Printing Stable Patterns on Curvilinear Surfaces for Omnidirectional Antenna

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Introduction

With the advantages of low cost, light weight, and design freedom[1], conformal circuits have attracted widespread attention in the research for structural electronics recently. Those circuits are composed of complex conductive patterns on curvilinear surfaces and can be fabricated by water transfer, screen-pad printing, dispenser printing, and lithography[2-5]. Among these fabricating methods, omnidirectional printing with dispenser has shown its advantage in simple pattern formation with low-cost instrument. Printing quality of conformal circuits is important to device effectiveness. It has been reported that conductive traces with minor edge raggedness can induce negative impact for electronic devices and then cause deficient performance[6]. To print patterns with well-defined boundaries, it is crucial to control the contact line stability of the printed liquid trace. For printed liquid lines, defects such as broken lines, bulges, and ragged edges, are commonly observed due to contact line motion. To resolve these issues, previous studies have proposed proper fluid control methods, such as increasing ink viscosity or advancing angles, to enhance the boundary stability on flat surfaces. However, similar analyses have not been applied on curvilinear surfaces. Recently, it has been reported that liquid traces may be susceptible on curved surface due to high internal hydrostatic pressure[7]. Thus, printing quality control can be much more complicated than those on flat surface can and it is necessary to investigate the fundamental mechanism of edge stability. In this study, we explored the stability criteria for pattern fidelity on curved surface. Edge distortion, raggedness, or bulge formation associated with printing process will be carefully examined. Method or approaches to remove these printing issues will be proposed to attain great fidelity for printed liquid trace.

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Experimental section

Ethylene glycol (EG), methylene blue (MB) and Prussian blue (PB) powder were purchased from Sigma Aldrich, and were used without further purification. The MB ink was prepared by adding 0.3 g of MB into 5.7 g of EG, and stirred under magnetic stirring for 1 hour. For PB inks, suitable PB powders were added into EG, and was put in a sonication bath (Delta, Model DC300H) for 24 hours before used. The contact angle measurement was performed by using a home-made goniometer. The rheological measurement was conducted by using a Haake RheoStress 6000.

The schematic diagram of the experimental setup is illustrated in Figure 1. Next, the liquid patterns were written on the 30 mm diameter spherical glass by a home-made five-axis printer fluid dispenser. The motion of five-axis printer fluid dispenser was carried out with a computer program, which is compiled from C# interface, to print liquid pattern on the substrates. All liquid patterns were orthogonally observed by a charge-coupled device (CCD) camera (iCam Plus HDMI, MICROTECH). Finally, the line edge raggedness analysis was evaluated by using MATLAB image processing program.

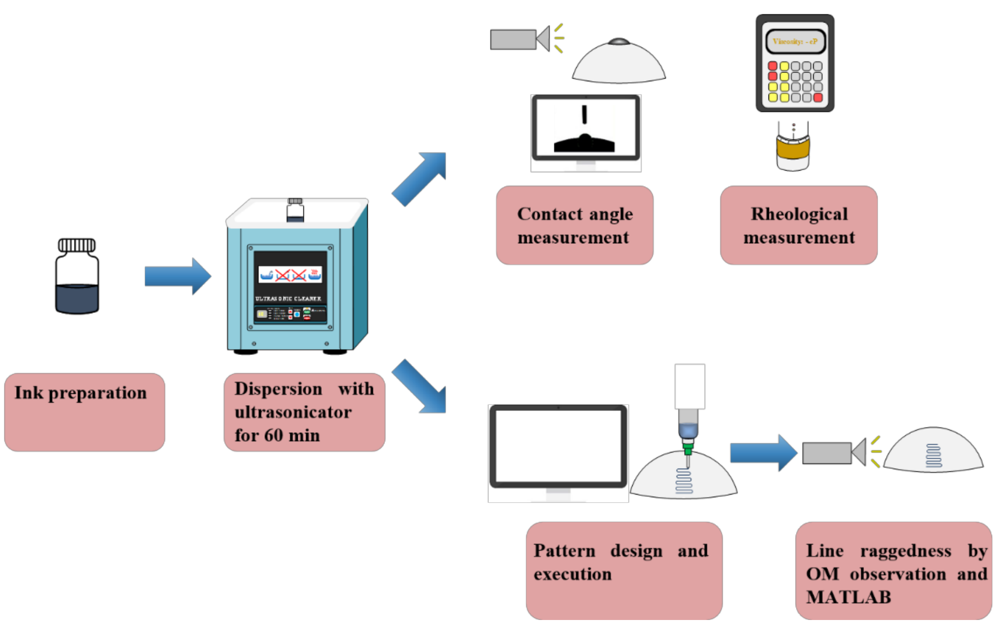

Figure 1. Experimental setup with ink preparation, ink characteristic, omnidirectional printing, and line raggedness analysis.

Results and discussion

The contact angles of MB/EG inks on the glass flat plate and sphere are first examined to ensure the same surface characteristics for both substrates. As shown in Figure 2, a droplet of 0.1 uL MB ink is deposited over the surfaces of the glass plate or sphere (of 30 mm diameter). The results show that the equilibrium contact angle (θ_1) is nearly the same for both flat plate and sphere. Moreover, the equilibrium contact angles also exhibit small variation for both substrates regardless of MB concentrations. Despite

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the same ink/substrate affinity shown by the contact angle measurements, it is noteworthy that the droplet of the same volume spreads wider on the glass sphere and has a larger circumference. This can be explained by the schematic shown in Figure 3. Consider a spherical liquid sessile drop with a fixed volume sitting on a flat or spherical surface, and the equilibrium angles (θ_1) are the same for both surfaces, one can calculate the width of the sessile drop based on the geometric arrangement as shown in the figure[8]. Similarly, one can also conclude that the height of liquid drop is taller on spherical surface than that on flat surface[9]. Based on these observation and theoretical deduction, it is intuitionally to expect a wider liquid trace over a spherical surface.

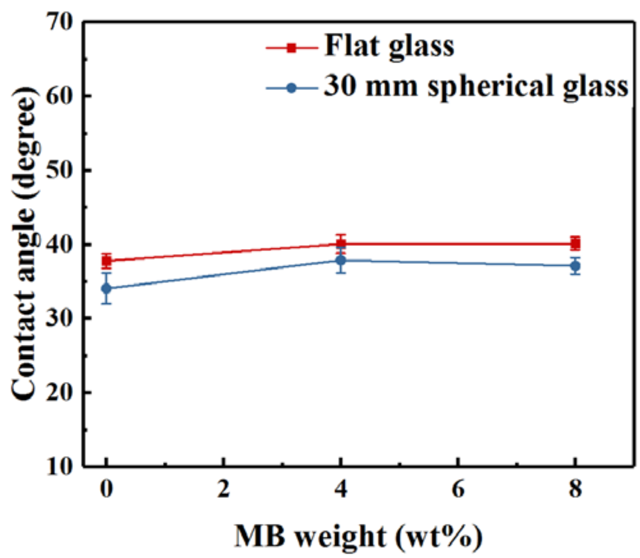
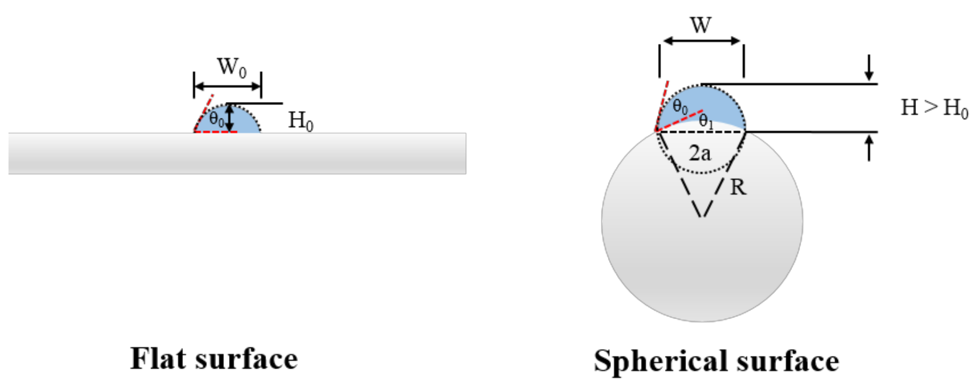


Figure 2. Contact angle for the inks on flat and spherical glass.



$$\theta_1 = \sin^{-1}\left(\frac{a}{R}\right)$$

$$H_0 = \frac{W_0}{2}\left(\frac{1}{\sin\theta_0} - \frac{1}{\tan\theta_0}\right)$$

$$H = \frac{W}{2}\left(\frac{1}{\sin(\theta_0+\theta_1)} - \frac{1}{\tan(\theta_0+\theta_1)}\right)$$

Figure 3. Schematic diagram of cross section for liquid line on flat and spherical surface.

The aforementioned width expansion leads to a different edge instability criterion for printed liquid traces on spherical surface. As shown in Figure 4(a), a bulge-free liquid line composed of 4% MB ink can be printed on the flat glass with a good edge definition. But using the same printing parameters (ink flow rate and pen velocity), the liquid line printed on spherical glass resulting in the significant bulge formation. The bulge formation is basically caused by the higher hydrostatic pressure due to the change in surface curvature.[7] To print a stable liquid line on the glass sphere, i.e., to print a thinner liquid trace, the applied flow rate is reduced to 0.23 uL/s (Figure 4(b)), and that results in a liquid trace with good edge definition without bulge formation. The trace on spherical glass has a width of 210 μm, and is much larger than that (170 μm) printed on flat glass with the same parameters. Furthermore, the edge of liquid line on spherical glass still shows some raggedness, implying the effect of internal pressure difference and the associated moving contact line problem.

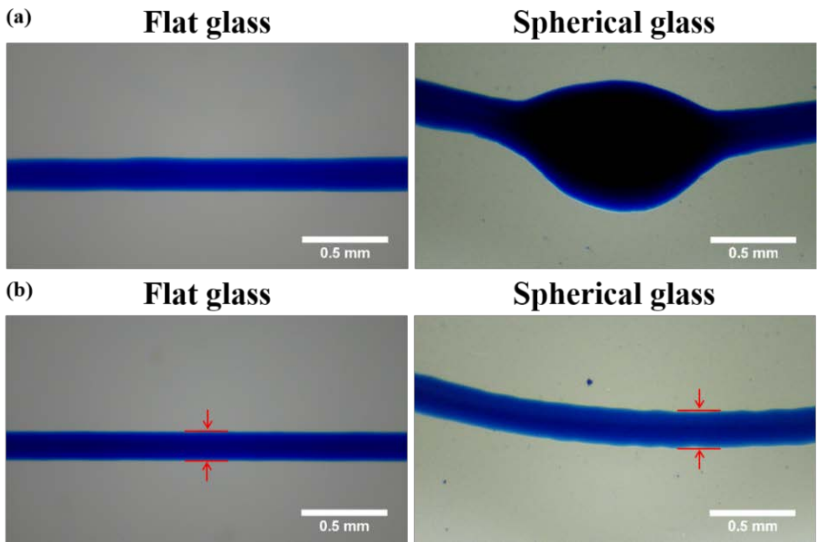


Figure 4. Liquid lines of 4% MB ink printed on a glass flat plate and a 30 mm diameter sphere. A fixed pen speed of 50 mm/s is used with different ink flow rates: (a) 0.32 μl/s and (b) 0.23 μl/s.

To attain a good print quality, i.e., to suppress the line widening from curvature, a pigment based in with large yield stress is used. As summarized in Table 1, the yield stress of the pigment-based ink is much higher than the dye-based MB ink. With less contact line motion, the pigment-based ink printed on spherical glass shows a much better edge definition (Figure 5). The edge raggedness is also examined by MATLAB programming to obtain quantitative evaluation. The raggedness defines that the residual of standard deviation for the vertical distance between the boundary curves. The line raggedness of the PB ink (6.3 um) is much smaller than that of MB ink (51.5 um), showing a much smoother line edge. Thus, ink with a suitable static yield stress can be conducive to retard the moving contact line on curved surfaces and improve the printing quality.

Table 1. Yield stress for various inks.

Sample	Yield stress (Pa)
4% MB	0.06
8% PB	1.14

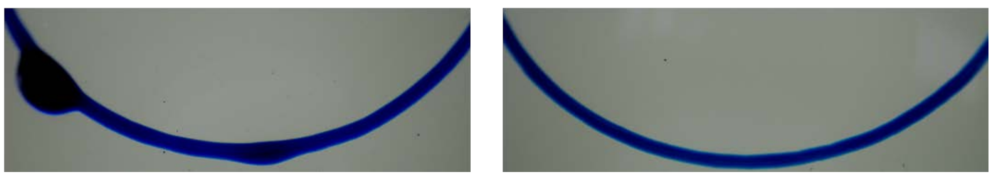


Figure 5. Printed liquid traces on spherical glass with the substrate speed of 15 mm/s and the applied flow rate of 0.23 μl/s with (a) 4% MB ink (b) 8% PB ink.

Conclusion

For liquid lines deposited on curvilinear surfaces, the line widths are wider than those on flat surfaces due to the surface curvatures. Besides width broadening, the surface curvature variation also leads to higher liquid film thickness and result in higher internal liquid pressure. Therefore, the stability criteria for bulge formation is altered. To avoid bulge formation or even edge distortion of printed liquid lines on curvilinear surfaces, one can increase ink yield stress to suppress the influence of internal hydrostatic pressure. This approach can effectively improve printed pattern fidelity on spherical glass and greatly enhance printing quality. Similar approach is applied to omnidirectional antenna fabrication, and the related signal reception data will be presented in the conference.

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