Journal of Colloid and Interface Science 418 (2014) 292–299

Contents lists available at ScienceDirect

Journal of Colloid and Interface Science

www.elsevier.com/locate/jcis

Formation of liquid sheets by deposition of droplets on a surface

Alireza Dalili [a],*, Sanjeev Chandra [a], Javad Mostaghimi [a], H.T. Charles Fan [b], Joseph C. Simmer [b]

[a] *Center for Advanced Coating Technologies, Department of Mechanical and Industrial Engineering, University of Toronto, Toronto, Ontario M5S 3G8, Canada*
[b] *Manufacturing Systems Research Lab, General Motors R&D, Warren, MI 48090, USA*

ARTICLE INFO

Article history:
Received 4 October 2013
Accepted 12 December 2013
Available online 21 December 2013

Keywords:
Drawback
Droplet deposition
Droplet coalescence
Overlap
Liquid film rupture
Thin liquid films
Inkjet printing

ABSTRACT

Experiments were done to observe the coalescence of highly viscous liquid droplets (87 wt% glycerin-in-water solutions) deposited onto a flat, solid steel plate. Droplets were deposited sequentially in straight lines or square droplet arrays. Droplet center-to-center distance was varied and the final dimensions of lines and sheets measured from photographs. When overlapping droplets were deposited surface tension forces pulled impacting droplets towards those already on the surface, a phenomena known as drawback. A dimensionless drawback index, quantifying the extent of droplet displacement, was calculated from experimental measurements for different values of droplet overlap. At large overlaps droplets deposited in a line or square array coalesced to form a circular film. When the droplet center-to-center distance increased, leading to less interaction, long, thin lines and square sheets were formed. As overlap was further decreased lines and sheets became discontinuous. A simple model was developed to predict the conditions under which rupture occurred. The lowest droplet overlap ratio (defined as droplet overlap distance divided by droplet spread diameter) at which a continuous liquid film could be formed was $\lambda = 0.293$. At large overlap ratios ($\lambda > 0.6$) droplets deposited in a square array formed a circular film. The minimum thickness of a continuous film formed by coalescence of droplets was shown to vary from 5% to 70% of the initial droplet diameter while increasing impact Weber and Reynolds number reduced the film thickness.

1. Introduction

An ink-jet printer creates text or images on paper by placing small ink droplets in a pattern. This well-established technology is increasingly being applied in newly emerging fabrication methods that use droplet-on-demand generators coupled with computer-controlled motion stages to deposit polymers to fabricate electronic circuits [1], build three-dimensional components out of wax, metal or ceramic [2], or even create organs by depositing living tissue on soft scaffold structures [3]. In all of these applications it is important that droplets remain where they are placed so that their desired configuration is maintained. However, capillary forces between touching droplets can displace them from their original position, an effect known as "drawback", reducing the resolution with which components can be made. Drawback reduces the resolution of ink-jet printed images, diminishes the dimensional tolerance of objects created by 3D printing and can cause displacement of solder bumps placed on printed circuit boards.

In painting and coating applications droplets are sprayed on a solid surface to form a smooth, continuous liquid film. It is often desirable to make the film as thin as possible, but surface tension may prevent droplets deposited on a solid surface from wetting the surface properly and flattening into a thin layer. Interactions between droplets and their subsequent movement can also make the surface of the liquid layer uneven. As the film dries and hardens these surface undulations become visible as defects in the coating.

This study was motivated by two questions. The first: how do droplet interactions influence the shape of a liquid film printed on a solid surface? For example, if we deposit droplets in a square array, will the perimeter of the sheet formed remain square? The second question: what is the biggest surface area (corresponding to the thinnest liquid layer) we can cover with a given volume of droplets before their spacing becomes so large that the liquid film ruptures due to drawback?

Numerous experimental and analytical studies have been carried out to investigate the coalescence of droplets [4–9]. Li et al. [8] examined drawback during the deposition of overlapping molten wax droplets while varying substrate temperature, droplet overlap ratio and the time between impacts of droplets. In a subsequent paper [10] they studied the coalescence of a falling droplet with a stationary sessile droplet, using high-speed video to record coalescence dynamics, shape evolution and contact line

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* Corresponding author. Address: Department of Mechanical and Industrial Engineering, University of Toronto, 5 King's College Road, Toronto, ON M5S 3G8, Canada. Fax: +1 (416) 978 7753.

E-mail addresses: adalili@mie.utoronto.ca (A. Dalili), chandra@mie.utoronto.ca (S. Chandra), mostag@mie.utoronto.ca (J. Mostaghimi), charles.fan@gm.com (H.T. Charles Fan), joseph.c.simmer@gm.com (J.C. Simmer).

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http://dx.doi.org/10.1016/j.jcis.2013.12.033

Nomenclature

L	droplet center-to-center distance, mm
D	diameter, mm
D_s	droplet spread diameter, mm
D_y	droplet line length, mm
A_W	wetted surface area, mm^2
A_{IW}	ideal wetted surface area, mm^2
A	area of liquid sheet, mm^2
P	perimeter of liquid sheet, mm
t	liquid film thickness, mm
U	droplet impact velocity, m/s
V	liquid volume, mm^3
We	Weber number
Re	Reynolds number

m	number of deposited droplets
n	row (Line) in a liquid sheet array

Greek letters

λ	overlap ratio
$\theta_{1D/2D}$	1-dimension/2-dimension drawback index
ξ	droplet spread factor
β_a	advancing contact angle, °
μ	viscosity, cP
ρ	density, kg/m^3
σ	surface tension, mN/m

movement. Gao and Sonin [11] investigated the conditions required for precise deposition of molten microdrops under controlled thermal conditions. Columnar, sweep deposition on flat surfaces and repeated sweep deposition for building larger objects were investigated. Duineveld [4] studied the stability of ink-jet printed line of liquid with zero receding contact angle on a flat uniform surface both experimentally and theoretically. Castrejon-Pita et al. [12] investigated the dynamics of impact and coalescence of glycerol/water droplets on a solid surface by high-speed particle image velocimetry. Graham et al. [13] considered the coalescence of a falling droplet with a sessile one on solid surface of various wettabilities through experimental and numerical analysis. The droplet diameter, impact velocity and distance between the impacting droplets were controlled. All of these studies were done using two or more droplets deposited in a line. There has been no work done to examine interactions between droplets deposited in two-dimensional sheets on a surface.

This paper reports the results of experimental investigation in which the droplets of 87% glycerin in water solutions, with viscosity two-orders of magnitude greater than that of pure water, were deposited in lines and square arrays on a metal surface and their coalescence photographed. The high viscosity of the liquid is typical of paints, polymers and waxes used in coating applications. Table 1 lists the properties of the test liquid along with those of some commonly used industrial fluids. The objective was to develop a simple criteria to predict when continuous lines or sheets of liquid could be formed for a given droplet size and spacing and what their shape and thickness would be.

2. Experimental system

Fig. 1 gives a schematic diagram of the experimental system used to form droplets in a pattern on a substrate. An x–y motion stage (XYR-1010, Danaher Precision Motion, USA) with 200 mm × 200 mm (8 in. × 8 in.) travel, controlled by software developed by Fang et al. [2], was used to position the substrate. The droplet generator system consisted of a stainless steel tank filled with liquid and connected to a centrifugal pump (PA411-50MT, The Berns Corporation, USA) that passes compressed liquid through stainless steel and plastic tubing to a solenoid valve (8262H020, ASCO Valves, USA). A partially open needle valve (S-1RS6, Swagelok, USA) was used to manually control the fluid flow upstream of the needle. That and a pressure regulator (26A, Watts Water Technologies, USA) maintained a closed loop for fluid flow and ensured no back flow into the pump. The solenoid valve was normally closed and could be opened for a pre-determined period of time with a timer circuit that was triggered by a computer and coordinated with the motion of the substrate. By varying the speed of the motion stage, the center-to-center distance between droplets (L) was controlled. Droplets were deposited at a constant frequency of 1 Hz. The exact position of the droplets varied due to variations in the delay between triggering the solenoid valve and detachment of a droplet from the tip of the needle. The uncertainty in positioning a droplet was ±0.14 mm.

Droplets of 87 wt% glycerin in water solution were made by opening the solenoid valve for 13 ms to allow liquid at 30 kPa pressure to pass through a 17 gage needle (7748-03, Hamilton Company, USA) (with 1.47 mm outer diameter) and detach from the tip as a droplet. The average droplet diameter (D) was measured to be 3.4 mm with a standard deviation of 0.01 mm; all droplets had diameters within two standard deviations of the mean. The droplets impacted with a velocity (U) of 1.1 m/s.

Still images of the final shape of droplets were captured at 2304 × 1728 pixel resolution using a video camera (Sony HDR-CX100, Sony Corporation, USA). The spread diameter of a single droplet (D_s) and the length (D_y) of a line formed by the coalescence of several droplets were defined as shown in Fig. 2 and measured using image analysis software (ImageJ, National Institute of Health).

3. Results and discussion

The equilibrium spread diameter of a single droplet after it impacted on the substrate was measured to be D_s = 5.86 mm and the

Table 1
Properties of 87 wt% glycerin in water solution and other fluids commonly used in painting and printing applications. The properties of 87 wt% glycerin in water solution and paint were measured at 25 °C. The properties of the paraffin wax and printer ink were measured at their respective melting temperatures of 70 °C and 95 °C.

	Density (ρ) kg/m^3	Viscosity (μ) cP	Surface tension (σ) mN/m
87 wt% Glycerin in water solution [14–16]	1224	124	63.5
Paint [14]	1004.4	110	32.3
Paraffin wax [17]	771	5.4	22.4
Printer ink [18]	820	34.3	27.6