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Control Characteristics of Toner Beam by Pulsed Voltage Applied to a Pair of Aperture Electrodes

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Abstract. *Toner cloud beam is a novel toner-based printing method that employs a conductive toner. In this method, the toner beam is controlled by applying a pulsed voltage to a pair of aperture electrodes. It is important to determine the pulse control characteristics of the toner beam. Hence, this study experimentally investigates the dependence of dot formation on the electrode voltages and the relationship between the dot size and the pulse duration. An enlarged model with an aperture diameter of 0.5 mm is used to confirm that dots are formed directly on paper in less than* 10^{-4} *s. The toner motion is characterized by a toner velocity of* $\sim 1-2$ *m/s and a toner motion relaxation time of* $\sim 3\times 10^{-4}$ *s. © 2011 Society for Imaging Science and Technology.*
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INTRODUCTION

Toner-based printing technologies have several attractive characteristics including the ability to print on plain paper at high speeds with high quality.[1–4] Electrophotography is the most important toner-based printing technology. As a result of major advances, electrophotography is currently used in a wide range of applications ranging from personal use to high-speed, high-volume office printing. However, electrophotographic printing involves six individual processes. To simplify these processes, several simpler toner-based printing processes have been proposed. The most well known of these is TonerJet®. It is already being used in printers,[5] and a compact prototype color printer using TonerJet® has been developed.[6] In addition, a simple printing mechanism has been proposed in which conductive toner is controlled by a stylus.[7]

Another simple printing mechanism that uses conductive toner has been proposed, known as toner cloud beam (TCB). TCB forms toner dots directly on paper by applying a pulsed voltage to a pair of aperture electrodes.[8–10] Previous studies[11–15] experimentally investigated the effect of the applied voltage, the distance between the two electrodes, and the aperture electrode thickness on dot formation in TCB. These studies also examined the effect of pulse duration on dot formation; however, greater understanding of dot formation at short pulse widths is needed.

In the present study, we investigate pulse control using a pair of aperture electrodes to understand dot formation at short pulse widths. In particular, the effects of short pulse durations and the electrode voltages are examined.

EXPERIMENTAL

Figure 1 shows a schematic diagram of the TCB experiment. The experimental toner control system in Fig. 1 consists of four electrodes: upper and lower electrodes and a pair of aperture electrodes. Voltages are applied to each electrode. The voltages applied to the upper and lower electrodes are designated the toner jumping (TJ) voltage and the toner pulling (TP) voltage, respectively. A voltage pulse is generated by amplifying the signal from the function generator. It is then applied to the upper gate control (GC) aperture electrode. The amplifier is a high-speed bipolar amplifier (NF, HSA4051). A function generator (NF, DF1905) generates the pulses. The aperture electrode is stainless steel (SUS304) and it has a 0.5 mm diameter aperture at its center. Table I lists the physical properties of the toner. Figure 2 shows a scanning electron micrograph (SEM) of the toner particles. The toner is produced by pulverization and it consists of irregularly shaped particles. Coated paper for electrostatic recording (Oji Paper Co.) is used in this experiment to prevent the toner rejumping from the paper (rejumping may occur due to charge injection from the paper). Table II lists the physical properties of the paper.

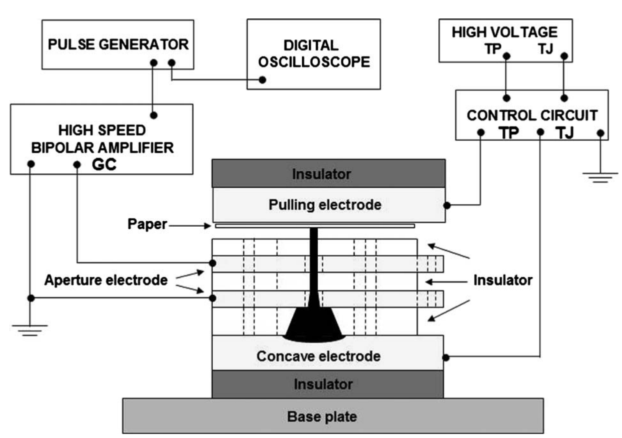

Figure 1. Schematic diagram of the TCB experimental system.

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Table I. Physical properties of the toner.

Physical property	
Average diameter (μm)	8–11
Density (g/cm^3)	0.75
Volume resistivity (Ω cm)	1.5×10^8

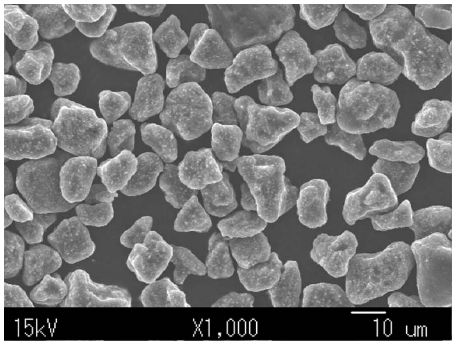


Figure 2. SEM image of the toner.

Table II. Physical properties of paper.

Paper property	
Thickness (μm)	68
Surface resistivity (Ω)	7.1×10^{11}
Volume resistivity (Ω m)	1.7×10^{11}

As Figure 3 shows, TCB has two states: an "off" state in which toner cannot pass and an "on" state in which toner can pass. The on state is realized by applying a pulsed voltage to the GC electrode (see Figure 4). In this experiment, the toner is controlled by switching between the on and off states by applying a voltage pulse. In this printing mechanism, toner adheres to the control electrodes. Adhered toner is removed by applying a voltage and any residual toner particles are removed by rubbing.

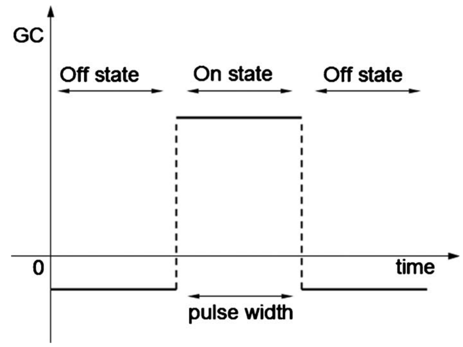


Figure 4. Time dependence of the GC voltage.

Table III. Experimental conditions.

TJ (V)	−400 to −550
GC (V)	−20 (off), 200–300 (on)
TP (V)	450–750
T1 (mm)	0.4
T2 (mm)	0.4
Ø (mm)	0.5
D1 (mm)	0.5
D2 (mm)	0.5
D3 (mm)	0.5

Table III lists the experimental conditions. A negative voltage is applied to the GC electrode to prevent the toner from passing through the aperture electrode. TJ is applied to the lower electrode to generate a toner cloud between the lower electrode and the lower aperture electrode. TP is then applied to the upper electrode as the pulling voltage. When a positive voltage pulse is applied to the GC electrode and the pulse duration exceeds the time it takes for the toner to travel between the two aperture electrodes, the toner passes through the aperture electrode, and it forms a dot on the paper.

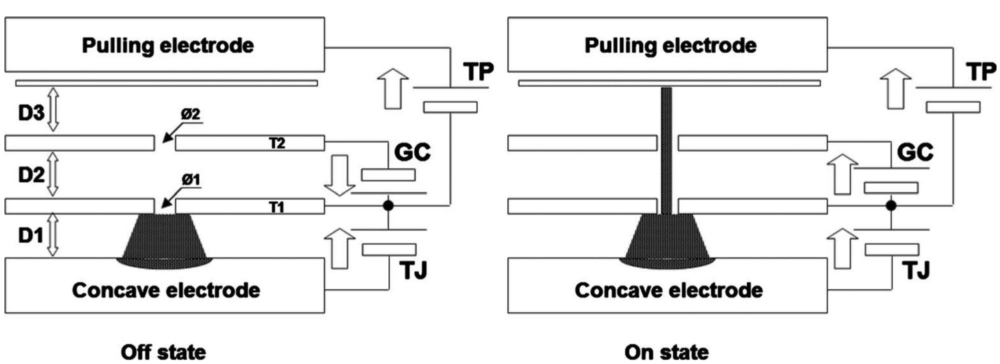


Figure 3. TCB states: (a) off and (b) on states.

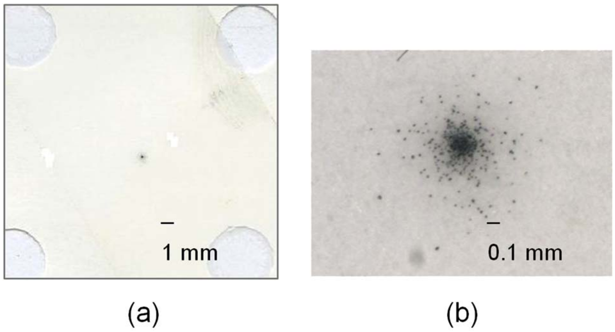


Figure 5. Typical images of dots: (a) original image and (b) image enlarged by a factor of 10.

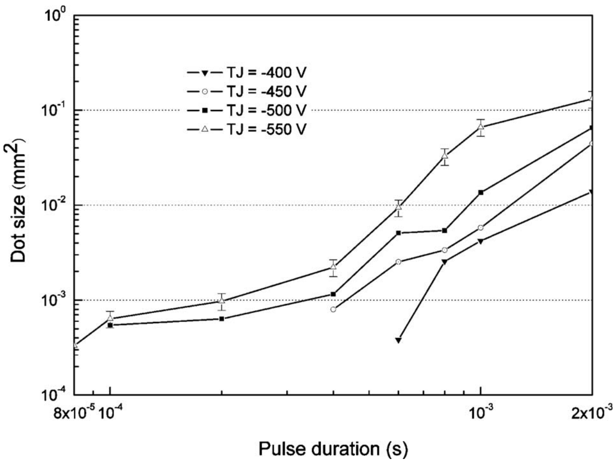


Figure 6. Dependence of dot size on pulse duration plotted on a log scale for four different values of TJ.

RESULTS AND DISCUSSION

Effect of Applied Voltage and Pulse Duration

Toner Jumping Voltage Dependences

In this experiment, the dependence of the dot size on the pulse duration was investigated by varying TJ in the range of −400 to −550 V. The GC electrode potential and TP were kept constant at 250 and 750 V, respectively. Figure 5(a) shows an image of a dot and Fig. 5(b) shows the same image enlarged by a factor of 10. We used an image analysis system (PIAS-II, QEA) to determine the dot size by applying a threshold of 40%. Although toner scattering occurs with TCB, we were easily able to determine the size of the largest dot by applying the above threshold. Reduced toner scattering is possible by optimizing the applied voltage.

Figure 6 shows the experimental results obtained. Above a certain pulse duration threshold, the dot size increases with increasing pulse duration. When TJ is increased, the dot size increases and the threshold pulse duration for dot formation decreases.

We propose that the increase in dot size with increasing pulse duration is due to more toner reaching the paper. The reduction in the threshold pulse duration is thought to occur because the time required for toner to pass between the aperture electrodes decreases since toner does not pass through the aperture electrodes if the pulse duration is shorter than this required time. In addition, the toner velocity is considered to increase as TJ increases. Thus, the threshold pulse duration decreases and the dot size increases with increasing TJ. TJ causes the toner to jump; if TJ is too high, the electric field experienced by the toner causes the toner to pass through the aperture electrodes directly, making it difficult to realize the off state. Consequently, it is important to determine the optimum TJ.

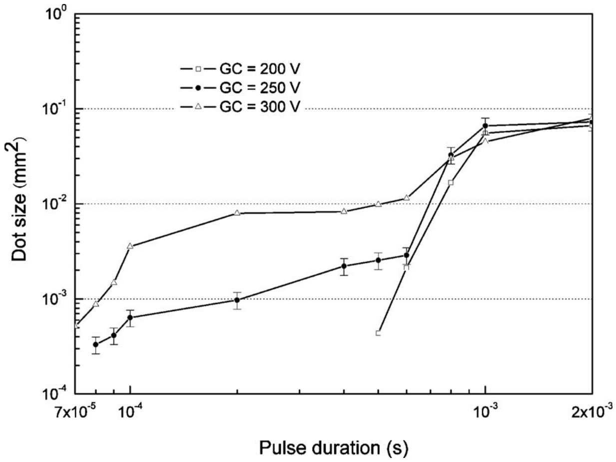


Figure 7. Dependence of dot size on pulse duration plotted on a log scale for three different GC electrode voltages.

GC Electrode Voltage Dependences

Figure 7 shows a plot of the dot size as a function of the pulse duration for GC electrode voltages of 200, 250, and 300 V. TJ and TP were kept constant at −550 and 750 V, respectively. The curves in Fig. 7 shift to shorter pulse durations in the small-dot region with increasing GC electrode threshold voltage in the on state. This implies that the toner passes through the aperture electrodes in a shorter time with increasing GC electrode voltage.

Figures 8(a)–8(c) show electric field analysis results near the aperture electrodes for GC electrode voltages of −20, 200, and 300 V, respectively. Fig. 8(d) shows the potential at the central axis of the aperture. The slope of the potential is proportional to the electric field that controls the toner speed. The slope increases with increasing GC electrode voltage. Thus, the toner can pass through the aperture electrodes in a shorter time with increasing GC electrode voltage.

Toner Pulling Voltage Dependences

Figure 9 shows a plot of the dot size as a function of the pulse duration for four different TP voltages between 450 and 750 V. TJ and the GC electrode voltage were kept constant at −550 and 250 V, respectively. The curves in Fig. 9 shift to shorter pulse durations in the small-dotted region with increasing TP. The dot size varies little when TP is in the range of 550–750 V and the pulse duration is in the range of $(0.4-2)\times 10^{-3}$ s. The toner is thought to pass through the aperture electrode more rapidly with increasing TP. The amount of toner that passes through the electrode may increase as TP increases from 550 to 750 V; however, the dot size does not increase. Instead, the toner concentration along the central axis increases with increasing TP.

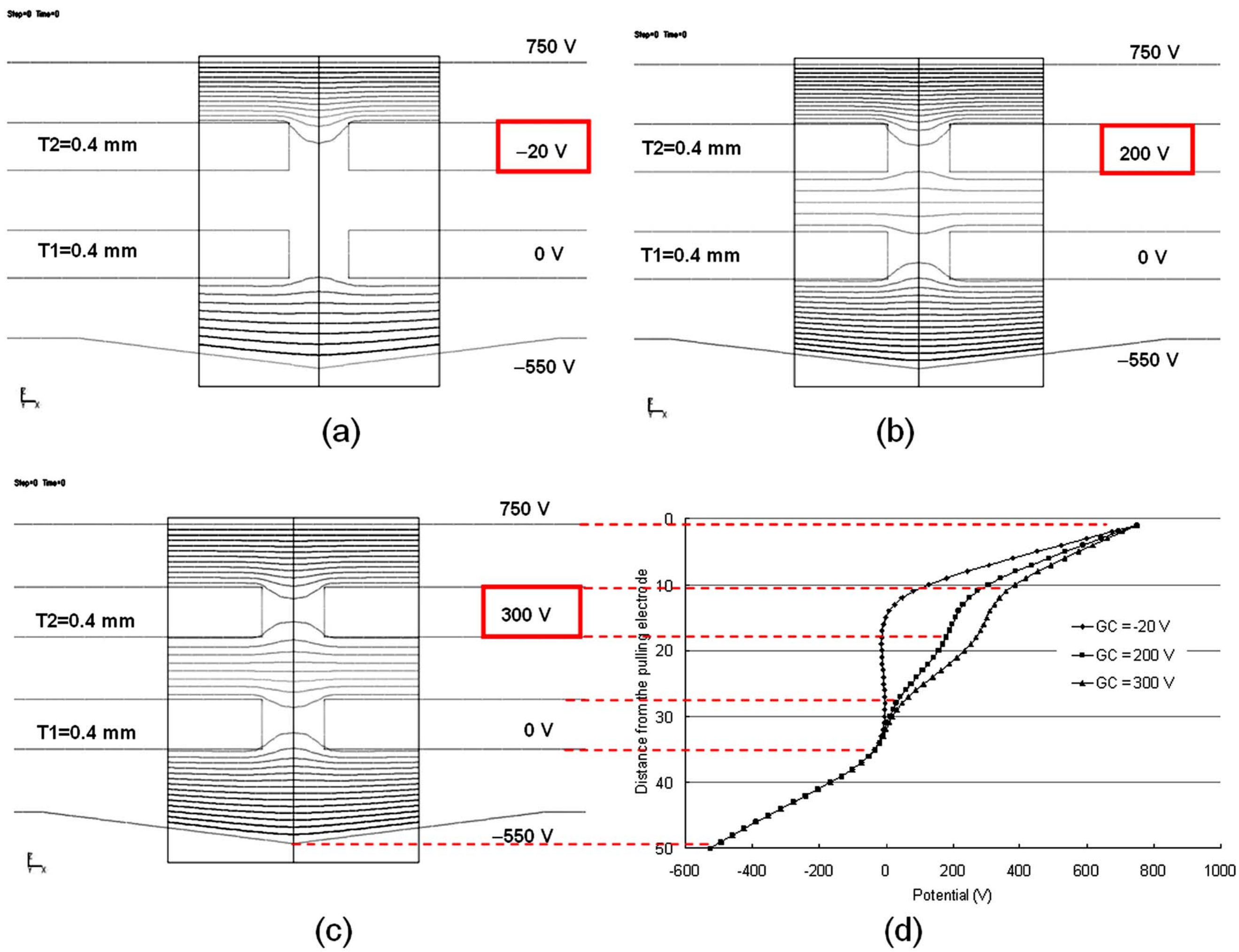


Figure 8. Analysis results for the potential for the (a) off and (b) on states when the GC electrode voltage is 200 V, (c) the on state when the GC electrode voltage is 300 V (equipotential lines are shown), and (d) the potential at the central axis when the GC electrode voltages are −20, 200, and 300 V.

Toner Motion Estimation

Toner motion between the aperture electrodes is important in the TCB printing process, especially transient toner motion during transitions between the on and off states. The toner particles have irregular shapes; however, the toner is assumed to have a fluid dynamic radius a. The toner motion is then described by the equation

$$m\frac{d^2\mathbf{r}}{dt^2} = Q\cdot\mathbf{E} - 6\pi\mu a\frac{d\mathbf{r}}{dt} - m\mathbf{g},$$

where m is the mass of the toner, $\mathbf{r}$ is the position of the toner, Q is the charge of the toner, $\mathbf{E}$ is the electric field at the toner, μ is the viscosity of air, and $\mathbf{g}$ is the Earth's gravitational acceleration. The effective toner radius a is 5 μm, its density is 10^3 kg/m^3, m is estimated to be 5.2×10^{-13} kg, and μ is known to be 1.8×10^{-5} Pa s (at 20°C).

The toner is charged by induction at the lower electrode and it starts to jump at approximately 300 V when the electrode distance is 0.5 mm. The toner charge Q is estimated to be

$$Q = 1.65\times 4\pi a^2\times\varepsilon\times E = 2.7\times10^{-15}\ \mathrm{C}.$$

Therefore,

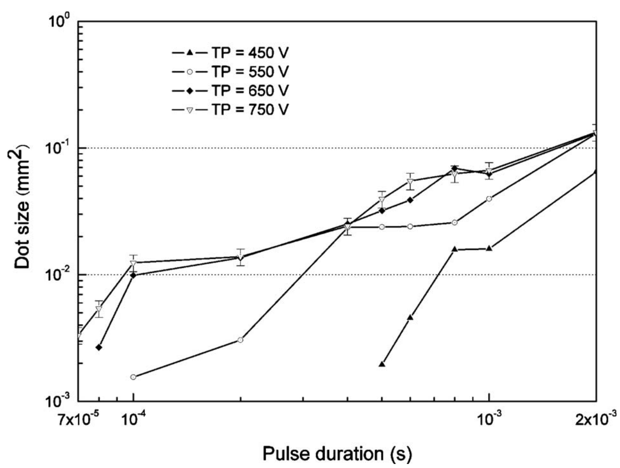
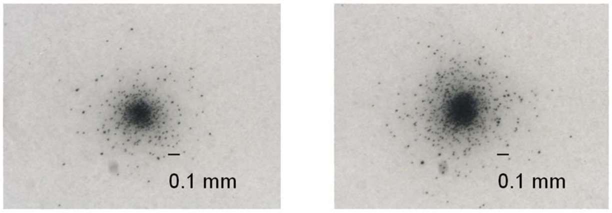


Figure 9. Dependence of dot size on pulse duration plotted on a log scale for four different values of TP.



(a) (b)

Figure 10. Enlarged images of dots: (a) TJ=−500 V, TP=750 V, and $t=6\times10^{-3}$ s; (b) TJ=−500 V, TP=750 V, and $t=6\times10^{-3}$ s.

$$m\mathbf{g}/QE \sim 10^{-3},$$

implying that the term $m\mathbf{g}$ can be neglected. The two terms that characterize the toner motion are the toner steady-state velocity and the relaxation time of the toner motion. The steady-state velocity of the toner is

$$V_s = \frac{QE}{6\pi\mu a} \sim 1.7 \text{ m/s},$$

and the relaxation time of the toner motion is

$$\tau_r = \frac{m}{6\pi\mu a} \sim 3 \times 10^{-4} \text{ s}.$$

The characteristic length is $\ell_c = V_s \times \tau_r \approx 0.5$ mm; the inertia of the toner must be considered at distances on the order of the characteristic length or less.

Even in the off state, toner enters the aperture electrode region by passing through the lower aperture electrode. However, application of an electric field in the opposite direction causes the toner to return to the lower toner cloud.

The steady-state velocities of the toner, V_s, are 0.64, 1.3, and 2.4 m/s when E are 400, 800, and 1500 V/mm, respectively. Under typical conditions, the toner velocity is approximately 1–2 m/s and the distance between the aperture electrodes is 0.5 mm. In this condition, the toner travels between the aperture electrodes in 0.25–0.5 ms and a dot is formed on the paper within 0.5 ms (see Figs. 6, 7, and 9). In addition, as TJ, TP, and the GC electrode voltages increase, the toner velocity increases, and the acceleration area around the aperture electrode increases, causing a dot to be formed on the paper for even shorter pulse durations.

Toner Scattering

This printing mechanism suffers from toner scattering, as shown in a preliminary experiment. Figure 10 shows enlarged dot images obtained for two different values of TJ. Toner scattering is reduced slightly when TJ is reduced. The toner velocity distribution is thought to be narrower when TJ is reduced. It should be possible to reduce toner scattering by optimizing the control voltage and the electrode structure.

CONCLUSIONS

The pulse characteristics of a toner beam controlled by aperture electrodes were investigated and the dependences of dot formation on the voltages that generate the toner cloud, control the toner passing through the apertures, and pull the toner from the aperture electrode were obtained experimentally. It was found that a dot is generated in shorter pulse durations as these voltages are increased. A dot could be formed in less than 10^{-4} s at the shortest pulse duration of 7×10^{-5} s. The toner motion was discussed in terms of the toner steady-state velocity (0.6–2.4 m/s) and the toner motion relaxation time (3×10^{-4} s), and the dependence of dot formation on the pulse duration was thereby explained.

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