

A Numerical and Experimental Investigation for Deposition of Conductive Ink on Multiple Substrate with Different Surface Energy and Ink Surface Tension

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Abstract

A simulation study of fluid dynamic model representing the deposition process of silver conductive ink on three different substrate was conducted to predict the topological characteristics of the printed ink track and validated through experimental works using syringe deposition system. The model that was researched in previous study only applied for general substrate and this study aimed to improve the model by including substrate surface energy and ink surface tension. Deposition parameters including deposition speed, pressure deposition height and nozzle tip size were set constant while the type of substrate and viscosity of ink were varied and investigated. It was observed that both simulation and experimental outcomes demonstrated the effectiveness of the dynamic model used with regards to change of the topological characteristics when deposition parameters were varied. A higher substrate surface energy results in increment of line width while a higher viscosity and ink surface tension result in narrower line width. The finding showed an improvement of 22.95% error differences with the improved model when compared to 37.6% error differences with the previous model.

1. Introduction

The topic of printed electronics is one of many fields in human endeavor that is full of possibilities and challenges. A printing process consists of controlling a substance's deposition onto a substrate to generate a pre-defined pattern and generate identical multiples of a pattern. Printed electronics, on the other hand, can be defined as a manufacturing approach that involves using novel materials, such as inductive ink, to print onto various substrates, resulting in the creation of electrical devices. One of many methods for printing electronics is the syringe deposition method.

This precise three-dimensional micro-positioning method uses a pressure-controlled syringe with a fine-bore exit needle to deposit conductive ink on the desired substrate. The dimension for the deposited ink can be predicted as the mathematical model has been developed by Vozzi et al. (2002) from the research on microsyringe based deposition of two-dimensional and three-dimensional polymer scaffolds. The Vozzi model assumes a basic geometry at the tip in which the dimension of the ink does not change as the solvent evaporates. It was discovered that the resultant wideness of ink track depends mainly on a few characteristics such as

printing speed, printing pressure, the viscosity of the ink, the empirically measured feature height, and the radius of the nozzle tip.

2. Materials and Methods

Three substrates with various substrate surface energies will be chosen for this study. Therefore, the three substrates examined for substrate surface energy are aluminum, ceramic and cardboard. Three levels of viscosity were also chosen as the manipulated variable so that there are three different ink surface tension that is used in the improved mathematical model. All the printing parameters associated with the fluid dispensing system were determined. Due to time restrictions, factors like nozzle diameter stay constant, suggesting less impact on the ink track's physical properties.

2.1 Materials

Different types of substrates have different surface energy. When the substrate surface energy increases, the contact angle of the ink decreases resulting in a more disperse shape of the ink. This occurs due to molecules preferring to remain in a lower energy state whenever it is feasible. Since surfaces are less stable than the bulk of the material, when a liquid comes in contact with the surface, the material seeks to drag the liquid over the surface in order to form more stable bonds and reduce the energy of those connections. Besides the physical properties of the ink, the substrate surface energy can affect the consistency of the printed pattern quality (Htwe et al., 2021). If substrate surface energy was not considered, it will cause discrepancy between the setting value and actual width (Lee et al., 2005). The substrates that are used for this experiment are aluminum, ceramic and cardboard.

Type of ink also will play a role on the dimension of the printed track. This is due to the viscosity and surface tension for most conductive ink will determine the wettability or droplet formation to be dispensed on a substrate (Khirotdin et al., 2017). Moreover, in inkjet printing, surface tension and viscosity of conductive ink are two major physical properties that dominate the behavior of the jets and drops (Shen et al., 2013). The relationship between the ink content and viscosity and surface tension of the ink was observed to be nearly linear as shown in Figure 1. Thus the viscosity of ink were varied to simulate the disposition of ink.

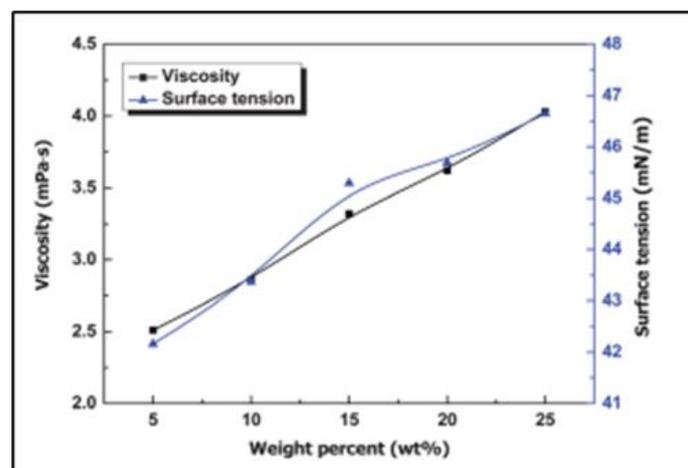


Fig. 1 Viscosity and surface tension of silver nanoparticle inks with different silver contents (Shen et al., 2013)

2.2 Methods

The model of the three substrates will be validated using Microsoft Excel and Matlab. Calculations in the simulation are used to establish the line thickness. The printing speed, printing pressure, nozzle diameter, and pattern thickness will all be held constant when the line width of the patterns is checked. The substrate surface energy and ink surface tension will vary to three levels each. The result of the model will show the relationship between the width of the ink track and both substrate surface energy and ink surface tension.

The next step is the boundary and parameter setting towards the experimental works. A suitable range is identified using the Full Factorial method. Then, set the printing parameter towards the dynamic model selected from research by Vozzi in 2002. Lastly, the data that is collected from the experimental works is used to validate the simulation that has been done on Excel and MATLAB.

2.3 Equations

The driving pressure (P), the weight of the ink (mg), the external pressure (P*) due to vapor pressure of the solvent, surface tension between ink and air (γ), dynamic friction between fluid and glass (μ), and the diameter of the inner section of syringe tip ($2R_s$) are some of the variables that is considered to predict the cross sectional of the ink. To simplify the model, the driving pressure was assumed as the dominant variable while others were neglected. The equation for disposition of ink according to Vozzi are as the following:

$$\alpha = \frac{\pi R_s^4 P}{8\mu v_n h h_z} \quad (2.3.1)$$

Where α refers to the line width pattern, R_s refers to the internal radius of the nozzle tip, μ refers to the ink viscosity, v_0 refers to the printing speed, h refers to the thickness of printed pattern, P refers to applied printing pressure and h_z refer to the length of the tapered zone of the capillary. By including the 0.substrate surface energy and ink surface tension into the mathematical model, the equation become:

$$\alpha = \frac{\pi R_s^4 P SSE}{8\mu v_n h h_z IST} \quad (2.3.2)$$

where SSE is substrate surface energy and IST is ink surface tension.

3. Results and Discussion

The simulation in Excel is done by using the parameter used to carry out the printing process. The radius of tip needle used is 0.41 mm, the printing speed is 5 mm/s, the printing pressure is 150 kPa and height of the ink is 0.2 mm. The value of substrate surface energy in the simulation are 65 mJ/m² for glass, 45 mJ/m² for ceramic and 43 mJ/m² for aluminum.

The result in table 1 shows the simulation result for the base equation without including substrate surface energy and ink surface tension. From the table, the ink viscosity was taken as the variable and width of the ink track is observed. The result shows that an increment in viscosity will result in a decrease of width of the ink track.

Table 1 Simulation result without surface energy and surface tension

π	R_s^4 mm	μ mPa.s	h mm	v mm/s	P kPa	hz mm	α mm
3.141593	0.028258	1600	0.2	5	150	1	1.04
3.141593	0.028258	2000	0.2	5	150	1	0.83
3.141593	0.028258	2400	0.2	5	150	1	0.69

The result in table 2 shows the simulation result for the equation including substrate surface energy and ink surface tension. From the table, the type of substrate and ink viscosity were taken as the variable and width of the ink track is observed. The result shows that an increment in viscosity will result in a decrease of width of the ink track. Glass has the highest substrate surface energy followed by aluminum and ceramic has the lowest surface energy. On the other hand, the value of viscosity of the ink will manipulate the value of ink surface tension. When the viscosity increases, the ink surface tension will increase. The result shows that when substrate surface energy increases, the width of ink track will increase while when the ink surface tension increases, the width of ink track will decrease.

Table 2 Simulation result with surface energy and surface tension

Substrate	π	R_s^4 mm	μ mPa.s	h mm	v mm/s	P kPa	hz mm	sse mJ/m ²	st mJ/m ²	α mm
Glass	3.14	0.02826	1600	0.2	5	150	1	63	38.25	1.71
Aluminium	3.14	0.02826	1600	0.2	5	150	1	45	38.25	1.22
Ceramic	3.14	0.02826	1600	0.2	5	150	1	43	38.25	1.17
Glass	3.14	0.02826	2000	0.2	5	150	1	63	76.49	0.69
Aluminium	3.14	0.02826	2000	0.2	5	150	1	45	76.49	0.49
Ceramic	3.14	0.02826	2000	0.2	5	150	1	43	76.49	0.47
Glass	3.14	0.02826	2400	0.2	5	150	1	63	114.74	0.38
Aluminium	3.14	0.02826	2400	0.2	5	150	1	45	114.74	0.27
Ceramic	3.14	0.02826	2400	0.2	5	150	1	43	114.74	0.26

3.1 Substrate Surface Energy vs Width of the Ink Track

Figure 2 shows that width of the ink track is directly proportional to the substrate surface energy. This shows that different types of substrates affect the dimension of the ink track. In this case, ceramic which has substrate surface energy of 43 mJ/m² produce the thinnest width of ink track followed by aluminum with surface energy of 45 mJ/m² and lastly glass with substrate surface energy of 63 mJ/m² which produce the widest width of the ink track.

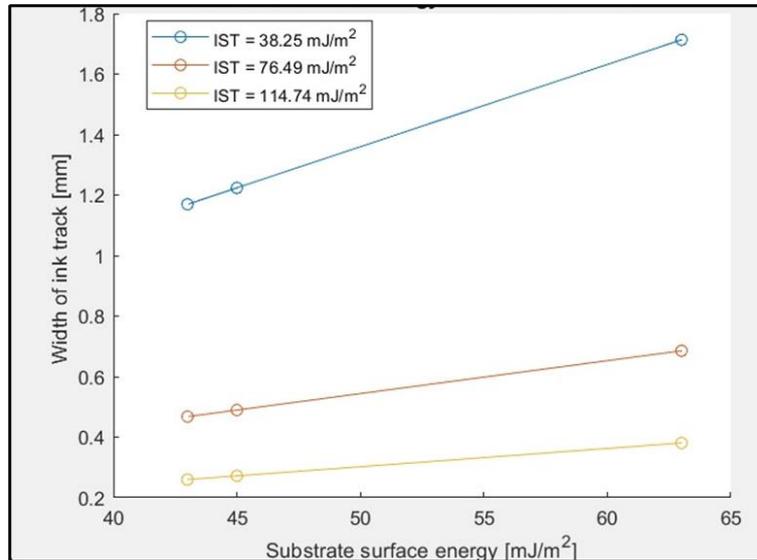


Fig. 2 Relationship between the substrate surface energy and width of the ink track

3.2 Ink Surface Tension vs Width of the Ink Track

Figure 3 shows that width of the ink track is inversely proportional to the ink surface tension. This shows that different values of ink surface tension also will affect the dimension of the ink track. In this case, the lowest surface tension of the ink which is 38.25 mJ/m² produces the widest width of ink track while highest ink surface tension which is 114.74 mJ/m² produce the thinnest width of the ink track.

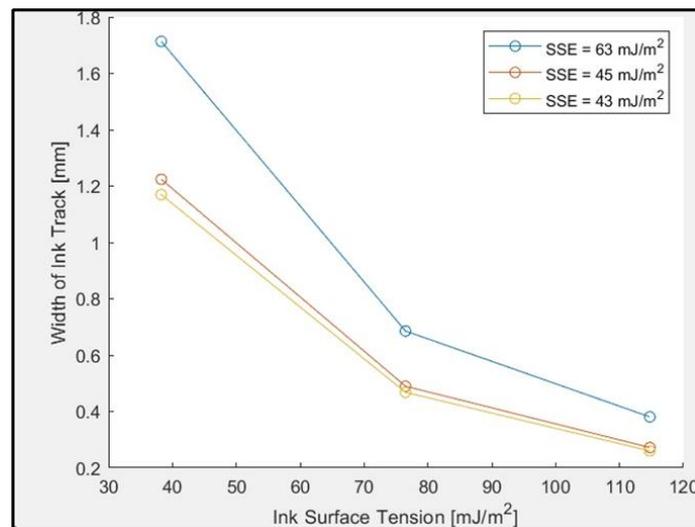


Fig. 3 Relationship between the ink surface tension and width of the ink track

3.3 Experimental Result

Based on the result of experimental works shown in table 3, different types of substrates will result in different width of ink track. The ink track on glass substrate has the widest ink track followed by aluminum and glass. Likewise, the viscosity of the ink will also manipulate the width of ink track where when the viscosity increases, the width of ink track will decrease. The result from table 3.3 can also be portrayed in figure 3.3 to make the result more clarified.

Table 3 Experimental results of disposition of ink

Substrate	μ mPa.s	First reading, mm	Second reading, mm	Third reading, mm	Average width, mm
Glass	1600	1.08	1.09	1.15	1.11
Aluminium	1600	1.03	1.06	0.99	1.03
Ceramic	1600	0.95	0.91	0.93	0.93
Glass	2000	0.42	0.4	0.45	0.42
Aluminium	2000	0.55	0.55	0.55	0.55
Ceramic	2000	0.48	0.45	0.5	0.48
Glass	2400	0.38	0.36	0.38	0.37
Aluminium	2400	0.34	0.33	0.32	0.33
Ceramic	2400	0.3	0.28	0.31	0.30

3.4 Discussion

As shown in figure 4, the experimentation results show difference in width of ink track based on its type of substrate. The base result that comes from the Vozzi equation only shows the same width of ink track even though the substrate is different which will result in error occurring when a different type of substrate is used. There was an abnormality occurred for ink with 2.0 Pa.s viscosity printed on glass substrate due to the pressure applied when printing process was less than the designated pressure. This error occurred due to the pressure being adjusted manually.

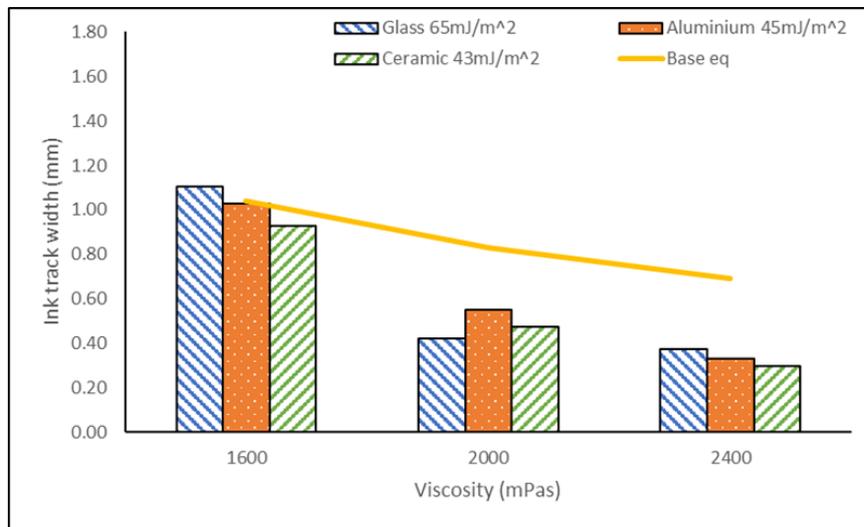


Fig. 4 Experimentation result of disposition of ink when compared to the original Vozzi simulation

On the other hand, the result from the simulation that has been improved by including substrate surface energy and ink surface tension as shown in Figure 5 produce the result similar to experiment as shown in figure 4 where different type of substrate will result in difference in width of ink track. This showed that the model has been improved when compared to the original model.

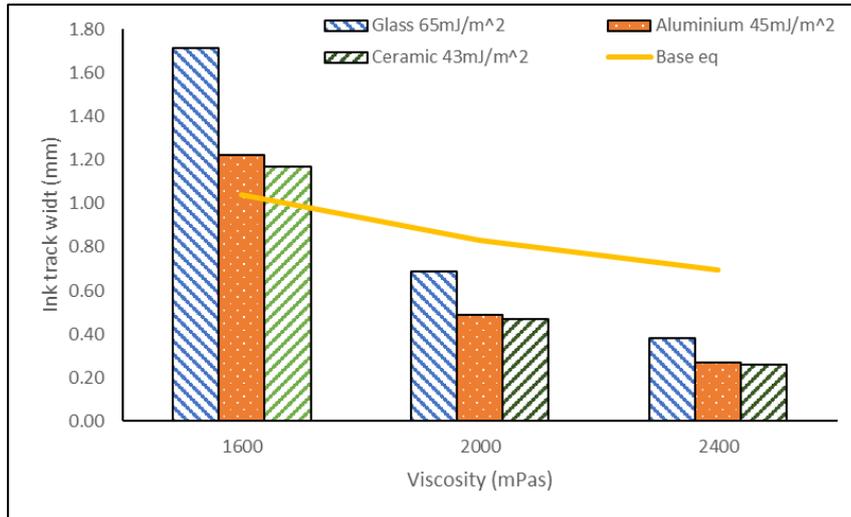


Fig. 5 Simulation result of disposition of ink when compared to the original Vozzi simulation

Table 4 had shown the Percentage of error between simulation and experimentation of disposition of ink. The percentage of error between the simulation result and experiment ranging from 1.84% to 61.91% depending on the type of substrate and viscosity of the ink. The average percentage for the whole experiment was 22.95%. The percentage of error of the simulation was more than 20% due to some anomalies occurred during the experimentation work. First, the pressure needed to be adjusted manually may result in inconsistent pressure during the printing process. Next, the apparatus used to measure the surface tension may not be sensitive enough to obtain accurate data. In addition, the substrate surface energy is obtained from previous study with the same type of material in which different substrate has different surface energy even it is made from the same type of material.

Table 4 Percentage of error between simulation and experimentation of disposition of ink

No	Constant Parameter	Variable Parameter		Average of Line Width, mm	Simulation of Line Width, mm	Percentage Difference Error of Line Width, %
		Type of substrate	Viscosity of Ink, Pa.s			
1	Tip radius of the needle, 0.41mm Printing Pressure, 150 kPa Printing Speed, 5 mm/s	Aluminium 63 mJ/m ²	1.6	1.03	1.22	19.22
2			2.0	0.55	0.49	10.97
3			2.4	0.33	0.27	17.57
4		Ceramic 45 mJ/m ²	1.6	0.93	1.17	25.76
5			2.0	0.48	0.47	1.84
6			2.4	0.30	0.26	12.38
7		Glass 43 mJ/m ²	1.6	1.11	1.71	54.84
8			2.0	0.42	0.69	61.91
9			2.4	0.37	0.38	2.01
Average Error						22.95

4. Conclusions

In conclusion, the objective of the study was accomplished. The first objective is to improve the mathematical model for deposition of conductive ink on multiple substrates by including substrate surface energy and ink surface tension. The goal was to determine the average percentage error between the two results. The average percentage error for the average line width was 22.95%, which marked an improvement compared to the previous researcher's 37.6% error. The second objective is to simulate and validate the improved mathematical model for the deposition of conductive ink through experimental works. The effectiveness of printing parameters on the average line width and line thickness of conductive ink tracks printed using a syringe deposition system was evaluated through a comparison of morphology analysis results from simulations and experiments. This suggests that the objective of the study, which aimed to simulate and experimentally analyse the deposition of conductive ink using a syringe deposition system, was successfully achieved. The study aimed to simulate a dynamic model and identify the printing parameters that impact the printed silver ink sample, while also comparing the simulation and experimental results.

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