Micro-Film Formation by Multi-Nozzle Electrostatic Jets

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Abstract

Applying micro spray of electrostatic inkjet, precision film coating was examined experimentally. Heretofore, high quality coating was demonstrated with using a single nozzle. A critical issue, however, lies in terms of productivity; the amount of liquid jetted from a single nozzle was too small to obtain sufficiently high coating speed. To overcome the situation, a possibility of multi-nozzle was investigated in this report. Two types of coating liquids were used, one of which was dilute dispersion and the other was viscous solution. As results, jetting with the dilute dispersion from seven nozzles made of stainless steel was fanned out toward the opposite plate electrode. By intentionally clogging the both end-nozzles and making them as electrodes, the direction was remedied and parallel jets were obtained. According to the increment of applied voltage, jetting mode was varied from dripping mode to cone-jet mode. Although the variation of jetting mode was qualitatively the same as that of the single nozzle, the higher voltage was required for the multi-nozzle system. Furthermore, the change of jetting mode and uniform distribution of droplets always started from the end-nozzles. Again, high voltage was required to alleviate the fluctuation of the droplet size. From cylinder coating experiments it was demonstrated that the multi nozzles with dummy electrodes at high applied voltage could jet well-oriented fine and uniform droplets to acquire quality film coating.

Introduction

Since the first inkjet printer appeared in market more than 50 years ago [1][2], the inkjet technology has progressed tremendously in quality and print speed. Although the electrostatic inkjet technology has not applied to commercial printers, it is attractive for the industrial application because of its versatility in jetting forms; an individual droplet on demand [3], fine droplets in micro spray state [4] and a thread for fabric [5]. Furthermore, it has the ability of jetting highly viscous liquid [6] and making (a) super fine, femtoliter-size, droplet(s) [3].

The authors are investigating the applicability of the micro spray state of electrostatic inkjet to precision film coating [7]. Using a single nozzle, it was found that electrostatic inkjet system could jet femtoliter-size droplets even from a viscous liquid and by piling those droplets, quality coating was demonstrated. A critical issue for industrial application, however, lies in terms of productivity; the amount of liquid jetted from a nozzle was too small to obtain sufficiently high coating speed. To overcome the situation, scale-up study of multi-nozzle system was tried in this report. At first, the most preferable jetting conditions were determined through experiments. Then, with those parameters examined, the possibility of quality coating was explored through experiments.

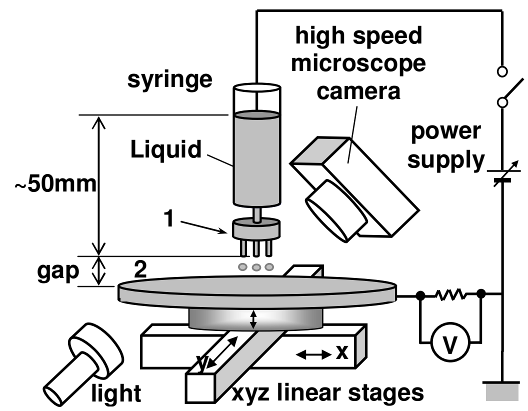


***Figure 1**. Experimental set-up of electrostatic inkjet jetting observation, 1: pin electrode=nozzle, 2: plate electrode.*

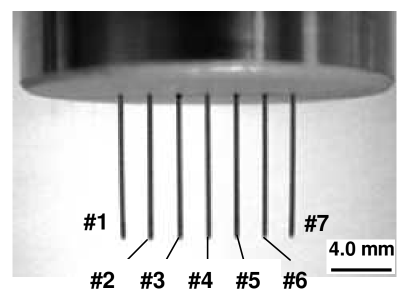


***Figure 2**. An example of multi-nozzle head made of stainless stea. Nozzle dimension is as follows; outer diameter :330 μm, innder diameter:150 μm, nozzle length:10mm and nozzle pitch 2 mm.*

Experimental

Experimental set-up

An experimental set-up for jetting observation is illustrated in Figure 1. During applying the voltage up to 30 kV by a high voltage amplifier, the jetting state is observed with a high-speed microscope camera. Nozzles, filled with liquid are assumed to be pin electrodes. The gap between the nozzle-tips and the plate electrode can be controlled by a mechanical stage.

Figure 2 is an example of a head with seven nozzles. The nozzles are equally aligned as shown in the figure. All the nozzles and the body were made of stainless steel. The tips of the nozzles are tapered and the outer surfaces of the nozzles are coated with a conductive material.

Figure 3 is a schematic of a bench for coating experiments. A metal cylinder was used as a coating substrate. Liquid is jetted from the multi-nozzle head which is mounted above the rotating cylinder. Whole area of the cylinder surface could be coated by traversing the multi nozzles into the x-direction in the figure by a linear stage. The position of the nozzle can be controlled by a mechanical stage.

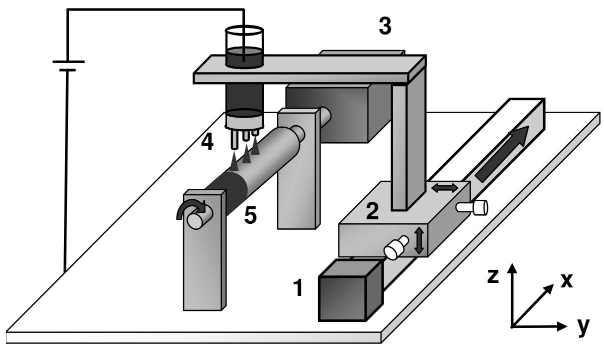


Figure 3. A schematic of a cylinder coating bench. 1: x-axis linear stage, 2: y-z mechanical stage, 3: motor for rotation, 4: multi-nozzle head, 5: a metal cylinder (coating substrate, which is grounded).

Table 1 Properties of viscous solutions. Liquid #1 is a dilute dispersion, characterized at 26.0 °C. Liquid #2 is a solution, characterized at 20.0°C.

#	Solid contens, wt%	conductivity, S/m	viscosity, mPa.s	surface tension, mN/m
1	4.1	1.15×10^{-6}	4.5	36.28
2	15.0	1.55×10^{-6}	172.0	35.74

Liquids

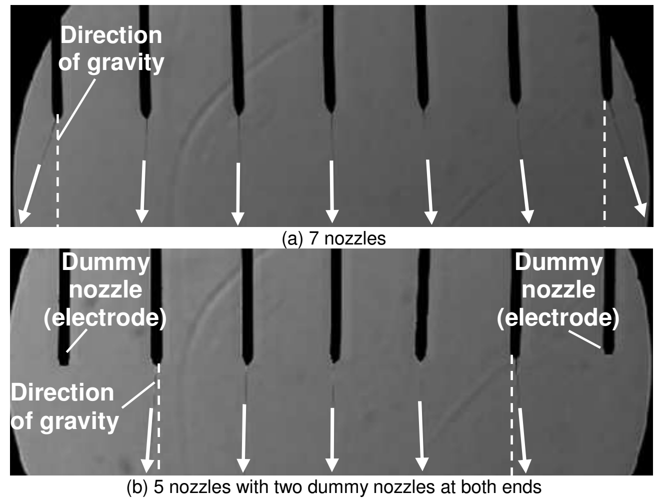
Two types of different liquids were examined [7]. One of which is a dilute dispersion consists of two solid components; poly(vinyl butyral) and an phthalocyanine-type pigment and cyclohexanone as a solvent. The other liquid was a viscous solution. The solid components consist of equal amount of polycarbonate and an arylamine-type low molecular component. These solid components were solved into cyclohexanone. The properties of these liquids are tabulated in Table 1. The conductivities of these liquids are in the range of spray mode of electrostatic inkjet system, 10^{-3}—10^{-11} S/m, reported by Drozin [8]

Results and Discussion

Jet direction

Figure 4(a) shows the result of the jetting of liquid#1 from all seven nozzles. The off-sets of jet directions from the direction of gravity were widened toward both ends of the nozzles (#1 and #7). It is well-known that this is the effect of the electrical field. Rulison et al. [9] proposed to add dummy nozzles at the ends of the aligned nozzles to control the electrical field. Figure 4 is the jet directions from five nozzles with two intentionally clogged dummy nozzles at the ends. As shown in Figure 4(b), the off-sets were narrowed but not sufficient. It was considered that this was the effect of Taylor cones protruding from the nozzle tips during jetting. To control the jet direction furthermore, the length of the dummy nozzles was elongated slightly by inserting Tungsten wire into the dummy nozzles as shown in Figure 5. In case of the 2 mm pitch multi nozzles, it was found that the direction of jets were evenly spaced with 1mm of the Tungsten wire protruded from the tips of the dummy nozzles, as shown in Figure 6.

To confirm the possibility of coating, line coating experiments were carried out by traversing a plate substrate on the plate electrode in Figure 1 into y-direction, which was set perpendicularly to the nozzle alignment. As is shown in Figure 7, at the applied voltage 7.5 kV and the gap 15 mm, the jetted droplets could be overlapped. This suggests the possibility of high quality coating because even such unevenness observed in Figure 7 could be alleviated by leveling of the film by piling up sufficiently smaller droplets than the target film thickness.



Figiure 4. Jet directions from multi nozzles. Applied voltage = 6.0 kV, Gap = 15 mm, Nozzle-pitch = 3 mm.

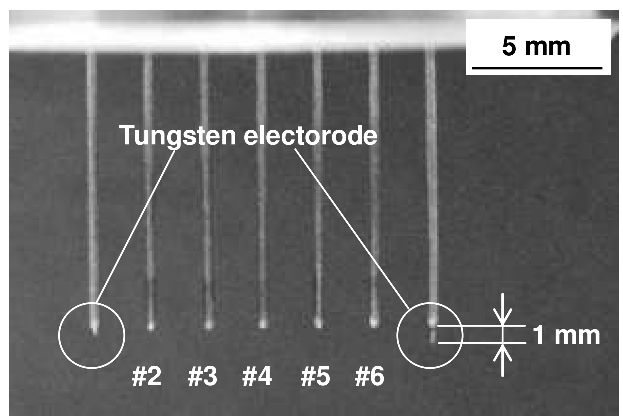


Figure 5. A view of multi nozzles with 100 μm Tungsten wires inserted into dummy nozzles at both ends. 1mm of the electrodes is protruding from the dummy nozzles. Nozzle-pitch = 2 mm.

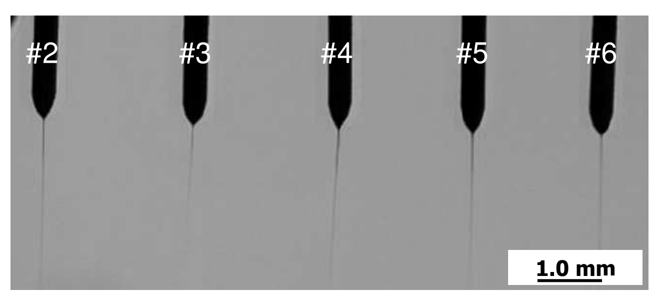


Figure 6. Corrected jet directions from the multi nozzles shown in Figure 5. Applied voltage = 6.0 kV, Gap = 15 mm.

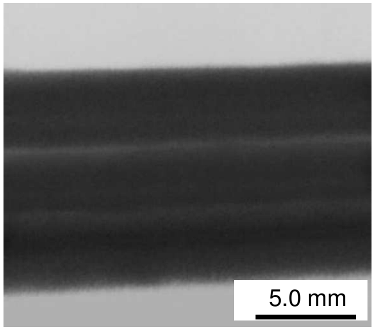


***Figure 7**. Line coating by the multi nozzles shown in Figure 5. Applied voltage = 7.5 kV, Gap = 15 mm.*

Jetting mode

As of a single nozzle case [7], the forms of jets with the dilute dispersion (liquid#1 in Table1) varied from dripping mode to cone-jet mode along increasing the applied voltage. Higher voltage was required for the mode change in case of multi-nozzle. The onset voltage of mode change for each nozzle was slightly different as shown in Figure 8. The applied voltage for the mode change of #2 and #6 (not shown in the figures) nozzle was always lower than the nozzles in the middle (Figure 8(a)). The highest voltage was required for the nozzle #4 (Figure 8(c)).

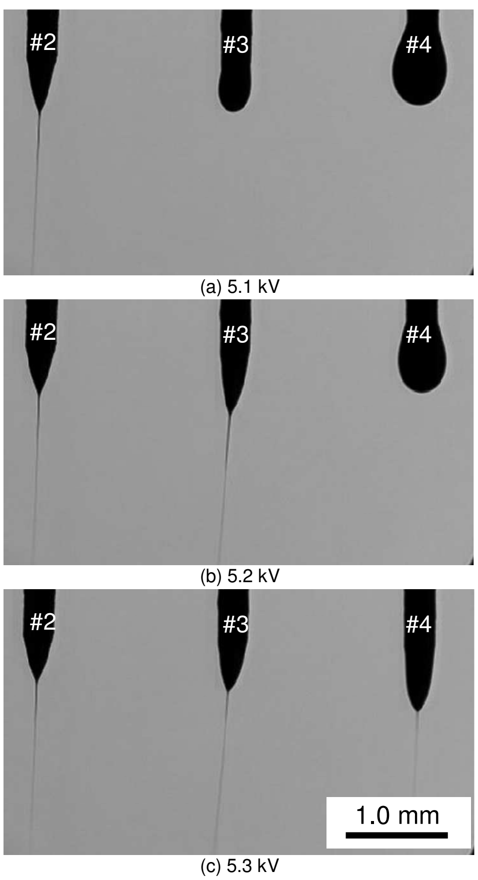


***Figure 8**. Jetting mode change of the multi nozzles shown in Figure 5 by applied voltages. Only three nozzles out of five jetting nozzles are shown. Gap = 15 mm.*

Drop size and distribution

Figure 9 is the estimate of the distribution of jetted droplet-sizes from deposited dots on a photo quality inkjet paper in the range of cone-jet mode for liquid #1. At the applied voltage 7.0kV, the difference in the distribution with each nozzle is not significant, although the distribution is broad and the sizes of the droplets are relatively large, more than 10μm. The droplet size tends to be smaller according to the increment of applied voltage and the distribution always approached mono-dispersedly from the edge nozzles. At the applied voltage 9.0 V, the distribution of each nozzle seems to be identical and the mode-diameter was small as 6-7 μm (the volume of which is about 0.1 picoliter). It is noted that the diameter obtained by a single nozzle is smaller, about 3-4μm. The flow rate in case of the condition in Figure 9(d) was about 55 mg/min.

Coating experiments

With the jetting condition in Figure 9(d) and the multi-nozzle configuration shown in Figure 5, coating trials with liquid #1 were carried out with the coating bench as shown in Figure 3. As a result, submicron quality coating and possibility of high speed coating was demonstrated as in Figure 10. Figure 10 is the developed view of the distribution of coating film thickness on a metal cylinder whose outer diameter was 30 mm. Traverse speed of the multi-nozzle head was 1.32 mm/s and the rotation speed of the cylinder was 200 rpm. The average film thickness was 0.39 μm and the grayscales in Figure 10 indicates that the deviation was about 0.2 μm.

Concluding Remarks

Ability of jetting fine droplets from multi nozzles and applicability of the spray state of electrostatic inkjet to quality and high-speed coating were examined experimentally. It was found that,

1. By adding intentionally clogged dummy nozzles to both ends of aligned multi nozzles, well oriented parallel jet could be obtained,
2. Identical and mono-dispersedly droplet distribution from each nozzle could be achieved at relatively higher applied voltage than a single nozzle in the range of cone-jet mode,
3. Submicron quality coating and possibility of high speed coating was possible with the above described jetting condition and the dummy-nozzle configuration.

Note that the experiments of multi nozzles with viscous solution as of liquid #2 in Table 1 is currently progressing.

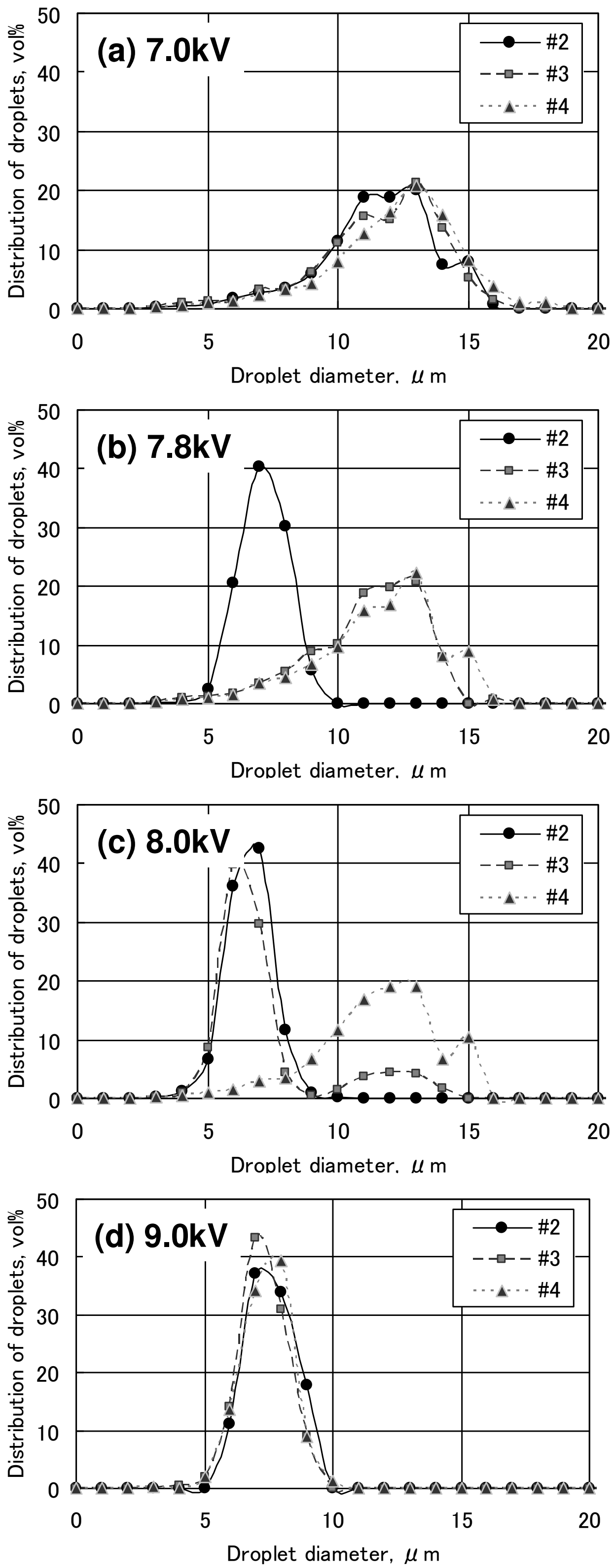


Figure 9. Droplet size distributions of the multi nozzles shown in Figure 5. Only data for three nozzles out of five jetting nozzles are shown. Gap = 15 mm.

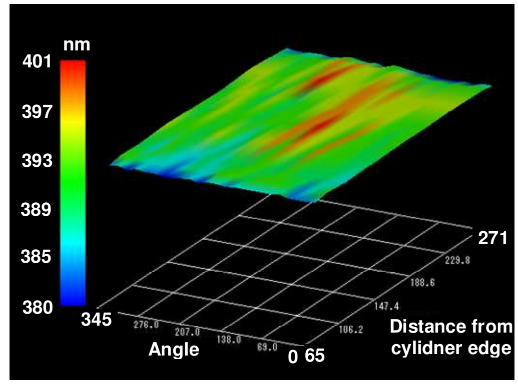


Figure 10. Developed view of the distribution of film thickness coated on a metal cylinder with the multi nozzles shown in Figure 5. Applied voltage = 9.0 kV, Gap = 15 mm. Traversed speed of the multi-nozzle head was 1.32mm/s. Rotation was 200rpm.

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Author Biography

Kazuyuki Tada started his professional career as an engineer in 1990 following completion of a M.S. degree at Keio University. Since then he has been working in a manufacturing engineering division of Fuji Xerox. From 1997 to 1999 he had a chance to study coating science and technology in University of Minnesota where he received another M.S. degree. During the stay in Minnesota, he participated in NIP14 at the first time as an audience in Toronto, CANADA. This is his third consecutive presentation at NIP/DF conference from 2008. Currently he enjoys double statuses of his career, a corporate engineer and a doctoral-course student at Waseda University.