Direct Observation and Numerical Study on Dynamics of Toner Particles in Magnetic Single-Component Development System of Electrophotography

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Abstract

Dynamics of toner particles in the magnetic single-component development system of electrophotography have been investigated to utilize for the improvement of the system. Two approaches have been adopted for the investigation: One is the direct observation of the toner motion in a development area with a high-speed microscope camera and another is the numerical simulation with the distinct element method. We have manufactured the mock-up apparatus that consisted of a pseudo-photoconductor, development roller, stational magnetic roller inside it, and doctor blade to form thin toner layer on the development roller. The development roller, magnetic roller, and blade were diverted from a commercial printer. Thin line electrodes were embedded on the pseudo-photoconductor drum to substitute for electrostatic latent images. The apparatus enabled high-speed (8,000 fps) observation of toner motion at the development gap with satisfactory image quality. Observed images showed that (1) toner particles formed chain-like clusters in the vicinity of the gap, (2) these chains vibrated at the development zone synchronized with an applied alternative electrostatic field, (3) at the latent image, chains crashed on the photoconductor and then fell apart from the photoconductor, and (4) at this moment, some of toner particles returned to the development roller but some adhered to the latent image to form a real image. Three-dimensional shapes of toner piles on the latent image were measured after the development by a scanned laser displacement meter. It has been clarified that both the width and height of the toner pile increased with an increase in the development voltage but these were saturated at the voltage higher than a threshold. Numerical simulation has been conducted to confirm the experimental results. The simulation method is based on a hard sphere model of the distinct element method with cyclic boundary condition. The method can be applied for the dynamics of small toner particles within reasonable calculation time.

Introduction

The development step of electrophotography usually determines the best image quality that the printer or copier will produce. Although there are several types of the development subsystem, such as magnetic brush development and nonmagnetic single-component development, the magnetic single-component development, so-called "jumping development," is most widely used in low speed black-and-white machines because it can realize high print quality with a relatively simple configuration.[1-3]

Figure 1 shows a typical single-component development system, based on insulating toner, magnetic transport, and noncontact. The main function of the development step is to draw an image, using toner particles, on the electrostatic latent image presented on the surface of the photoreceptor. The photoreceptor drum and the roller are both turning in opposite directions. Inside the development roller, a multi-pole magnet forms the so-called magnetic roller. Magnetic toner particles are attracted to the stationary magnetic roller, and by the magnetic and friction forces, they are transported around by the rotating development roller. The thickness of the toner layer is controlled by a doctor blade. The doctoring process determines the amount of toner particles on the development roller in the development zone. As the development roller rotates, the toner particles are charged by the blade, a process called triboelectrification. Once in front of the photoreceptor, the toner particles jump towards the photoreceptor drum or return to the roller near the development zone depending on the direction of force applied to the toner particles. DC voltage superposed on AC voltage is applied to the development roller to create the electric field at the gap between the photoconductor drum and the development roller.

Although this development process critically affects the image quality, significant aspects of the development physics, particularly with respect to the dynamics of toner particles, are currently not well developed because the motion of toner particles is caused by complex dynamics determined by many factors such as the electric field, magnetic field, and adhesion.

In the present paper, we have investigated the motion of toner particles in the development area with a high-speed microscope camera and the three-dimensional shapes of toner piles created on the latent image of the photoconductor after the development process. Numerical simulation with the hard-sphere model of the distinct element method (DEM) has also been conducted to confirm the dynamics and utilized for the design of the system.

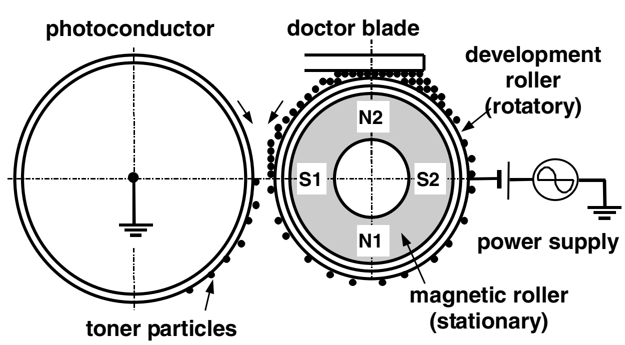
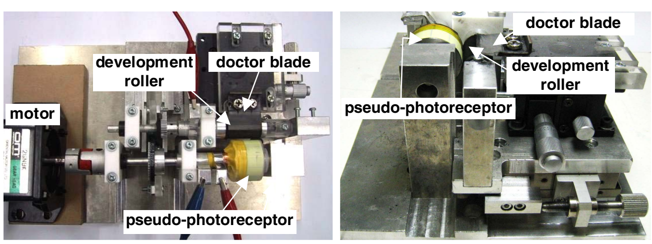


Figure 1. *Single-component magnetic development system in electrophotography.*

Experimental

Figure 2 shows the mock-up apparatus of the development system. The effective longitudinal length is 10 mm that is sufficient for the observation of the toner motion from the lateral direction of the development zone. Because high-intensity light must be exposed to observe the motion of toner particles with the high-speed microscope camera, the actual photoconductor could not used to form latent image. An electrostatic image was formed with the line electrodes made of aluminum foil (thickness: 0.5 μm, width: 300 μm) insulated by acetate tapes (thickness: 55×2 μm, relative permittivity: 2.5) and embedded on the pseudo-photoreceptor made of aluminum parallel to the rotating axis, as shown in Fig. 3. The electrodes generated the electric field similar to the latent image by applying DC voltage to the electrodes. AC voltage is applied to the development roller. The diameter of the development roller was 16 mm and that of the pseudo-photoreceptor drum was 32 mm. The gap between the rollers was 400 μm, the process speed was 34 m/s (6.8 ppm A4 size), and the AC frequency was 1.5 kHz. The motion of toner particles was observed by the high-speed camera (Fastcam-max Imager, Photron) with 8,000 fps frame speed and 0.1 ms shutter speed.

The magnetic roller and the development roller in the commercial laser printer (LBP-1760, Canon) were disassembled, cut for short length, and assembled in the mock-up apparatus. The magnetic field formed by the magnetic roller is estimated from measured discrete data of the magnetic flux density on the roller surface based on the assumption that magnetic dipoles distributed on the roller and two-dimensional distribution of the magnetic flux density was calculated by superposing the magnetic flux density created by each dipole.[4] Figure 4 shows the tangential and normal distributions of the magnetic flux density measured by a gauss meter (Model 421, Toyo Corp.) at 3.2 mm apart from the surface of the magnetic roller to the radial direction and the estimated magnetic flux density surrounding the roller.



(a) top view (b) lateral view

Figure 2. Mock-up apparatus of magnetic single-component magnetic development system.

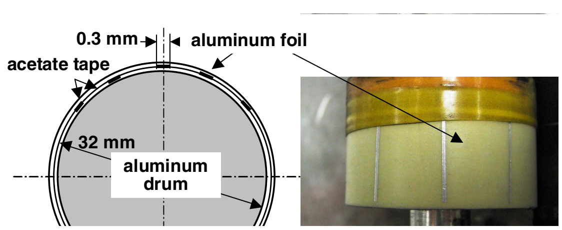


Figure 3. Pseudo-photoconductor. Aluminum foils are insulated and embedded on aluminum drum.

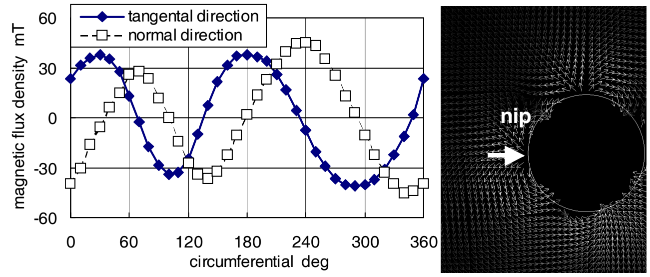


Figure 4. Measured tangential and normal distributions of the magnetic flux density at 3.2 mm apart from the surface of the magnetic roller to the radial direction (left) and estimated magnetic flux density surrounding the roller (right).

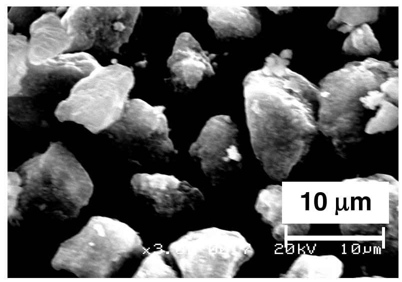


Figure 5. SEM photograph of pulverized toner particles used for experiment.

Commercially-produced magnetic toner particles (GP215, Canon) were used for the experiment. Averaged particle size was 6.7 μm and its standard deviation was 2.0 μm. Figure 5 shows the SEM image of toner particles.

Numerical

A numerical simulation was conducted based on a three-dimensional hard-sphere model of the distinct element method to clarify the dynamics of toner particles in the development process.[5] The basic motion equation is a 6-degree-of-freedom system of particle i.

$$m_i \frac{d\boldsymbol{v}_i}{dt} = \boldsymbol{F}_i\,, \quad I_i \frac{d\boldsymbol{\omega}_i}{dt} = \boldsymbol{M}_i \qquad (1)$$

where m is mass of particle, $\boldsymbol{v}$ $(= v_x\boldsymbol{i} + v_y\boldsymbol{j} + v_z\boldsymbol{k})$, velocity of particle, I, inertia of particle; $\boldsymbol{\omega}$ $(= \omega_x\boldsymbol{i} + \omega_y\boldsymbol{j} + \omega_z\boldsymbol{k})$, angular velocity of particle; and $\boldsymbol{M}$, moment. The assumed external force $\boldsymbol{F}_i$ applied to the particle i consists of the Coulomb force due to the electrostatic field created by voltage application, Coulomb force due to other charged particles, electrostatic image force, magnetic force, Van der Waals force, capillary force, gravitational force, and air drug.

In the soft-sphere model of the orthodox DEM, the mechanical interaction force and moment between particle−particle, particle−roller, and particle−drum are included in the external force term.[4] The mechanical interaction force is estimated based on the Voigt model from the Hertzian contact theory in the normal direction and the Mindlin contact theory in the tangential direction. However, it takes extremely long time to calculate behavior of small toner particles, because the time step must be short for the stable calculation. Therefore, in this calculation, based on the hard-sphere model of DEM, initial conditions of velocities are renewed when collisions take place. Linear and angular velocities after collision are calculated by a two-body impact equation that includes repulsive and frictional effects. Linear and rotational motions interact with each other at the collision. This method enables the time step to be ten times longer than that of the soft-sphere model and the calculation time was reduced to about one sixth to that of the soft-sphere model. However, calculations by using the soft-sphere model of DEM sometimes cause a numerical instability due to the simultaneous multi-contact that is apt to occur when particles are densely packed. This trouble was improved by estimating the accurate order of collisions between the particles from the position and velocity of each particle at several time steps before collision. Diameters of particles were assigned randomly to each particle but these distributions were conformed to measurements. The charge variation with time is neglected. A periodical boundary condition is employed to simulate vertically infinite number of toner particles within acceptable calculation time.[4]

Results and Discussion

Effect of Development Voltage

Figure 6 shows the toner motion observed by the high-speed camera. DC and AC applied voltages were adopted as parameters. The thickness of the toner layer before the development was adjusted to be 45 μm in all cases. It was observed that toner particles formed chain-like clusters, and chains vibrated synchronizing with AC voltage, when AC voltage was applied. At the latent image, chains separated from the development roller and crashed on the photoconductor. Then, some parts of chains returned to the development roller and the rest adhered to the latent image on the photoconductor drum, thus the development was realized. Chains moved to the latent image was increased, when the DC application was high, but the chain density was almost independent to the AC voltage.

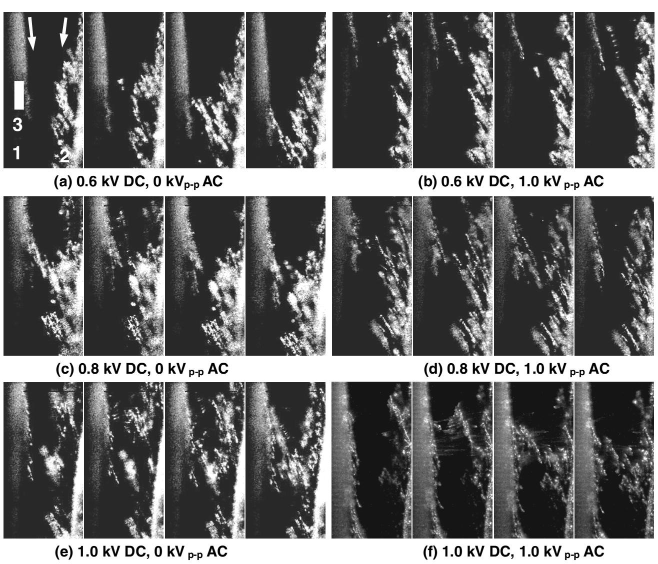


Figure 6. *Snapshots of toner motions observed at the development gap. (1: photoreceptor 2: development roller 3: latent image, thickness of toner layer before development: 45 μm)*

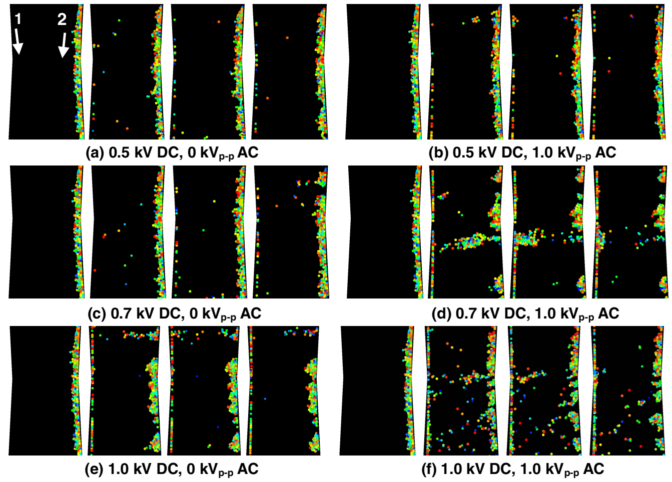


Figure 7. *Snapshots of calculated toner motions. (1: photoreceptor 2: development roller)*

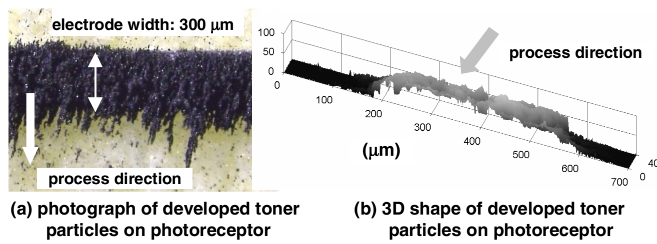
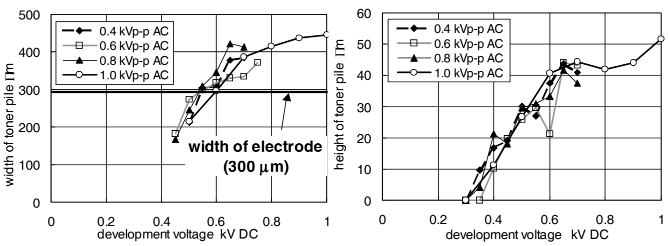


Figure 8. *Line image developed on the photoreceptor. (1.0 kV DC, thickness of toner layer before development: 45 μm)*

Figure 7 shows the calculated motions of toner particles. The calculated results agreed qualitatively to the measured results, although the latent image was not included in the calculations.

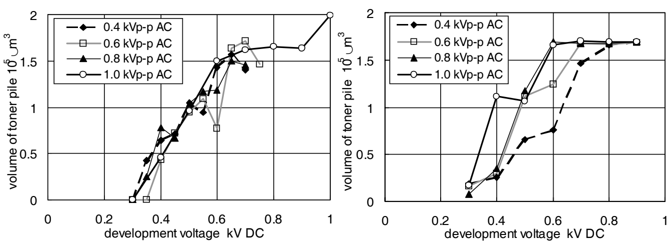
Figure 8 showed an example photograph and three-dimensional shape of the toner pile on the photoreceptor drum after the development. The 3D shape was observed by a scanned laser displacement meter. It is seen in Fig. 8 that the developed toner pile consisted of chain rows parallel to the process direction as anticipated from the observation of toner motion at the development zone.

Figure 9 shows the averaged width and height of toner piles derived from the 3D profiles of toner piles. The volume of the toner pile, shown in Fig. 10 (a), was deduced by multiplying the width of the electrode and the measured height in 10 mm length. Toner particles were developed over the threshold voltage, 0.3 kV, and developed toner particles increased with an increase in the DC voltage up to 0.7 kV but saturated at higher than 0.7 kV. On the other hand, the amount of the developed toner particles was almost independent to the AC applied voltage as observed in Fig. 6. The saturated width of the toner pile was wider than that of the latent image. Characteristics mentioned above agreed well to the calculated results shown in Fig. 10 (b).



(a) averaged width of toner pole (b) averaged height of toner pile

Figure 9. *Averaged width and height of toner piles derived from the 3D profiles of toner piles. (thickness of toner layer before development: 45 μm)*

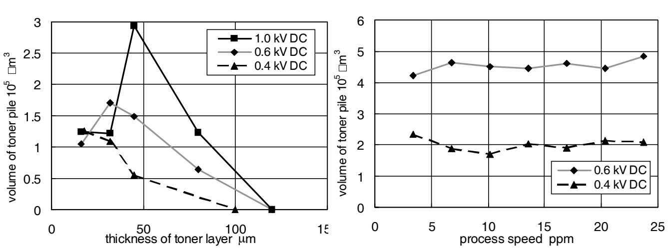


(a) measured (b) calculated

Figure 10. *Measured and calculated volume of toner pile developed on photoreceptor in 10 mm length. (thickness of toner layer before development: 45 μm)*

Effect of Thickness of Toner Layer and Process Speed

Figure 11 shows the volume of the toner pile with respect to the thickness of the toner layer on the roller (Fig. 11 (a)) and the process speed (Fig. 11 (b)). The thickness was adjusted by adjusting the gap between the doctor blade and the development roller. Although developed toner particles were almost independent to the process speed, these were increased with an increase in the thickness of the toner layer on the development roller at thin layer region but these were decreased at thick layer region. It was also observed that less toner clusters existed on the latent image in case of the thin toner layer and smooth toner pile was developed and the high quality image was realized by the thin toner layer, although the minimum thickness is necessary to develop sufficient image density.



(a) effect of toner layer thickness (b) effect of process speed

Figure 11. *Measured volume of toner pile developed on photoreceptor in 10 mm length with respect to the thickness of toner layer (left) and process speed (right).*

Concluding Remarks

Experimental and numerical investigations have been carried out to clarify the dynamics of the magnetic single component development system in electrophotography. The following features have been clarified.

(1) In the vicinity of the development zone, toner particles formed chain-like clusters, separated from the development roller, flied toward the latent image, and crash on the photoconductor drum. Although some chains returned to the development roller, some adhered to latent image, thus the development was realized.

(2) Effects of the development voltage, the thickness of the toner, and the process speed were clarified.

(3) Calculated toner motions showed similar figures to the experimental results and the calculated characteristics of the development agreed well to the measured results. It is expected that the numerical method is utilized for the improvement of the system.

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