Bead-Carry-Out Phenomenon in Two-Component Development System of Electrophotography

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Abstract

During the operation of a magnetic two-component development system used in electrophotography, some carrier particles adhere to a photoreceptor surface and cause serious image defects. This phenomenon is called "bead-carry-out" or "carrier development." The author has observed the phenomenon using a high-speed CCD camera and has measured the number density of carrier particles that adhere to the photoreceptor surface after the development process under various conditions of the development voltage, toner particle concentration, and size of the carrier particles. The experimental results indicated the following characteristics. (1) Some particles were separated from the top of bead chains immediately after the chains separated from the photoreceptor at the outlet of the development nip. (2) A threshold voltage existed for the occurrence of bead-carry-out. (3) The threshold was low when the diameter of the carrier particles was small and the toner particle concentration was low. (4) The number density of the adhered carrier particles increases with an increase in the applied voltage and a decrease in the toner particle concentration. It has been clarified by a separate experiment that the effective conductivity of the bulk mixture of carrier and toner particles was significantly related to these characteristics. Because the carrier particles are conductive and toner particles are insulative, the latter disturbs the electrical conduction in the chain, and therefore, the electrical charge at the top of the chain induced by the voltage application is decreased at a critical concentration of the toner particles in the chain. This condition causes a reduction in the Coulomb force applied to the top of the chain and improves the bead-carry-out phenomenon. Quantitative characteristics of these features have also been elucidated by a numerical simulation. Some countermeasures against this phenomenon were also proposed based on the experiment and calculation.

Introduction

Although there are several types of development subsystems in electrophotography, such as the magnetic single-component development subsystem, two-component magnetic brush development subsystem, and nonmagnetic single-component development subsystem, a two-component development process is most widely used in high-speed and/or color laser printers because it provides high image quality and high reliability. A schematic drawing of this system is shown in Fig. 1. Magnetized carrier beads form chain clusters on a rotating sleeve in the magnetic field generated by a stationary permanent magnet. Toner particles electrostatically attached to the magnetic bead chains are transported to the development zone by the rotation of the sleeve. In the development area, an electrostatic force acts on the toner particles and they move to electrostatic latent images on the photoreceptor surface to form real images.[1][2]

The electrostatic force acts not only on the toner particles but also on the carrier chains, and therefore, carrier bead(s) sometimes separate from the chains and move to the photoreceptor surface if the electrostatic force exceeds the magnetic force. This phenomenon is widely known as "bead-carry-out" (BCO) or "carrier development." Because the carrier beads attached to the photoreceptor surface cause significant image defects, it is important to clarify a mechanism and the requirements to prevent BCO. Williams first introduced this phenomenon and provided basic information in his textbook.[1] Nakayama et al. carried out a model experiment and numerical study and they confirmed that BCO occurs when the electrostatic force is larger than the magnetic force.[3] However, they did not consider the existence of the toner particles, although the toner particle concentration is one of the most important parameters of BCO. No practical study has been published on this subject after the report of Nakayama at al., although there has been a well-accepted consensus in the electrophotography community that BCO is one of the most serious issues in the two-component magnetic brush development system.

In this study, experimental and numerical investigations have been carried out on the BCO phenomenon to clarify the mechanism and effects of parameters such as the bead diameter, toner particle concentration, and development voltage. We have observed the phenomenon with a high-speed CCD camera; number density of the adhered carrier particles was measured and effects of the carrier particle diameter, toner particle concentration, and electrostatic field were evaluated.

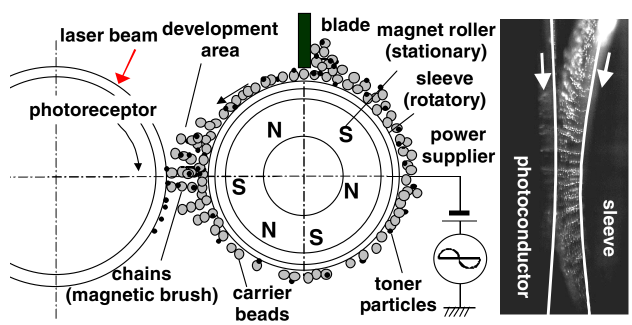

Figure 1. *Schematic drawing of two-component magnetic brush development system in electrophotography (left) and photograph of magnetic brushes in the development area (right).*

Experimental

Figure 2 shows a schematic drawing of the experimental setup to observe the dynamic characteristics of the BCO phenomenon in the development area. A mock-up machine was used for the experiment instead of a commercial printer. The mock-up machine comprises a photoreceptor drum, a developer, and driving systems. The drum is not coated with a photoconductive film; however, an aluminum drum with an insulative coating of polypropylene (thickness: 40 μm, relative permittivity: 2.2) is used because high-intensity light must be used to observe the toner motion in the development area with a high-speed microscope camera. The diameters of the drum and development sleeve are 100 mm and 25 mm, respectively, and the gap between the drum and the sleeve is 400 μm. The rotational speeds of the drum and development sleeve are 29 rpm and 218 rpm, respectively. The magnetic flux density generated by the magnetic roller in the development sleeve is reported in reference [4]. The DC development voltage was applied between the drum and the sleeve. The AC voltage was not superposed on the DC voltage. The dynamic behavior of the toner and carrier particles at the development area was observed at the right end of the development gap by the high-speed microscope camera (Photron, Fastcam-Max 120K model 1) with a frame speed of 4,000 fps and a shutter speed of 0.25 ms.

Spherical-shaped soft magnetic carrier particles and nonmagnetic toner particles provided by Samsung Yokohama Research Institute were used for experiments. The magnetic carrier particles comprised soft ferrite with average diameters of 40, 50, and 60 μm and a volume density of 2,200 kg/m^3. On the other hand, the toner particles are yellow pigmented with an average diameter of 8.5 μm averaged and a density of 1,200 kg/m^3. Figure 3 shows SEM photographs of both the carrier and toner particles.

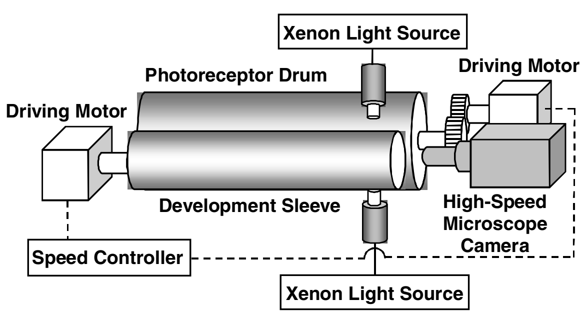

Figure 2. Experimental setup to observe the dynamic behavior of carrier and toner particles in the development area with the high-speed microscope camera.

Figure 3. SEM photographs of carrier particles, toner particles, and mixture of both particles.

Figure 4. Example of bead-carry-out.

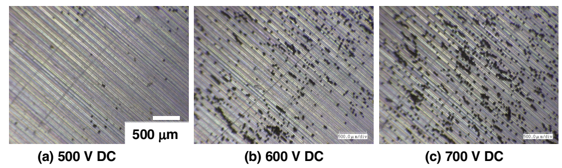

Figure 5. Examples of photographs of the drum surface taken after the development process (diameter of carrier particles: 40 μm, toner particle concentration: 6 wt%).

Observation of BCO Phenomenon

Carrier chains were formed by virtue of the magnetic field generated by the magnetic roller. At the inlet of the development zone, chains leaned to the sleeve and these get up gradually when chains approached to the development gap, because carrier chains were formed almost parallel to the magnetic flux line. The magnetic roller was designed in such a manner that the magnetic flux line is almost normal to the roller at the center of the development gap; however, this flux line is inclined at the inlet and outlet of the development area, as reported in a previous report [4]. When the chains approached the nip, the carrier chains came into contact with the photoreceptor drum and depressed. Chains slipped to the drum and swept the drum under this condition. The slip speed is low before the chains reach the center of the development gap, and the slip speed coincides with the relative speed of the photoreceptor drum and the sleeve (0.135 m/s) only at the center; subsequently, it becomes higher than the relative speed at the exit of the development area. Finally, the chains become suddenly free. At this moment, a spring back of the chains occurs and the top particle(s) in the chain occasionally separate from the chain and adhere to the photoreceptor drum, thereby giving rise to BCO. An example of the BCO phenomenon is shown in Fig. 4. BCO is likely to occur in long and thin chains.

Number Density of Adhered Carrier Particles

Photographs of the drum surface were taken after the development process, and the number of carrier particles adhering to the drum was counted by performing image data processing. Figure 5 shows some example photographs.

Figures 6 (a), (c), and (e) shows plots of the number density of the adhered carrier particles against the applied DC voltage. The diameter of the carrier particles and the concentration of the toner particles were selected as the parameters to be studied. The results indicated the following characteristics. (1) A threshold voltage exists for the occurrence of the BCO phenomenon. (2) The threshold voltage is low when the carrier particles are small and the toner particle concentration is low. (3) The number density of the adhered carrier particles is high for small carrier particles and it increases with an increase in the applied voltage. (4) The number density of the adhered carrier particles is drastically increased when the toner particle concentration is lower than 6–9 wt%.

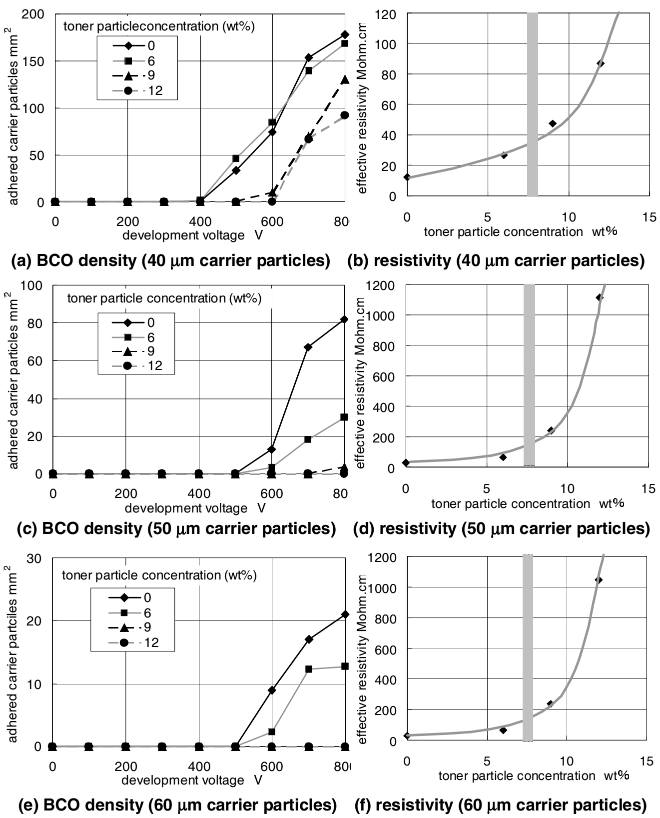

Figure 6. *Number density of adhered carrier particles on the photoreceptor drum (left) and the effective resistivity of a mixture of both carrier and toner particles (right). Confirm that the maximums of the ordinates in (c) and (e) are 50% and 15% of that of (a), respectively.*

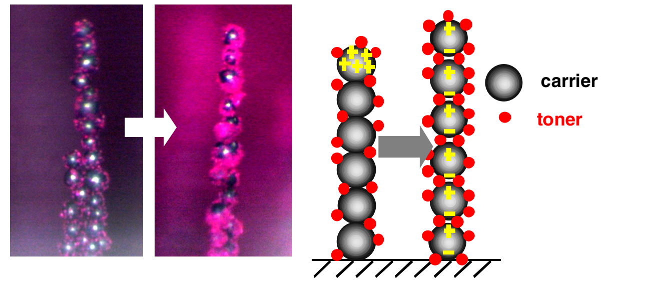

Figure 7. *Photograph of chains to which the toner particles adhered and conceptual drawing of charge distributions in the chains that contain rare and sufficient number of toner particles.*

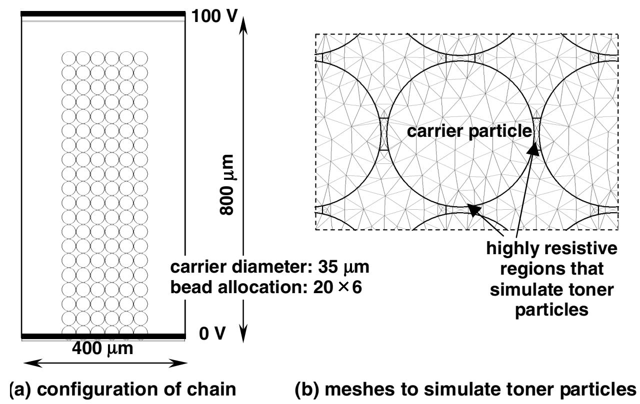

Figure 8. *Calculation conditions: configuration and dimensions of the calculation domain and meshes to simulate the presence of toner particles.*

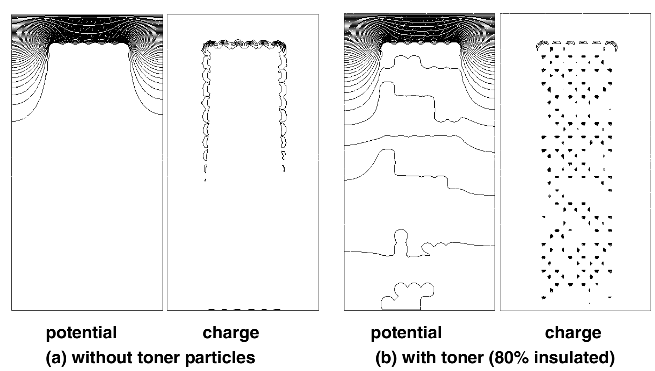

Figure 9. *Distributions of steady-state potential and charge density in conductive carrier chain with and without insulative toner particles.*

Discussion

The charge distribution in the chain is related to the dependence of the number density of the adhered carrier particles on the toner particle concentration. Figure 7 shows a conceptual drawing of this phenomenon. Because the carrier particles are conductive and the toner particles are insulative, the latter disturbs the electrical conduction in the chain; hence the electrical charge at the top of the chain, induced by the voltage application, is decreased when the concentration of the toner particles in the chain is larger than the threshold. This condition causes a reduction in the Coulomb force applied to the top of the chain and improves the BCO phenomenon.

The resistivity of a mixture of the carrier and toner particles was measured to support the hypothesis. The measured values are plotted in Figs. 6 (b), (d), and (f). The effective resistivity is gradually increased with the toner particle concentration; however, it is drastically increased at the critical concentration of 9–7 wt% that coincides with the toner particle concentration so that the number density of the adhered carrier particles is drastically increased.

A numerical calculation was performed to confirm that the insulative toner particles affect the distribution of charge density. The charge and potential distributions in the chain can be calculated by the following Poisson's equation (2) and the conservation equation of charge (3):

$$-\nabla(\varepsilon\nabla\phi) = \rho \ , \tag{2}$$

$$-\frac{\partial\rho}{\partial t} = \nabla\cdot\left(-\sigma\nabla\phi\right) \ , \tag{3}$$

where ϕ is the electric potential; ρ, the charge density; ε, the permittivity; and σ, the conductivity. A two-dimensional rectangular chain, as shown in Fig. 8 (a), was assumed and the presence of toner particles was simulated by assuming the presence of highly resistive meshes between the toner particles, as shown in Fig. 8

(b). The toner particles were randomly distributed and the total number of toner particles was varied accordingly to the toner particle concentration.

Figure 9 shows the distributions for the steady-state potential and charge density calculated by the finite element method. It is clearly observed that without the toner particles, the electrical charge is concentrated at the top of the chain; however, if a sufficient number of toner particles are mixed in the chain, the charge in the chain is decreased and the charge density at the top of the chain also decreases.

Concluding Remarks

In this study, the BCO phenomenon in the two-component brush development system of electrophotography was investigated and the following characteristics have been clarified:

(1) At the outlet of the development area, after the carrier chains become suddenly free from the photoreceptor drum, the particle(s) at the top of the chain occasionally separate from the chain and adhere to the photoreceptor drum. This BCO phenomenon is likely to occur in long and thin chains.

(2) There is threshold voltage for the occurrence of BCO because BCO is caused when the electrostatic force applied to the top of the carrier chain is larger than the magnetic force. The threshold voltage is low when the carrier particles are small and the toner particle concentration is low.

(3) The number density of the adhered carrier particles is high for the small carrier particles and it increases with the applied voltage. It is drastically increased when the toner particle concentration is lower than 6–9 wt%. Because the insulative toner particles disturb the electrical conduction in the chain, the electrical charge at the top of the chain induced by the voltage application is decreased above the critical concentration of toner particles in the chain. This decrease in the electrical charge causes a reduction in the Coulomb force applied to the top of the chain, and the BCO phenomenon is improved.

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Author Biography

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