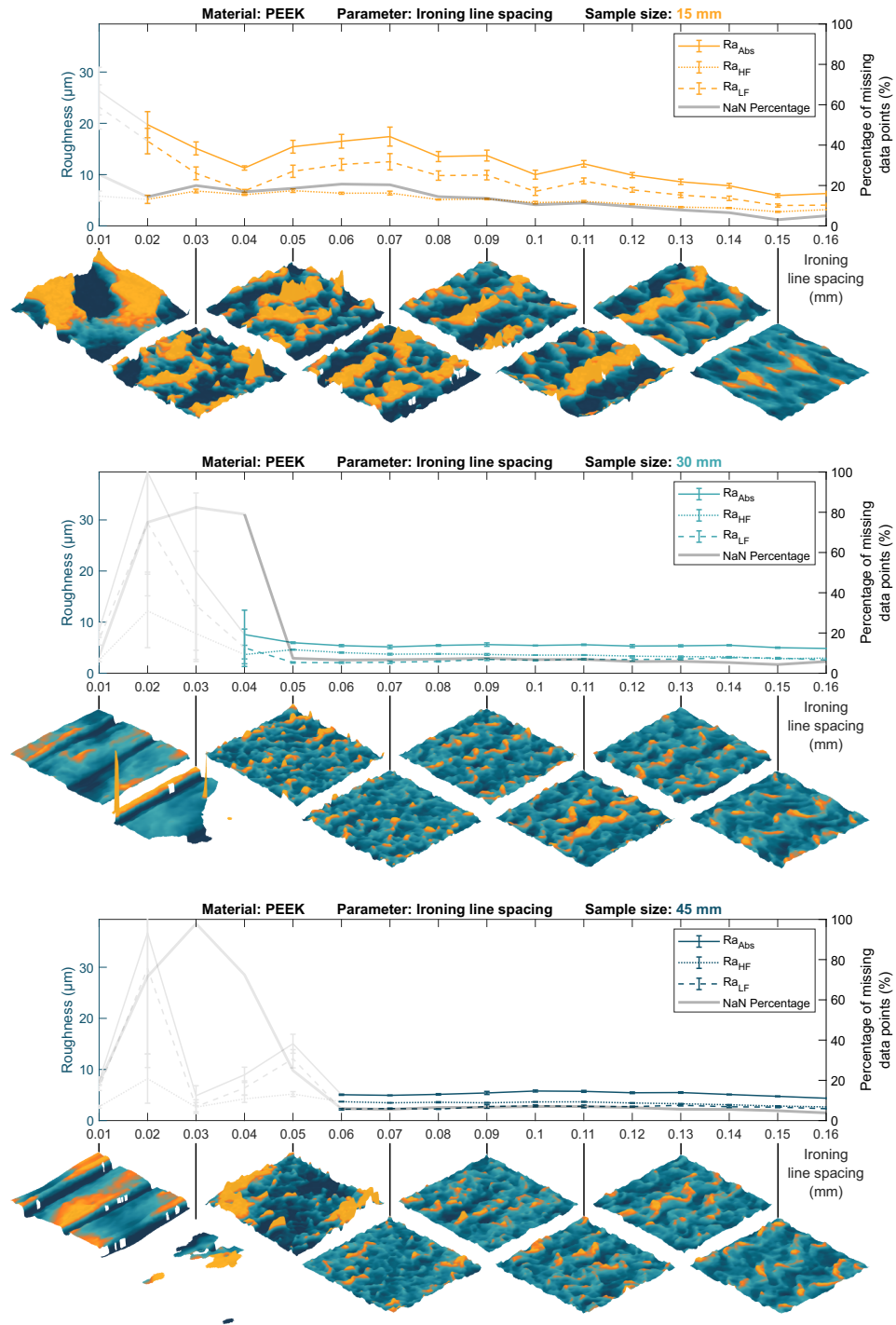


Figure 6-30. Effect of the ironing line spacing on roughness for PEEK. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

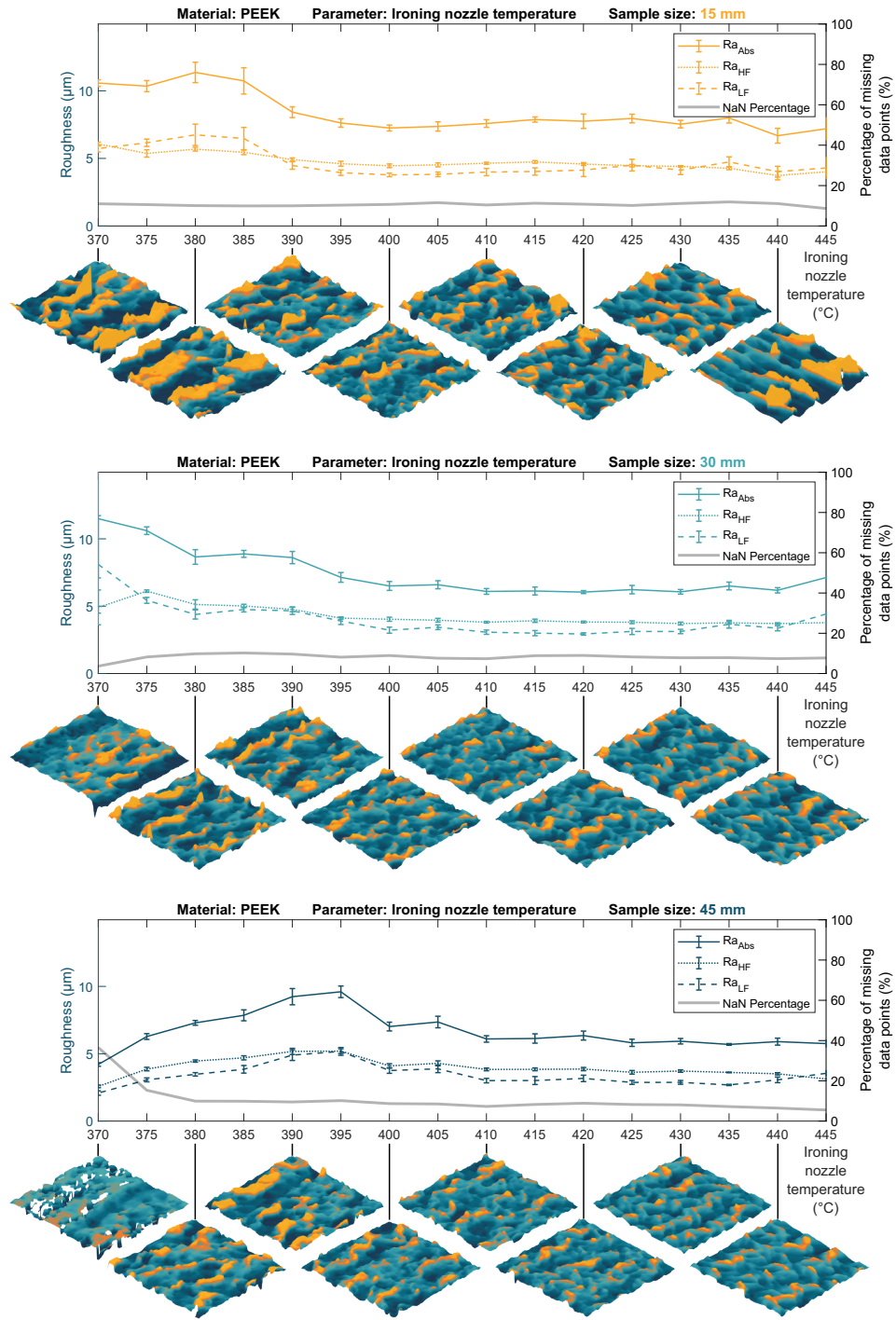


Figure 6-31. Effect of the ironing temperature on roughness for PEEK. The three different graphs correspond to the three different sample sizes (15, 30 and 45 mm).

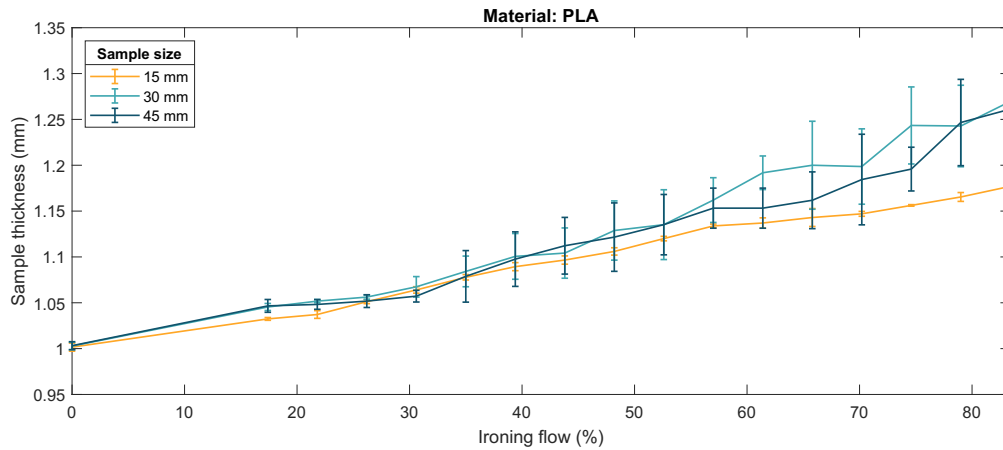


Figure 6-32. Effect of the ironing flow on the sample thickness for PLA. Increased ironing flow leads to linear deviations from the CAD-programmed sample thickness which was set to 1 mm.

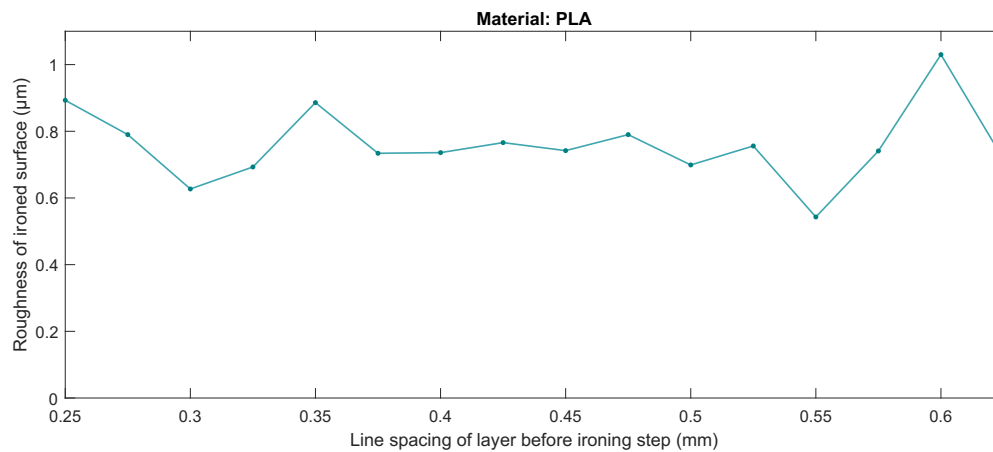


Figure 6-33. Effect of the line spacing of the layer before the ironing step. In this initial preliminary study with a slightly different sample design, the impact of this line spacing was found to be negligible, leading to the discontinuation of further studies.

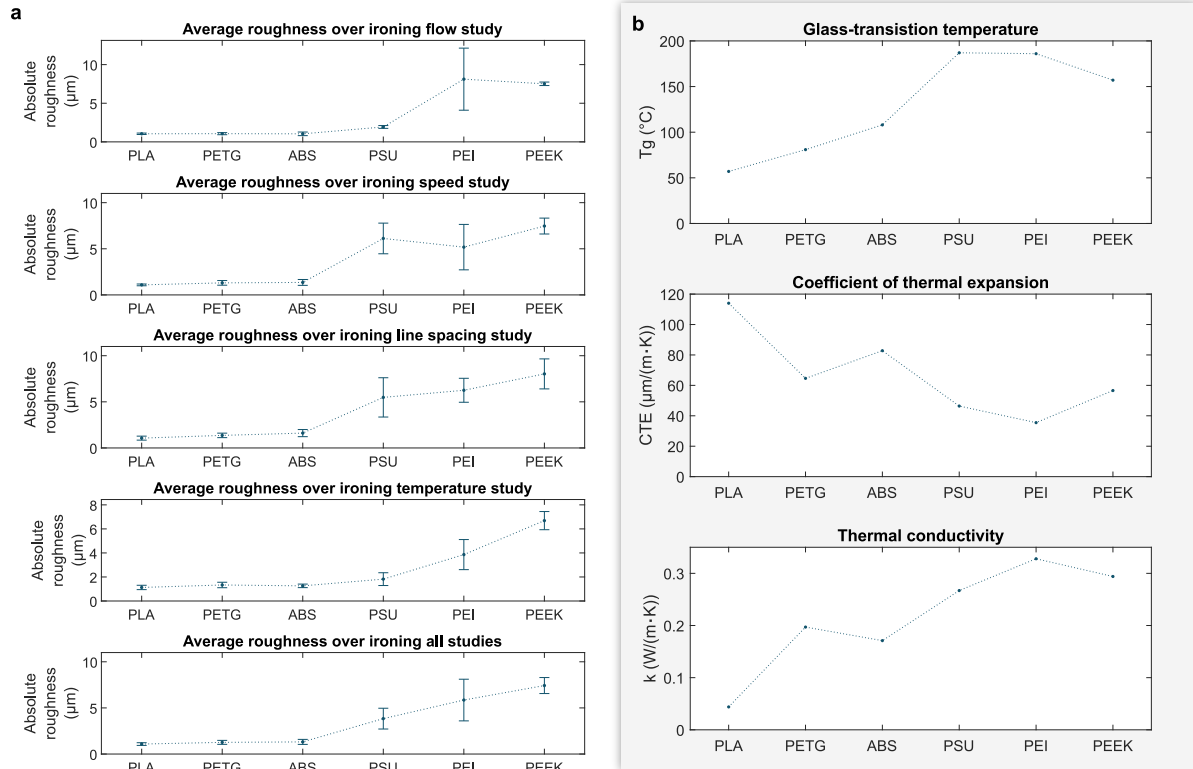


Figure 6-34. Material properties and ironing roughness. a) Average roughness of ironing parameter studies, averaged by material. b) Material properties sourced from <https://www.matweb.com/> (2023).

While no clear correlation between properties and roughness is observed, lower glass transition temperatures and thermal conductivity seem advantageous for optimal ironing results. Lower glass transition temperatures may enhance remelting during ironing, while lower thermal conductivity may concentrate heat, benefiting remelting behavior.

Table 6-1. Print settings of the samples analyzed under the scanning electron microscope.

Material	PLA	PETG	ABS	PSU	PEI	PEEK
Printing temperature	235 °C	247 °C	240 °C	380 °C	365 °C	440 °C
Build plate temperature	60 °C	80 °C	100 °C	170 °C	170 °C	180 °C
General flow	110.0%	111%	105.0%	114.0%	103%	118.0%
Ironing line spacing	0.1 mm	0.1 mm	0.1 mm	0.15 mm	0.05 mm	0.16 mm
Ironing flow	75.0%	48.0%	44%	79.0%	44%	105.0%
Ironing speed	75 mm/s	75 mm/s	75 mm/s	60 mm/s	65 mm/s	75 mm/s

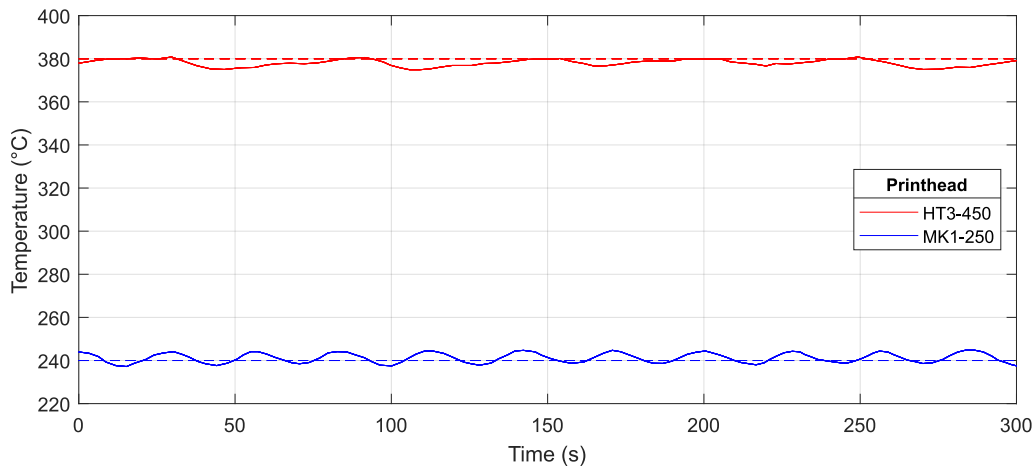


Figure 6-35. Nozzle temperature fluctuations of the two different printheads. The MK1-250 has been utilized to print the PLA, PETG, and ABS samples while the HT3-450 has been used to print the PSU, PEI, and PEEK samples. The dotted lines indicate the setpoint temperature. The temperature of the HT3-450 fluctuates by roughly 6 degrees while the MK1-250 fluctuates by 8 degrees.

Appendix B. Edge Roughness of Dispense Printed Lines

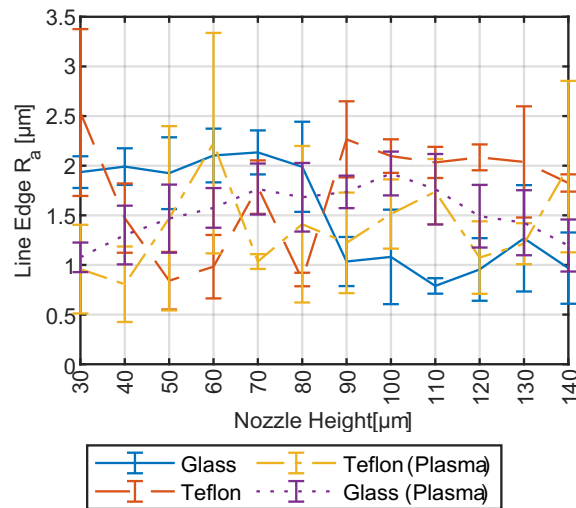


Figure 6-36. Nozzle height sweep of printing on the four surfaces using NovaCentrix Metalon HPS-FG77. The effect of nozzle height on edge roughness (R_a) is negligible.

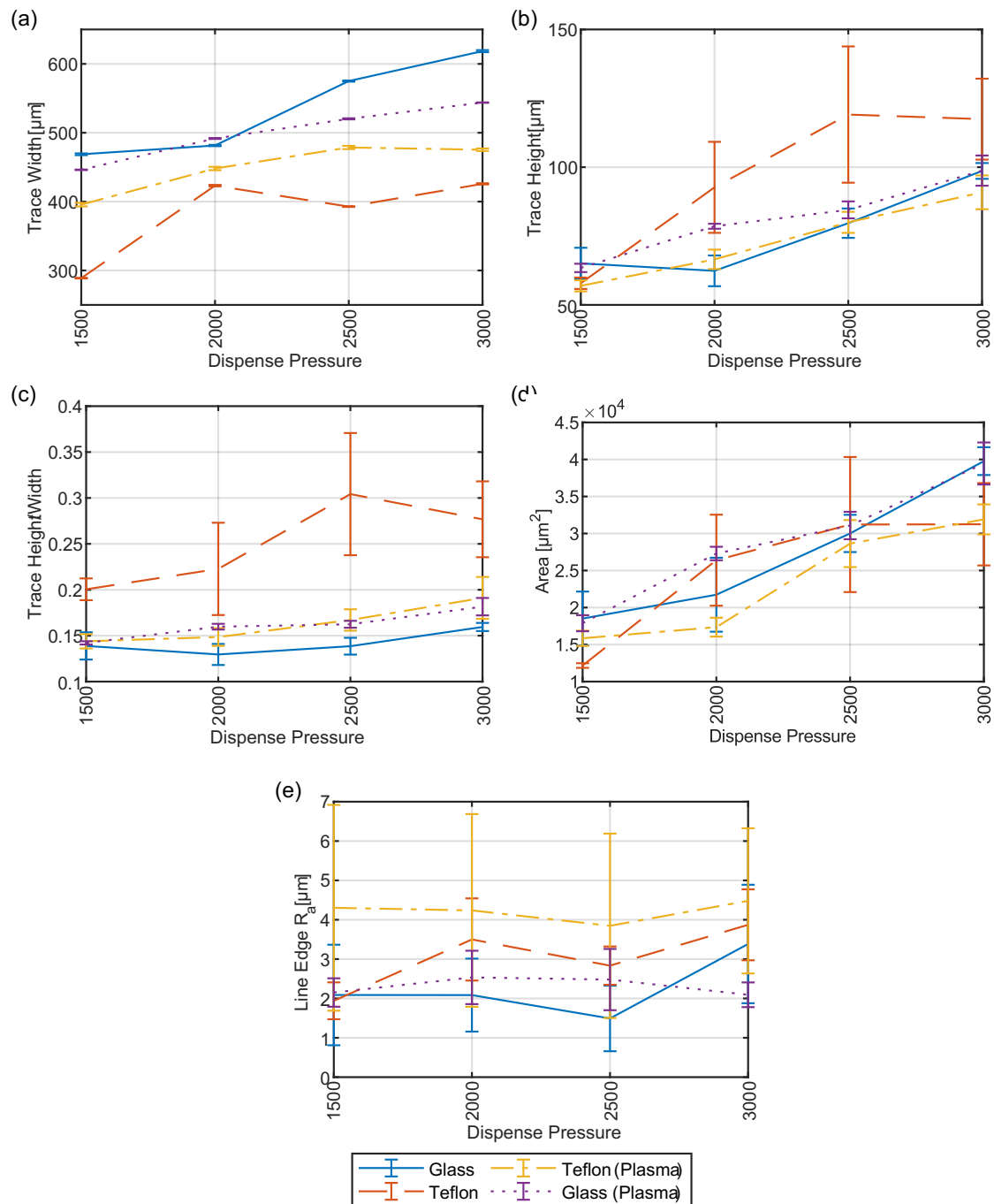


Figure 6-37. Dispense pressure sweep for large pressures of printing on four surfaces using NovaCentrix Metalon HPS-FG77. The effect of dispense pressure on a) trace width, b) trace height, c) trace height-to-width ratio, d) trace cross-sectional profile area, (e) line edge roughness (R_a).

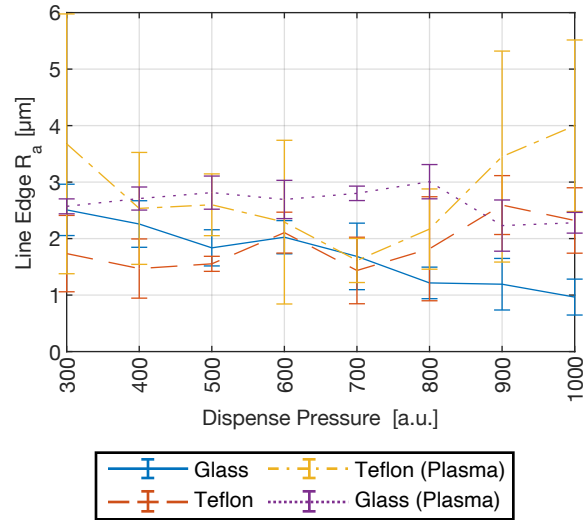


Figure 6-38. Dispense pressure sweep of printing on four surfaces using NovaCentrix Metalon HPS-FG77. The effect of dispense pressure on edge roughness (R_a) is negligible.

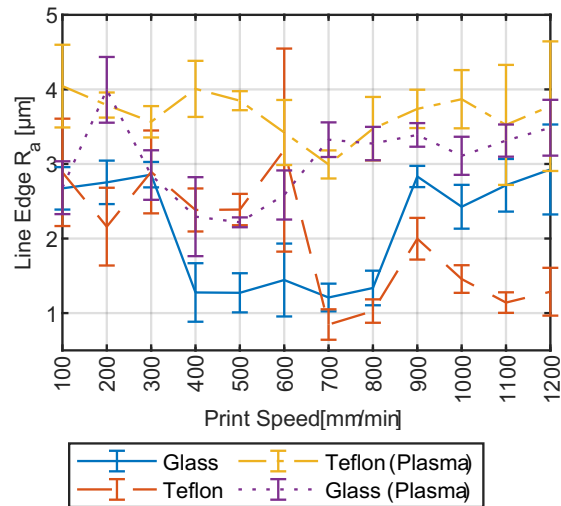


Figure 6-39. Print speed sweep of printing on the four surfaces using NovaCentrix Metalon HPS-FG77. The effect of print speed on edge roughness (R_a) is negligible.