19th Australasian Fluid Mechanics Conference
Melbourne, Australia
8-11 December 2014

Fitting Micro-sized Droplet into Thinner Line

Y.C. Lam[1] and C.Y. Lim[1]

[1]School of Mechanical and Aerospace Engineering
Nanyang Technological University, Singapore 639798.

Abstract

Experimental studies of micro-sized droplet impinging and spreading on a hydrophilic line across a hydrophobic surface are presented. Hydrophilic lines were patterned through UV ozone or oxygen plasma treatment on a polymer sheet coated with hydrophobic chemicals. A droplet with 81µm diameter was jetted at $1.2ms^{-1}$ on the line of smaller width. Droplets which were impinged at a finite lateral offset from the line migrated towards the hydrophilic area and conformed to the hydrophilic line. The spreading dynamics of the droplets were captured with a high speed camera. The effects of line width and wettability contrast between the line and the surrounding surface on the spreading behavior were examined. The key parameters affecting the translation and conformability of the droplet to the hydrophilic line are the ratio of the line width to the initial droplet diameter and the contact angle of the hydrophilic line. The droplet will only conform completely to the hydrophilic pattern if the line width is not overly small relative to the droplet and the contact angle of the hydrophilic line is sufficiently low. The outcome of this study can potentially be applied to control the deposition and spreading of inkjet droplets to produce accurate micro-sized lines or other features which are smaller than the droplets.

Introduction

Inkjet printing was first developed commercially for printing text or images on papers. However, over the past decade, inkjet printing has attracted much attention from the manufacturing industry due to its capability to produce micro-sized features with high resolution. Metals, ceramics and polymers can be deposited directly on a solid substrate through inkjet printing technology[1]. Its potential applications include the manufacturing of plastic transistor circuits[2] and light emitting diode (LED) display[3].

A typical inkjet dispenser produces droplet ranging from 10 to 100µm in diameter[1]. This imposes a limit to the resolution of the printed features. Surface wettability patterning has been proposed to overcome this limit and to achieve features which are smaller than the droplet size[2]. Water-based inkjet droplets can be steered away from the hydrophobic area and be guided to spread along the hydrophilic pattern to form the desired features.

Literature Review

Despite its significance, the dynamics of droplet impingement on a surface with varying wettability is seldom studied in the literature. Typically, the end results of the printing process were studied instead of the dynamic process[4]. This is partially due to the difficulties in capturing the impact process of a micro-sized droplet which occurs in a very short time scale. On the contrary, millimetre-size droplet spreading process on a heterogeneous surface which occurs over a longer time scale has been investigated extensively in the literature[5]. Recent advances in high speed imaging [6] and flash photography [7] have permitted the observations of the impact and spreading dynamics of micro-sized droplets. However, these investigations only focused on the spreading dynamics of droplets on a homogenous surface without any wettability patterns.

This paper presents the high speed imaging and experimental analysis of a micro-sized droplet jetted on a surface with wettability patterns. Specifically, the experimental investigation aims to reveal the interaction between an impinging droplet with the hydrophilic line across a hydrophobic surface. A proper understanding of this process can improve the accuracy of material deposition and allow smaller features to be printed on a substrate.

Experimental Setup

Surface Patterning

The substrate employed in the experiments is polyethylene terephthalate (PET) sheet. The surface patterning procedures are described in our previous paper [8] and are summarized here (see Figure 1). To generate a hydrophobic surface, the PET sheet was dip-coated with 3M Novec 1700 electronic grade coating which is a clear solution with fluorochemical acrylic polymer carried in a hydrofluoroether solvent. The concentration of the solution was diluted to 0.1 weight % from the original concentration of 2 % to reduce the coating thickness and time for selective removal of coating. The solvent was evaporated in an oven at 120^{o}C for 10 seconds.

The hydrophobic coating can be selectively removed from the PET sheet with ultra-violet (UV) ozone or oxygen plasma treatment. A nickel mask of 50µm thick with long slits of 50µm width was placed on top the coated PET sheet. Magnet was placed below the PET sheet to hold the nickel mask firmly against the PET surface. The sandwich was then placed into an ultra-violet (UV) ozone exposure unit (Senlight PL16) which generates 10.2 mW/cm^2 of UV with 185nm wavelength and 32.7 mW/cm^2 of UV with 254nm wavelength for 25 minutes. The treatment selectively removed the hydrophobic coating according to the slits on the mask. Upon the removal of the hydrophobic coating, the treatment further modified the exposed area on the PET sheet into hydrophilic region.

The average contact angles of the hydrophobic coated and UV ozone modified PET surfaces were measured to be 107^{o} and 17^{o} respectively. The process produced hydrophilic lines with a sharp wettability contrast of 90^{o} to the surrounding hydrophobic surface. Hydrophilic lines with different width (27µm, 37µm and 53µm) were produced to investigate the effect of line width on the droplet spreading behaviour.

Instead of UV ozone treatment, the coating on PET sheet can also be removed with oxygen plasma treatment (March PX-500). At a power of 100W, a pressure of 70mTorr and 45 seconds exposure time, the hydrophobic coating was removed, with little modification to the PET surface. The water contact angle was measured to be 77^{o} (similar to a pristine PET surface). Increasing the exposure time to 2 minutes not only removed the coating, but also lowered the contact angle of the PET sheet to 40^{o}.

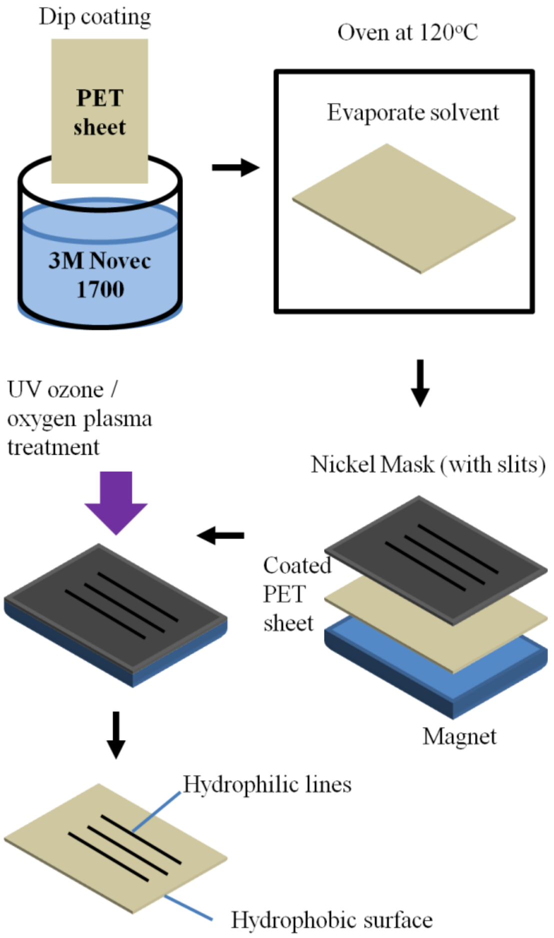

Figure 1. Patterning of hydrophilic lines over hydrophobic coating on PET sheet.

Hydrophilic lines with different contact angles (17°, 44° and 77°) over a hydrophobic surface (contact angle of 107°) were produced to investigate the effect of wettability contrast on the dynamic behavior of an impinging water droplet.

Droplet Dispensing and High Speed Imaging

Water droplet was jetted on the surface with an inkjet dispenser head (MD-K-130 Microdrop Technologies) with a nozzle diameter of 70µm. A driving voltage pulse of 105V with 30µs pulse width generated a droplet of 81µm in diameter, which impinged the PET substrate at 1.2ms^{-1}.

The bottom view of the droplet impingement and spreading process was captured through a high speed camera (Photron Fastcam SA5 monochrome) attached to an inverted microscope (Nikon Ti-S Eclipse). The capturing rate of the camera was set to 100,000 fps. Due to the short exposure time, a high intensity light source was required to capture the images at high speed. The white light illumination was supplied by ultra high pressure mercury lamp (Nikon Intensilight 130W). A UV cut-off filter was attached to the filter cube of the microscope to remove the UV component from the light source.

Experimental Results

Effect of Line Width

The effect of hydrophilic line width on the droplet spreading behavior was investigated. Figure 2 shows the bottom view image sequence of droplets impinging on hydrophilic lines with different line widths. The contact angles for the lines and the surrounding surface are 17° and 107° respectively. All droplets were impinged on the center of the hydrophilic lines with negligible offset (smaller than 5µm).

For t < 0.05ms, the behavior of the two droplets did not differ significantly despite the difference in contact angle of the lines (see Figure 2). The initial phase of droplet spreading upon impingement is driven by the inertial effect and unaffected by the surface properties. At approximately 0.3s after impact, the droplet conformed to the 53µm hydrophilic line as both the upper and lower contact lines coincided with the wettability boundary (see Figure 3). However, as the line width was reduced to 37µm and 27µm, the droplets were not confined completely within the hydrophilic region even after 0.5 second. Although the droplet impinged on the 37µm line showed significant spreading and elongation along the line, the liquid transport on the thinner hydrophilic region was insufficient to fully divert the fluid away from the central blob. The droplet impinged on the 27µm line was only elongated slightly and most of the liquid stayed on the hydrophobic surface. The small hydrophilic area did not provide sufficient capillary force to drive the fluid from the central blob.

These experimental results illustrate the limitation of exploiting surface wettability contrast to print lines smaller than the diameter of an inkjet droplet. A water-based inkjet droplet is expected to conform to the pre-patterned line width which is larger or equal to 0.65 times of the droplet diameter. However, reducing the line width further would result in the formation of residual blob at the impact location and inhomogeneous deposition of material along the line. The effect of contact angle contrast between the hydrophilic lines and the surrounding surface are discussed in the next section.

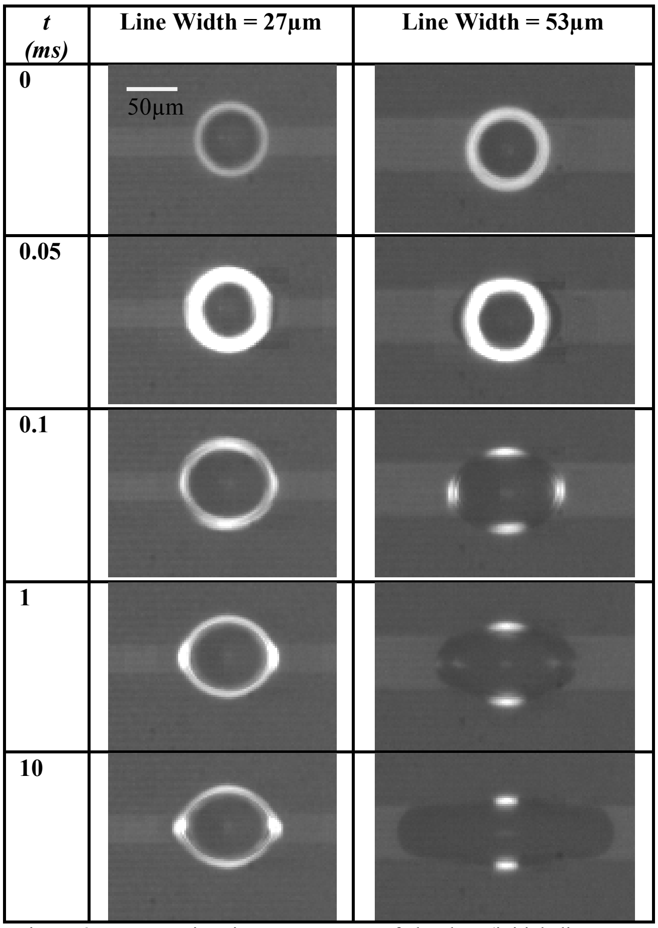

Figure 2. Bottom view image sequence of droplets (initial diameter = 81µm) impinging on hydrophilic lines with different widths. Contact angles of hydrophilic line and surrounding surface are 17° and 107° respectively. Impact velocity = 1.2ms^{-1}.

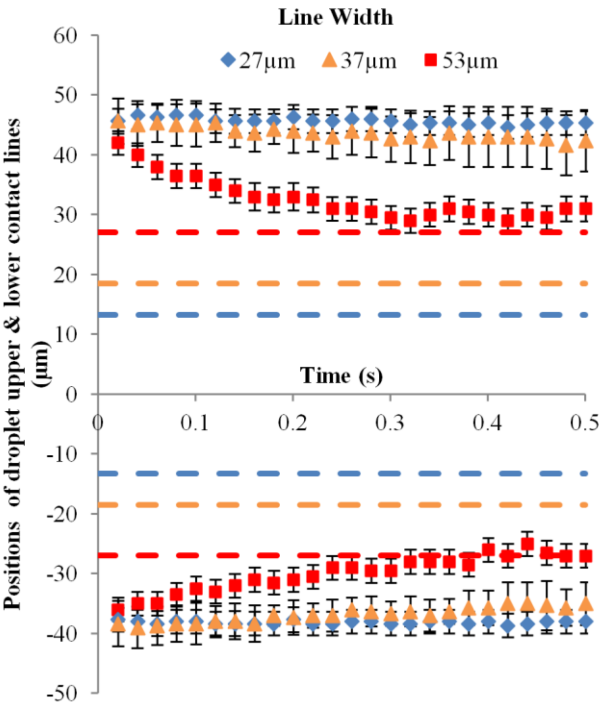

Figure 3. Positions of droplet upper and lower contact lines from center of hydrophilic lines with various line widths. Droplet initial diameter = 81µm. Impact velocity = 1.2ms^{-1}. Contact angles of hydrophilic line and surrounding surface are 17^{o} and 107^{o} respectively. Dash lines represent the line width of corresponding marker color.

Effect of Wettability Contrast

Figure 4 illustrates the droplet spreading on hydrophilic lines of different contact angles. The contact angle of the surrounding surface was constant at 107°. For the line with a contact angle of 17^{o}, the droplet spread along the strip and stayed within the confinement of the wettability contrast. As the contact angle of the hydrophilic surface was increased, the droplet spread diameter reduced significantly. For lines with contact angles of 44° and 77°, a central blob was formed at the hydrophilic region and the upper and lower edges of the droplet stayed outside of the hydrophilic lines (see Figure 5).

Brinkmann and Liposky [9] analytically derived the criterion for the transition between the two regimes of droplet spreading on a hydrophilic strip over a surrounding hydrophobic surface. The droplet only stays within the stripe when the contact angle of the stripe is less than ~38^{o} [9]. This criterion is applicable when the contact angle of the hydrophobic surface surrounding the strip is larger than 90^{o}. When the contact angle of the hydrophilic stripe is larger than 38^{o}, a droplet with diameter larger than the width of the stripe would stay as a central blob with limited spreading along the line. Our experimental results agree with the theoretical prediction of the transition between the two types of droplet morphologies. At low contact angle (17^{o}), the droplet conform to the hydrophilic line while at contact angle higher than 38^{o} (44^{o} and 77^{o}), a central blob is formed (see figure 4). Hence, a high contact angle contrast between the hydrophilic pattern and its surrounding is crucial for the printed droplet conformity to the desired line width.

If the droplet is not impinged exactly at the middle of the hydrophilic line but at an offset of 50µm, the droplet migrated towards the hydrophilic area (see Figure 6). At t = 50ms after impact, the droplet appeared to be the same as the droplet which was impinged exactly on the line. This behavior is important for inkjet printing technology. The final printed feature is independent on the initial impact location as long as part of the droplet touches the hydrophilic line. Despite an offset or inaccuracy of the initial impact location, the droplet will migrate towards the line and conform to the required line width.

Conclusions

Images of a micro-sized droplet impinging on a hydrophilic line with a surrounding hydrophobic surface have been captured with a high speed camera. The effects of line width and contact angle contrast on droplet spreading were investigated. The contact angle of the hydrophobic surface was kept constant at 107^{o} throughout the studies. A micro-sized droplet impinged on the hydrophilic line conforms to the line width if the line width is larger than or equal to 0.65 times of the droplet initial diameter. When the line width is reduced or contact angle of the line is increased, the droplet failed to conform completely to the line width. A residual blob of liquid remained at the initial impact location due to the lack of spreading on the hydrophilic line with a smaller width. When the droplet is not impinged exactly at the middle of the hydrophilic line, the droplet migrated towards the hydrophilic area before conforming to it. This study demonstrates that wettability patterning can potentially enhance the robustness for producing micro-sized features at higher resolution through inkjet printing.

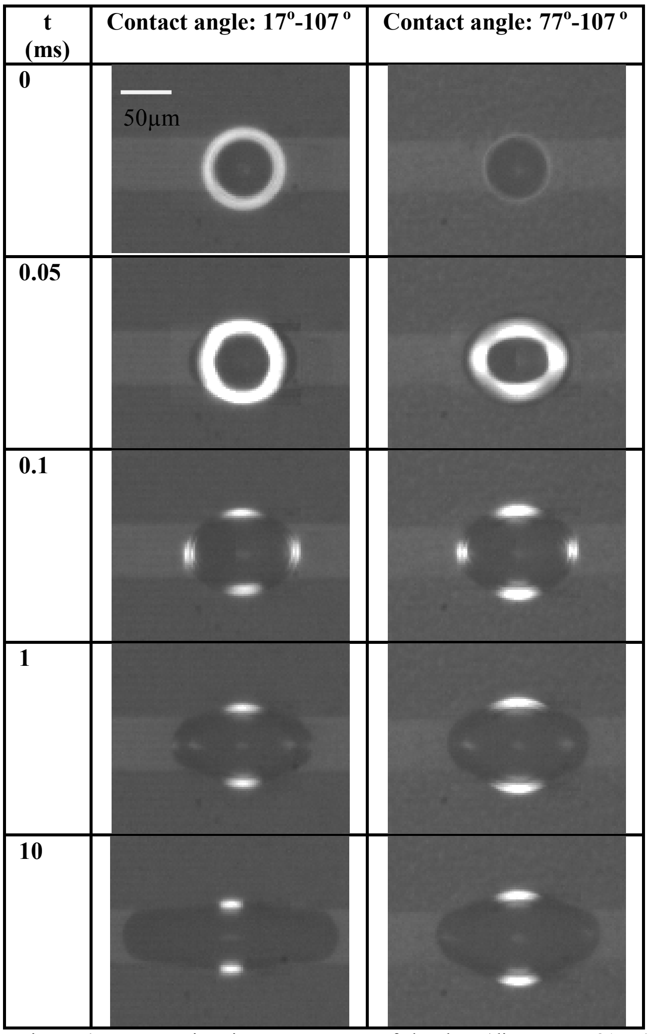

Figure 4. Bottom view image sequence of droplets (diameter = 81µm) impinging on hydrophilic lines with different contact angle contrast. Hydrophilic line average width = 53µm. Droplet initial diameter = 81µm. Impact velocity = 1.2ms^{-1}.

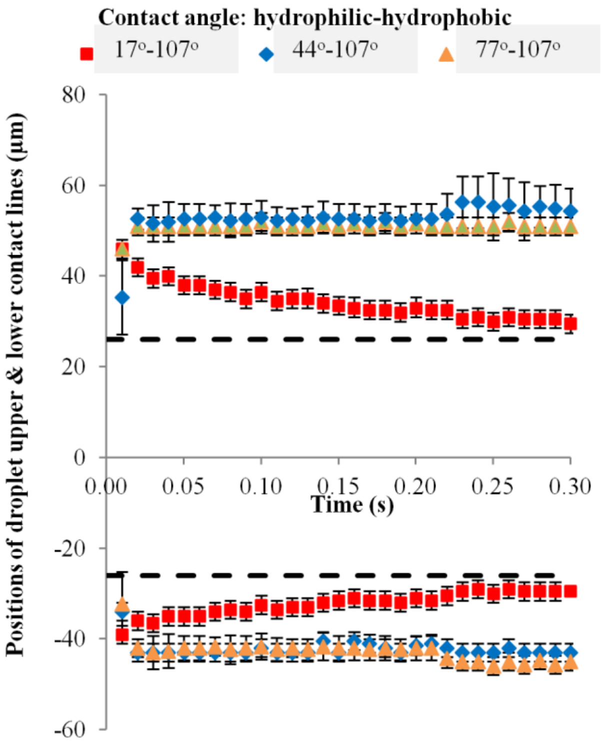

Figure 5. Positions of droplet upper and lower contact lines (relative to center of the line) impinged on hydrophilic lines with various contact angle contrast to surrounding hydrophobic surface (contact angle 107°). Hydrophilic line width = 53μm (indicated by black dashed lines). Droplet initial diameter = 81μm.

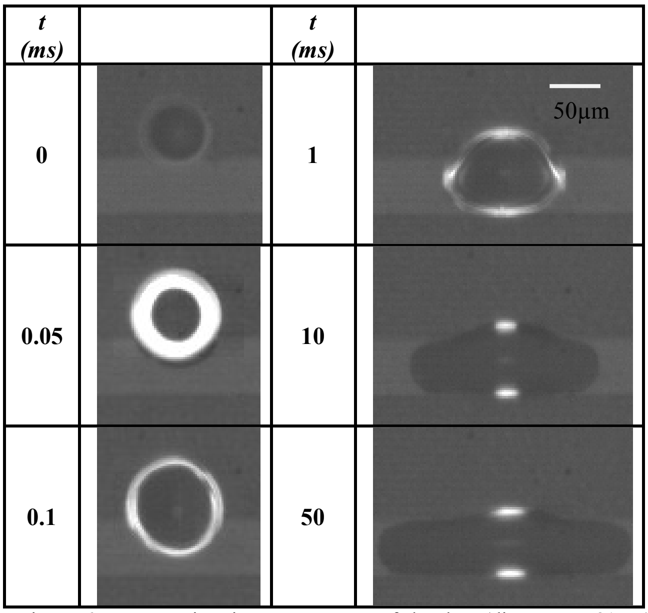

Figure 6. Bottom view image sequence of droplets (diameter = 81μm) impinging on hydrophilic lines at 50μm offset distance. Contact angles of hydrophilic line and surrounding surface are 17° and 107° respectively. Hydrophilic line width = 53μm. Droplet initial diameter = 81μm. Impact velocity = 1.2ms^{-1}.

Acknowledgments

The authors gratefully acknowledge the Agency for Science, Technology and Research (A*STAR) Singapore for its financial support (grant no. 102 170 0140).

References

[1] Hutchings, M.I. & Martin, D.G., *Inkjet Technology for Digital Fabrication*. 2013: John Wiley & Sons Ltd.

[2] Sirringhaus, H., Kawase, T., Friend, R.H., Shimoda, T., Inbasekaran, M., Wu, W., & Woo, E.P., High-Resolution Inkjet Printing of All-Polymer Transistor Circuits. *Science*, 2000. **290**(5499), 2123-2126.

[3] Koo, H.S., Chen, M., Pan, P.C., Chou, L.T., Wu, F.M., Chang, S.J., & Kawai, T., Fabrication and chromatic characteristics of the greenish LCD colour-filter layer with nano-particle ink using inkjet printing technique. *Displays*, 2006. **27**(3), 124-129.

[4] Léopoldès, J., Dupuis, A., Bucknall, D.G., & Yeomans, J.M., Jetting Micron-Scale Droplets onto Chemically Heterogeneous Surfaces. *Langmuir*, 2003. **19**(23), 9818-9822.

[5] Bliznyuk, O., Seddon, J.R.T., Veligura, V., Kooij, E.S., Zandvliet, H.J.W., & Poelsema, B., Directional Liquid Spreading over Chemically Defined Radial Wettability Gradients. *ACS Appl. Mater. Interfaces*, 2012. **4**(8), 4141-4148.

[6] Briones, A.M., Ervin, J.S., Putnam, S.A., Byrd, L.W., & Gschwender, L., Micrometer-Sized Water Droplet Impingement Dynamics and Evaporation on a Flat Dry Surface. *Langmuir*, 2010. **26**(16), 13272-13286.

[7] van Dam, D.B. & Le Clerc, C., Experimental study of the impact of an ink-jet printed droplet on a solid substrate. *Phys. Fluids*, 2004. **16**(9), 3403-3414.

[8] Nguyen, P.Q.M., Yeo, L.P., Lok, B.K., & Lam, Y.C., Patterned Surface with Controllable Wettability for Inkjet Printing of Flexible Printed Electronics. *ACS Appl. Mater. Interfaces*, 2014. **6**(6), 4011-4016.

[9] Brinkmann, M. & Lipowsky, R., Wetting morphologies on substrates with striped surface domains. *J. Appl. Phys.*, 2002. **92**(8), 4296-4306.