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A new electrohydrodynamic printing method for patterns fabrication with low viscosity fluid of silicone oil

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Silicone oil is a type of fluid with low viscosity, but it is not easy to form stable cone jet for electrohydrodynamic printing. In this paper, we proposed a new electrohydrodynamic printing method for patterns fabrication with this kind of low viscosity fluid. Dots array was first printed on the substrate at higher direct current voltage. Then by controlling the moving speed of the platform, the dots were connected into lines according to the fluidity of the silicone oil and its low surface tension. With the proposed method, the patterns with silicone oil can be successfully formed by electrohydrodynamic printing. In the experiment, the influence of main parameters including applied voltage, moving speed of substrate, distance from needle to substrate, and axial length of droplet on the quality of printed lines was studied. Finally, by optimizing the printing parameters, the silicone oil lines with width of 73 μm and low surface roughness were printed.

K e y w o r d s: electrohydrodynamic printing, fabrication, low viscosity, silicone oil

1 Introduction

As an advanced manufacturing technology, electrohydrodynamic printing technology has great potential in micro-nano manufacturing due to its high resolution [1-3]. Printing materials with different properties have their own application areas. Field's metal (32.5% Bismuth, 51% Indium, 16.5% Tin) has the advantages of low melting point and low resistivity, and it can be used to print two-dimensional (2D) and three-dimensional (3D) metal microstructures [4]. Functional ink can be used to print 3D solid cylindrical structure [5, 6]. Some traditional polymer materials such as PLA, PCL, due to their good forming properties, can be used to print 3D structures [7-10]. A solution (PEO, colloidal ink) blended with conductive media (nano-silver wire, nano-silver powder, or carbon nanotubes) allows printing of conductive 2 D patterns [11-14]. Using electrodynamic printing technology to print polymer materials which has special properties also has a great prospect in biomedical application [15, 16].

Polydimethylsiloxane (PDMS) as a kind of silicone oil material, because of its low price, excellent transmittance, superior elasticity and well insulation, has been widely used in manufacturing microfluidic chips and flexible electronic devices [17-19]. It is also used in biomedical industry [20]. However, few experimental reports have been reported on printing lines of PDMS by electrohydrodynamic printing technology. This is because it is a fluid with low viscosity, which makes it to diffuse easily on the base surface. Furthermore, based on our experiment results, we also found that silicone oil is easy to fall down in large drops during the printing process, but not to form a stable Taylor cone for printing.

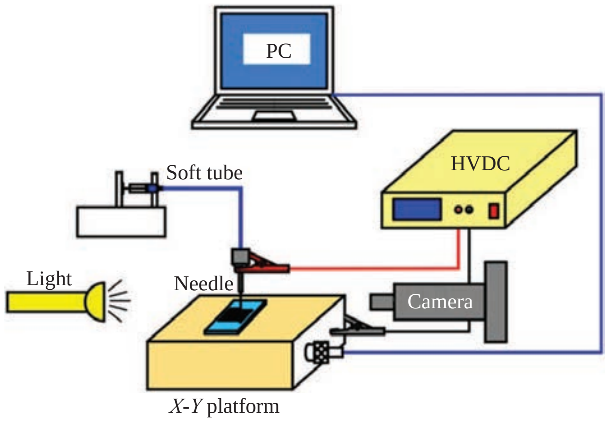

Fig. 1. Schematic of the printing apparatus

In this paper, a new method of electrohydrodynamic printing by silicone oil was proposed. In this method, a series of points of silicone oil were first printed at a higher direct current (DC) voltage. Then, based on the advantage of fluidity and low surface tension of the silicone oil, by controlling the platform's movement speed, the printed points were diffused across the substrate. Thus, the purpose of using silicone oil to print lines was realized. During the experimental process, the effect of printing parameters (applied voltage, the droplet length, the moving speed of the platform and the needle-substrate distance) on the width of lines was investigated. The influence of printing parameters on the surface roughness was also studied to enhance the quality of printed patterns. Finally, with the optimized parameters, silicone oil lines of 73 μm width were printed by using the stainless needle with the inner diameter of 260 μm .

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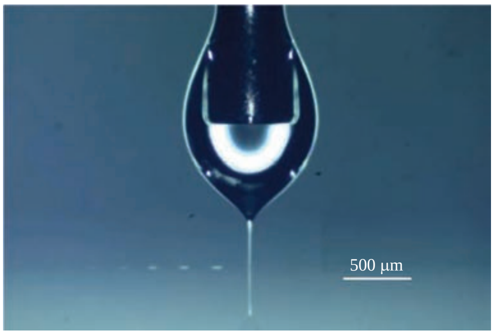

Fig. 2. Intermittent cone jet of silicone oil

2 Experimental details

2.1 Apparatus and material of printing

The experimental apparatus used for our work is shown in Fig. 1. It consists of a high DC voltage power supply, a syringe pump, a microscope, and a computer-controlled X-Y movement stage. The high voltage direct current (HVDC) power supply was used to provide an electric field between the needle and the substrate. The syringe pump was used for micro-feed of silicone oil during the printing process. The microscope was used to observe the morphology of the liquid droplets on the tip of the needle.

In the experiment, the printing material was silicone oil, purchased from Dongguan Huachuang Chemical Company. The substrate material was glass slide (7101P).

2.2 Experimental process

In the experiment, a high voltage was applied between the needle and the substrate, and then the silicone oil was slowly extruded from the needle by the syringe pump. The feeding of syringe pump should be stopped when a larger silicone oil droplet was accumulated at the tip of the injection needle. Due to the electric field force and the hysteresis effect of the silicone oil in the soft tube, the droplet at the tip of the needle will continue to grow. After the droplet volume and droplet axial length are stable, other working parameters were adjusted to preset values for printing experiment.

3 Results and discussions

In our work, silicone oil with viscosity of 500 cs was selected as the printing material. The effect of the applied voltage, the needle-substrate distance, the volume of the droplet, and the platform moving speed on the width and surface roughness of the printed lines was studied by experiment.

In the experimental process, by using a higher DC voltage, a series of silicone oil points were printed, and then the silicon oil would diffuse on the substrate with the characteristics of low surface tension. Meanwhile, by controlling the moving speed of the platform, these series of printed points were connected to a line. Thus, the process of printing lines by using silicon oil was complete.

In the experiment, when the droplets at the tip of the needle were stabilized, a high voltage was applied. Then, intermittent jet would be generated at the tip of the needle, and a series of points will be printed, as shown in Fig. 2. But stable and continuous cone jet can not be produced. This is because an applied voltage induces charges on the surface of the droplet at the tip of the needle, and creates an external electric field. At this time, the cone jet is generated at the needle tip and it is stretched under the applied voltage. However, due to the low viscosity of silicone oil, the cone jet can not withstand the tensile force. Therefore, the silicon oil can only form intermittent jet at the tip of the needle, but can not form a stable cone jet.

3.1 Analysis of applied voltage on printed lines quality

During the printing process, the applied voltage, the needle-substrate distance, the axial droplet length, and the platform moving speed are four major factors which have significant influence on the printing patterns quality of silicone oil. First, the effect of the applied voltage on printed structures of silicone oil was investigated. Except for the applied voltage, the other main working parameters were set to constant values. The speed of platform movement was set to 300 μm/s. The droplet length was 0.5 mm, and the distance from the needle to the substrate was 1mm.

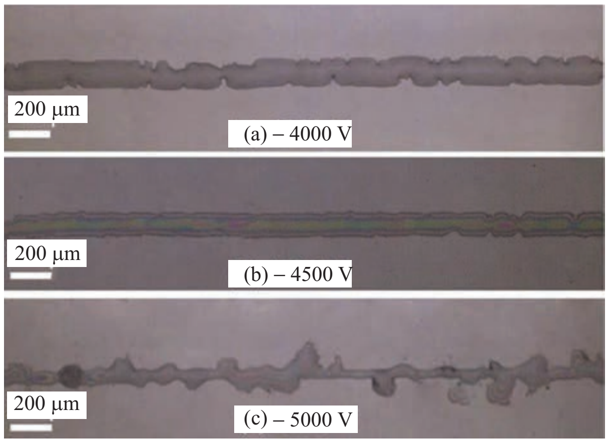

Fig. 3. Micrographs showing the printed patterns at different applied voltages

Figure 3 shows the experimental results when the applied voltage was increased from 3000 V to 5000 V with an interval of 500 V . Figure 4 shows the relationship between the applied voltage and the width of printed lines. It can be seen from Fig. 4 that the width of the lines significantly decreases when the applied voltage increases from 3000 V to 4500 V . As the applied voltage continuously increased from 4500 V to 5000 V, there is only a moderate width decrease, but the roughness of the printed lines was increased obviously as shown in Fig. 3. This is

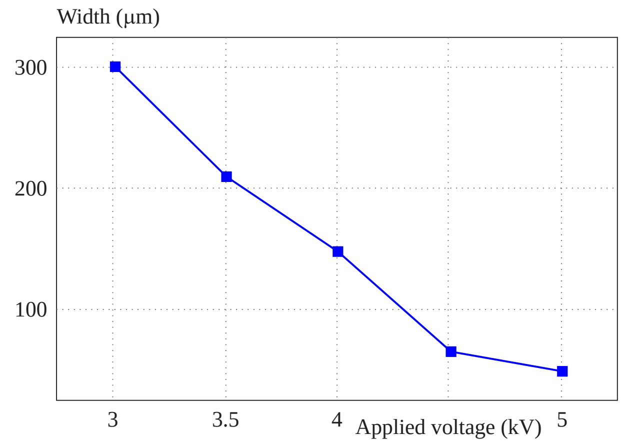

Fig. 4. The relationship between the applied voltage and the width of printed lines

because as the voltage increases from 3000 V to 4500 V, the volume of the dripping droplet decreases, and the frequency at which it drops increases. The smaller dripping droplet volume reduces the width of the printed line. The larger droplet dropping frequency increases the number of printed silicone oil points per unit length and reduces the surface roughness of silicone oil lines finally printed.

However, when the voltage rises to 5000 V, the silicone oil droplets at the tip of the needle become unstable because of the higher voltage. So the dripping droplets that fall down are also unstable. Thus, the printed dots are unable to connect into lines and make the surface roughness become worse. According to the analysis above, we can conclude that the best applied voltage for printing is 4500V.

3.2 Influence of droplet axial length on the printed lines quality

In addition to the applied voltage, the droplet axial length at the tip of the needle also plays an important role in the printing process.

Figure 5 shows the experimental results when the droplet axial length ranged from 0.3 mm to 0.7 mm at a constant applied voltage 4500 V, a platform moving speed 300 μm/s, and a needle- substrate distance 1 mm. It was observed from Fig. 5 that the width of the printed lines decreases first and then increases when the droplet axial length increases from 0.3 mm to 0.7 mm. The reason for this phenomenon is that when the droplet axial length is 0.3 mm, the droplet volume is smaller, and the printing process is very unstable. But when the droplet axial length is 0.7 mm, the droplet is closer to the substrate. As a result, the droplet is subjected to an increased electric field force, which also makes the printing process unstable. As the printing process is unstable, it will leads to an increase in line width and surface roughness inevitably. Besides, as the droplet axial length is 0.3 mm, 0.5 mm and 0.7 mm, the corresponding microscope image of the experimental results is shown in Fig. 6. It can be clearly seen that compared with the droplet axis length of 0.3 mm and 0.9 mm, when the droplet length is 0.5 mm, the continuity and surface roughness of the printed line are relatively better. Moreover, when the length of the droplet is 0.9 mm, the droplet was easy to be broken and appeared multi-jet phenomenon. Thus, the axial length 0.9 mm of the droplet can not be used for printing. It can be concluded from the above analysis that 0.5 mm is the appropriate axial length of droplet.

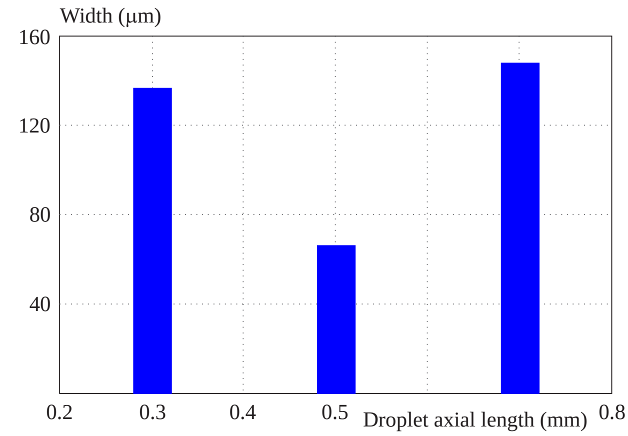

Fig. 5. The influence of droplet axial length on the width of printed lines

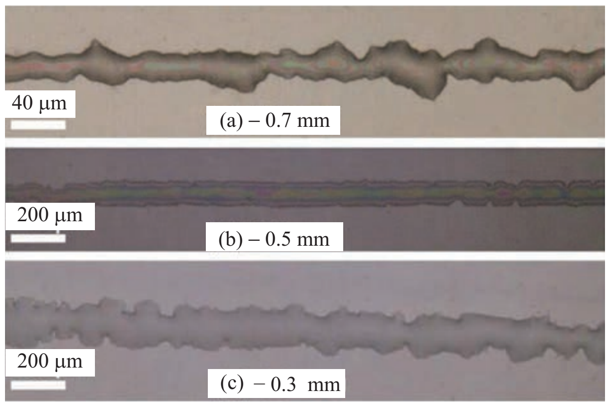

Fig. 6. Micrographs showing the printed patterns at different axial lengths

3.3 Effect of needle-substrate distance on the printed lines quality

The distance from the needle tip to substrate is also an important parameter in the printing process. The impact of this parameter was investigated. In the experiment, the applied voltage and droplet length were set to 4500 V and 0.5 mm respectively, which were optimized according to the previous experiment. The moving speed of the platform was set to 300 μm /s. Fig. 7 shows the experimental results when the distance from the needle tip to substrate ranged from 0.8mm to 1.4 mm.

As shown in Fig. 8, the printed line width increases as the needle-substrate distance increases from 0.8 mm to 1.4 mm . This is because as the distance between the needle and the substrate increases, the strength of the electric

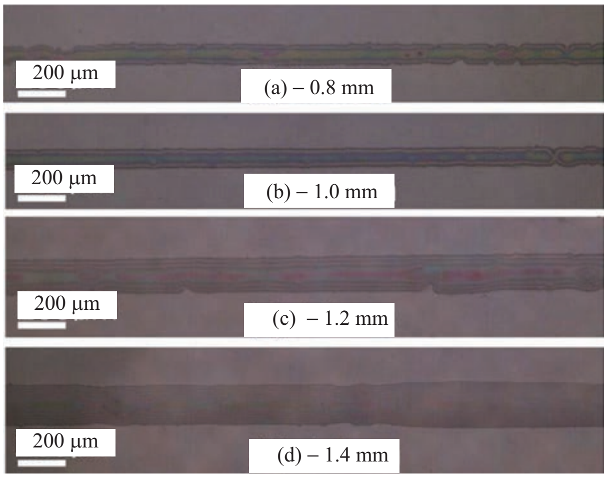

Fig. 7. Micrographs showing the printed patterns at different needle-substrate distance

field between them decreases. Therefore, the electric field force acted on the droplet decreases. Consequently, the dropping volume of droplet increases. Thus, the printed line width becomes wider. When the distance between the needle and the substrate is smaller, the droplet will easy to break. According to the analysis above, we can conclude that the best distance from the needle tip to substrate is 1mm.

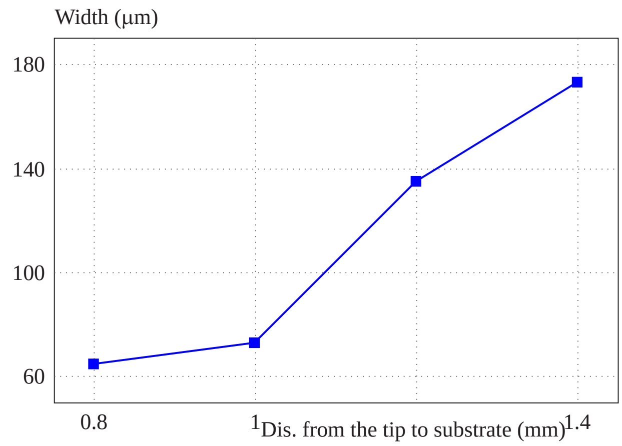

Fig. 8. The effect of needle-substrate distance on the printed line width

3.4 Optimization the parameter for the moving speed of the platform

The moving speed of the platform also has a considerable influence in the printed process. For optimizing this parameter, the effect of this parameter on the printed line quality was investigated. The applied voltage, droplet length and the needle-substrate distance were kept constant at 4500 V, 0.5 mm and 1 mm, respectively. Fig. 9 shows the experimental results when the moving speed of the platform ranged from 100 μm/s to 500 μm/s. It can be seen that as the moving speed of the platform increases, the width of the printed lines gradually decreases. This is because the silicone oil lines are connected by the silicone oil points, and when the moving speed of the platform is reduced, the printed points become dense. Thus, the continuity of the printed line is better, but the line width is larger. When the platform moves faster, the printed silicone oil points become sparse. Therefore, the line width is smaller but the continuity of the printed line becomes worse. When the moving speed of the platform is increased to 400 μm/s or 500 μm/s, the continuity of the printed lines and surface roughness of patterns is not well, as shown in Fig. 10.

The final optimized printing parameters for patterns fabrication are the applied voltage of 4500 V, needle-substrate distance of 1 mm, droplet axial length of 0.5 mm, and platform moving speed 300 $\mu m/s$.

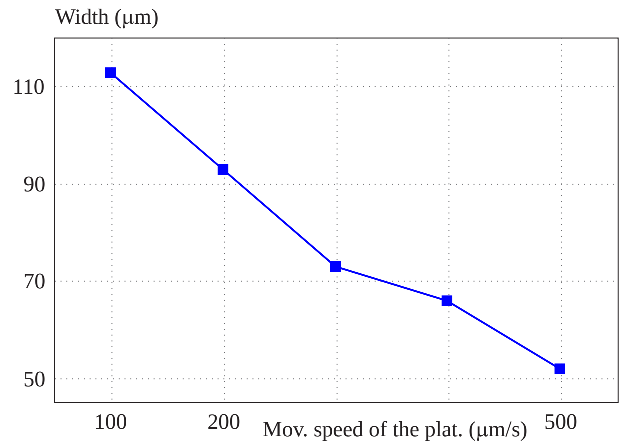

Fig. 9. The effect of moving speed of platform on the printed line width

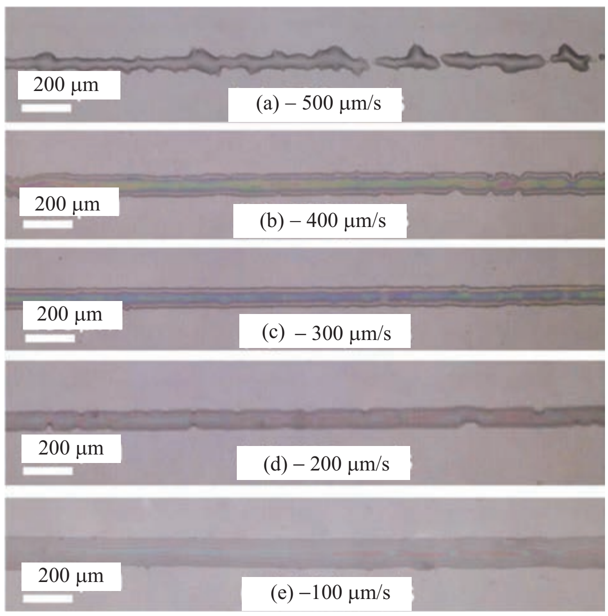

Fig. 10. Micrographs showing the printed patterns at different platform moving speed

4 Conclusion

This paper presents a new electrohydrodynamic printing method for patterns fabrication with low viscosity fluid of silicone oil. In this method, the point arrays of silicon oil were first printed at a high DC voltage. Due to the low viscosity of silicone oil, the points are easy to diffuse on the substrate surface. Thus, the printed silicone oil points are connected into lines, and the purpose of lines printing and patterns fabrication with silicone oil was realized. In our work, the influence of the main parameters in the printing process on the width of the printed line and the roughness of the surface was studied. These main parameters include the applied voltage, droplet axial length, moving speed of the platform, and distance of the needle tip to the substrate. Finally, by optimizing the printing parameters, the silicon line with 73 μm width and good surface quality was printed successfully.

Acknowledgments

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