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Characteristics of Development and Bead-Carry-Out Phenomena in Two-Component Electrophotographic Development System[1]

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Abstract. *The dynamics of toner and carrier particles in a two-component development system used in electrophotography were studied to clarify the development characteristics and to reduce the image defects due to the bead-carry-out (BCO) phenomenon. The height of the developed toner line image and the density of carrier particles adhered to the photoreceptor surface after development were measured and the behavior of the toner and carrier particles was observed using a high-speed microscope camera. This study clarifies that development occurs not only in the contact area between the carrier brush and the photoreceptor but also in the pre- and postnip regions where the brush does not make contact with the photoreceptor and that the occurrence of BCO is reduced in the image area rather than in the nonimage area at a low dc development voltage at a high toner concentration and with the development sleeve at a high-speed ratio. The mechanisms of these phenomena are investigated using independent experimental and numerical analysis.* © *2011 Society for Imaging Science and Technology.*
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INTRODUCTION

The dynamics of toner and carrier particles in an electromagnetic field are of great importance in two-component magnetic brush development systems that are used in color and/or high-speed electrophotography machines. Magnetic carrier particles with electrostatically attached toner particles are introduced in the vicinity of a rotatory sleeve that encloses a stationary magnetic roller. The diameter of a carrier particle is on the order of several tens of micrometers and that of a toner particle is approximately 5–10 μm. The magnetized carrier beads form chain clusters, a so-called brush, on the sleeve in the presence of the magnetic field, as shown in Figure 1. The tips of the chains come into contact with the photoreceptor surface in the development area, and the toner particles on the chains move toward the electrostatic latent images created by a laser beam on the photoreceptor to form real images.[1–4] Many experimental investigations have been conducted on this system, and some simple static models have been presented to clarify the mechanism of the development physics. However, system parameters of these investigations are far from those used in present actual machines. For example, although the shape and diameter of carrier particles used in the present machine are spherical and 40 μm, those reported by Lee and Beardsley[4] were irregular and 140 μm and those reported by Schein[2] were spongelike and 200 μm, respectively. The present development gap (400 μm) is almost one-tenth of those reported by Lee and Beardsley (3.18 mm) and Schein (1.25–1.75 mm). Furthermore, high frequency ac voltage is superposed on the dc voltage in the present system to enhance the development. In this article, we have measured fundamental characteristics of the development using an up-to-date system.

In this process, the electrostatic force acts not only on the toner particles but also on the carrier chains, and therefore, carrier beads 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). Since the carrier beads attached to the photoreceptor surface cause significant image defects, it is important to clarify the BCO mechanism and what is required 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

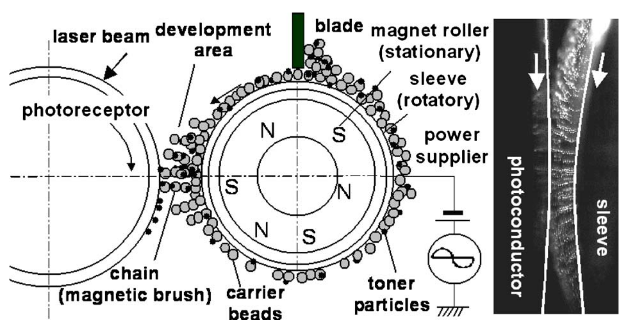

Figure 1. Schematic drawing of two-component magnetic brush development system in electrophotography (left) and image of magnetic brush in development area (right).

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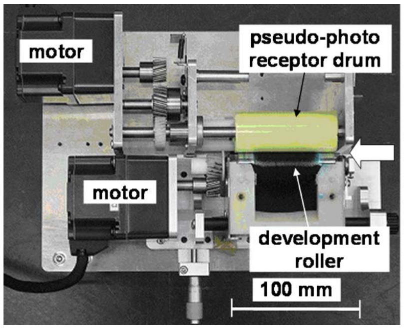

Figure 2. Apparatus used to model a two-component magnetic brush development system.

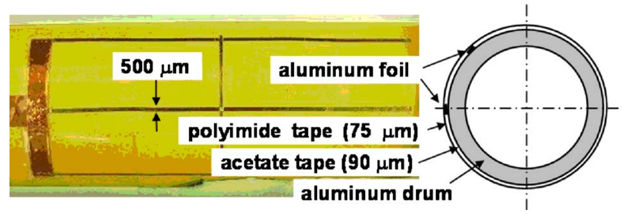

Figure 3. Pseudophotoreceptor drum. Insulated line electrodes made of aluminum foil are embedded on insulated drum.

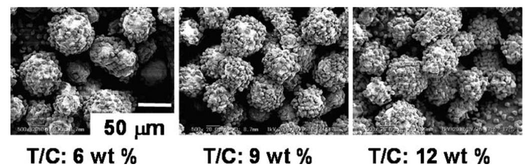

Figure 4. SEM *images of mixtures of toner* (6 μm) and carrier (40 μm) particles.

when the electrostatic force is larger than the magnetic force.[5] However, they did not consider the toner particles, although the concentration of toner particles is one of the most important parameters of BCO. No practical study has been published on this subject since the report of Nakayama et al., although there has been a well-accepted consensus in the electrophotography community that BCO is one of the most serious issues for the two-component magnetic brush development system.

In this study, an experimental investigation was carried out on the development characteristics and BCO phenomenon to clarify the effects of parameters such as development voltage, the ratio of toner-to-carrier particles in the brush, and the rotating speed of the development sleeve. In addition to the parameter experiment, the behavior of the toner and carrier particles in the development area was observed with a high-speed microscope camera and the three-dimensional (3D) shapes of toner piles formed on the latent image after the development process was examined with a scanning laser displacement meter. Some interesting findings, which are related to the development and occurrence of the BCO phenomenon, were obtained in these experiments.

EXPERIMENTAL

Figure 2 shows a schematic of the experimental setup used to investigate and to observe the dynamic characteristics of the development and BCO phenomenon in the development area. A model machine was used in the experiment instead of a commercial printer. This machine consisted of a short photoreceptor drum, a development sleeve, a magnetic roller, and the driving systems. The drum, which was made of aluminum, was not coated with a photoreceptor; however, it was coated with a nonconductive tape (thickness: 90 μm; relative permittivity: 2.0) because high intensity light had to be used in order to observe the motion of the carrier and toner particles in the development area with a high-speed microscope camera. An electrostatic latent image was formed using line electrodes that were made of aluminum foil (thickness: 10 μm; width: 500 μm) and insulated with polyimide tape (thickness: 75 μm; relative permittivity: 3.2). These electrodes were embedded parallel to the rotating axis of the aluminum drum, as shown in Figure 3. On application of a dc voltage V_e to the electrodes, the electrodes generated an electrostatic latent image that was similar to a latent image created on an actual photoreceptor drum. Before conducting experiments, the surface of the drum was wiped with a piece of alcohol impregnated tissue paper to neutralize the surface potential. The drum and development sleeve were 30 and 18 mm in diameter, respectively, and the gap between the drum and sleeve was set at 400 μm. The standard rotational speed of the drum was 150 mm/s, but the sleeve speed could be altered during the parametric experiment. The magnetic flux density at the surface of the sleeve was 120 mT normal to the gap at the center of the development area. A dc voltage, V_s, was applied between the drum and sleeve, and an ac voltage (1.5 $kV_{p.-p.}$, 6 kHz sine wave) was superposed onto the dc voltage. The dynamic behavior of the toner and carrier particles in the development area was observed at the right end of the development gap using a high-speed microscope camera (Photron, Fast-cam SA5).

Spherical soft magnetic carrier particles and pulverized nonmagnetic toner particles were used in the experiment. The magnetic carrier particles were comprised of soft ferrite with an average diameter of 40 μm. The toner particles were cyan pigmented with an average diameter of 6 μm. Figure 4 shows scanning electron microscopy (SEM) images of mixtures of the carrier and toner particles.

RESULTS AND DISCUSSION

Amount of Developed Toner

After the surface potential of the drum was neutralized, the drum and the sleeve were rotated 360° and then stopped so developed images on the drum could be observed. Figure 5 shows the developed line images on the pseudolatent images. dc voltage, 200 V, was applied to the development sleeve. Therefore, the voltage difference between the line electrode and the sleeve, $V_e - 200$ V, corresponded to the dc development voltage designated in Fig. 5, and the voltage difference between the sleeve and the nonimage area on the drum was −200 V. The dc development voltage, toner concentration

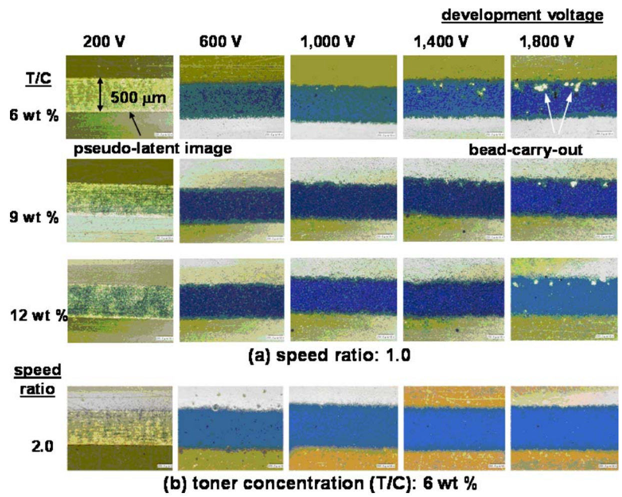

Figure 5. Developed line images on pseudolatent images: (a) effect of toner concentration (speed ratio=1.0); (b) effect of speed ratio (toner concentration=6 wt %).

(toner-to-carrier ratio, T/C), and speed ratio (sleeve speed to drum speed) were parameters. The following characteristics were clarified through the observation of these photographs.

The toner particles were developed above the threshold voltage, 200 V, and the number of developed toner particles increased with the dc development voltage, toner concentration, and speed ratio. The width increased slightly with an increase in the development voltage. The saturated width of the toner pile was larger than that of the latent image. These characteristics were confirmed quantitatively by measuring the three-dimensional shape of the toner particles developed on the pseudolatent image using a scanning laser displacement meter (Keyence, LT-8100). Figure 6 shows the average height of the toner piles that were derived from the 3D profiles of the observed toner piles. It was confirmed that the toner particles were not developed below the threshold voltage, that the number of the developed toner particles increased linearly with the development voltage in the range between about 200 and 1000 V, and that development ceased at voltages higher than 1000 V. The development system was operated in the linear region and the average toner height was 1–1.5 times as large as the toner diameter because the standard development voltage is approximately 700 V.

Lee and Beardsley[4] reported a unique model of the conductive magnetic brush development system based on two assumptions: (a) toner particles can jump between carrier beads anywhere along the chain where a non-negligible electric field is present and (b) irregular carrier beads can rotate. However, as described below, our direct observation does not support these assumptions probably because the system parameters of the model of Lee and Beardsley are far from the present system, especially the shape of the carrier beads. The configuration of the toner and carrier mixture shown in Fig. 4 is completely different to that illustrated by Lee and Beardsley. On the other hand, Schein[2] proposed a theory that assumes infinite conductivity down the bead chain and field stripping of toner from the carrier beads adjacent to the

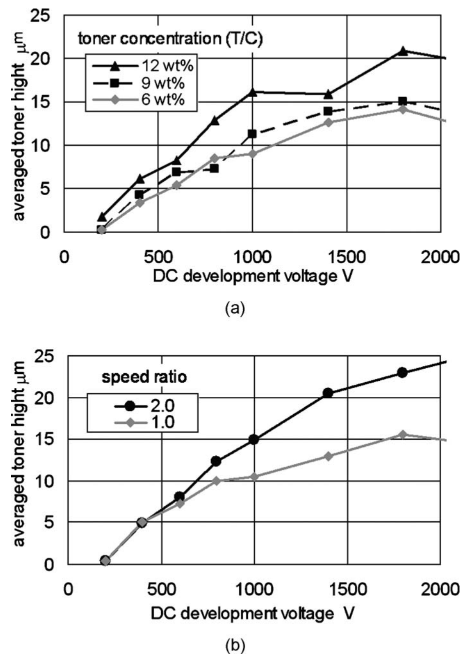

Figure 6. Average toner height of developed toner piles: (a) effect of toner concentration (speed ratio=1.0); (b) effect of speed ratio (toner concentration=6 wt %).

photoconductor. However, we observed that toner particles separated from inside of the mixture and formed a toner cloud in the pre- and postnip regions, and airborne toner particles adhered to the latent image. Because many coupled factors dynamically affect the development process, it might be impossible to describe the process by a simple one-dimensional static model. Another model must be established to clarify the mechanism of the development in the present system.

Bead-Carry Out

Carrier particles that adhered to the drum after the development process were collected using a permanent magnet, and then the number of collected carrier particles was counted by image data processing. Figure 7 shows the number density of the adhered carrier particles against the dc development voltage. In this experiment, the line electrode was not attached to the drum, the surface of the drum was maintained at 0 V, and the dc voltage applied to the development sleeve V_s was controlled. Therefore, the voltage applied to the sleeve, V_s, corresponded to the dc development voltage designated in Figures 7 and 8. The experiment was conducted five times under identical conditions, and average values were plotted.

The BCO phenomenon was more likely to occur when a positive voltage was applied than when a negative voltage was applied. Toner particles were developed on the drum when a negative voltage was applied. One major reason for the occurrence of this phenomenon is simple: the effective voltage at the development gap was reduced by the surface voltage because the photoreceptor was covered with negatively charged toner particles where they adhered to it.[6]

Such a reduction in the surface voltage due to the application of a dc voltage was confirmed experimentally, as

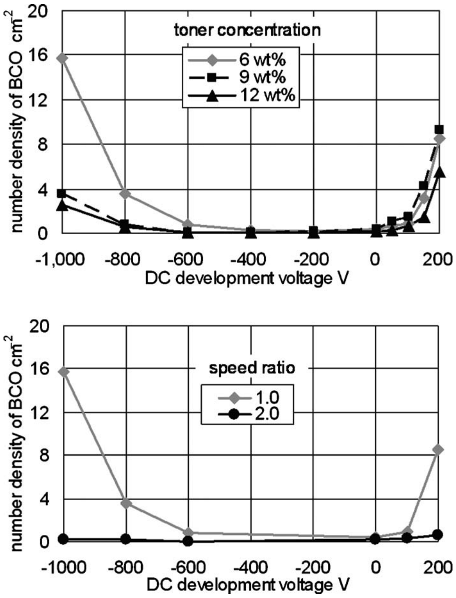

Figure 7. Number density of adhered carrier particles on photoreceptor after development.

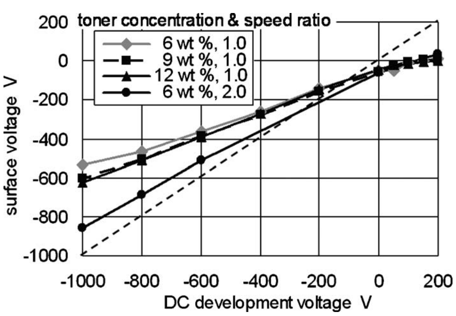

Figure 8. Surface voltage of photoreceptor after development, with respect to dc development voltage.

shown in Fig. 8. The surface voltage of the photoreceptor drum was measured using a surface potential meter (Trek, Model 344) after the development process. It was clearly observed that a surface voltage was induced when a dc voltage was applied. However, although the number density of the adhered carrier particles was high when the toner concentration was low [see Fig. 7(a)], the induction of a surface voltage was almost independent of the toner concentration (see Fig. 8). This implies that an additional mechanism is operative in BCO, which is discussed in the next section.

Charge Distribution in the Chain

The charge distribution in the chains is related to the toner particle concentration. Toner particles disturb the electrical conduction in the chain because the carrier particles are conductive and the toner particles are nonconductive; 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 a certain threshold. This condition causes a reduction in the Coulomb force applied to the top of the chain and leads to an increase in the occurrence of the BCO phenomenon.

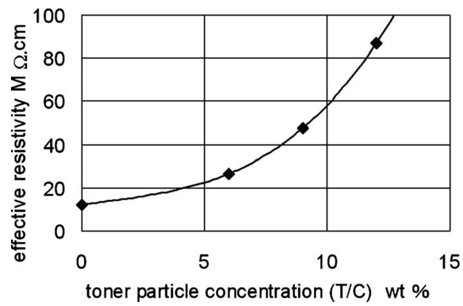

Figure 9. Effective resistivity of mixtures of both carrier and toner particles.

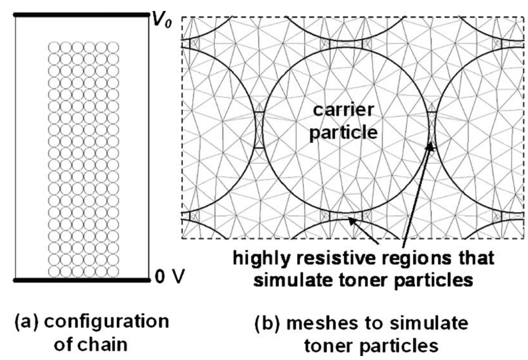

Figure 10. Configuration and dimensions of the calculation domain and the meshes for simulating the presence of toner particles.

The resistivity of a mixture of the carrier and toner particles was measured to support this hypothesis. The mixture was put in a plastic tube, the dc voltage was applied to both ends of the tube, and the resistivity was derived from the V-I relationship. The measured values are plotted in Figure 9. The effective resistivity gradually increases with the toner particle concentration. However, the effective resistivity drastically increases at the critical toner particle concentration of approximately 9 wt % and the number density of adhered carrier particles increases drastically.

Numerical calculations were performed to confirm that the nonconductive toner particles affect the distribution of charge density. The charge and potential distribution in the chain can be calculated from Poisson's equation [Eq. (1)] and the conservation equation of charge [Eq. (2)],

$$-\nabla \cdot (\varepsilon \nabla \phi) = \rho, \tag{1}$$

$$-\frac{\partial \rho}{\partial t} = \nabla \cdot (-\sigma \nabla \phi), \tag{2}$$

where ϕ is the electric potential, ρ is the charge density, ε is the permittivity, and σ is the conductivity. A two-dimensional rectangular chain, as shown in Figure 10(a), was assumed, and the presence of toner particles was simulated by assuming the presence of highly resistive meshes between the carrier particles, as shown in Fig. 10(b). The toner particles were randomly distributed and the total number of

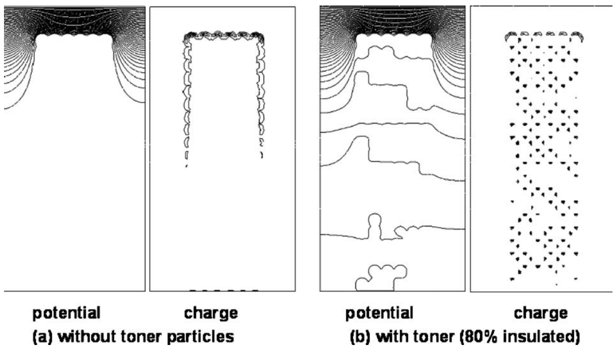

Figure 11. Distributions of steady-state potential and charge density in conductive carrier chain with and without nonconductive toner particles.

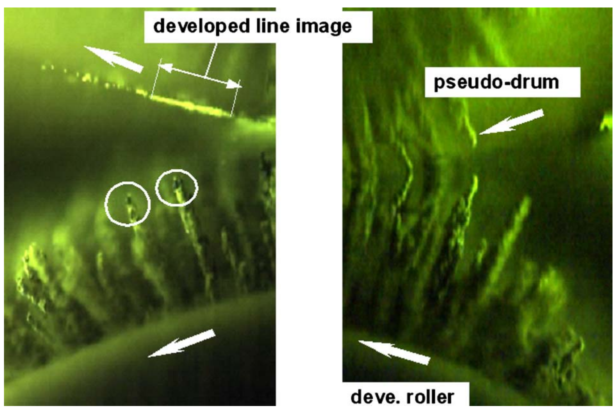

Figure 12. Observed behavior of toner and carrier particles in prenip (inlet) and postnip (outlet) regions of development area (T/C: 6 wt %; speed ratio: 1.0).

toner particles was varied accordingly to the toner particle concentration.

Figure 11 shows the distributions for the steady-state potential and charge density calculated using 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 on the chain is reduced and the charge density at the top of the chain also decreases.

Direct Observation

Figure 12 shows images of the pre- and postnip regions obtained using a high-speed microscope camera. The overall behavior of the brush was the same as observed in the absence of toner particles.[7] At the beginning of chain formation, chains were formed almost parallel to the magnetic flux lines and leaned against the sleeve, but they assumed an upright position as they approached the development gap. Then, the chains came into contact with the photoreceptor drum and were depressed by the drum. The chains slipped and brushed against the drum under these conditions. At the end of the nip, the chains again became free and aligned along the magnetic flux lines. The motion of the toner particles was observed and recorded as a video sequence. These images showed that development, i.e., adhesion of toner particles to a latent image on the photoreceptor, occurred not only in the contact area between the carrier brush and the photoreceptor but also in the pre- and postnip regions where the carrier brush did not come into contact with the photoreceptor. At the prenip region, carrier chains vibrated in the lateral direction when the leaning chains became erect due to the abrupt change of the magnetic flux line,[7] and, at the same time, toner particles were forced to separate from the inside of the chain. The separated airborne toner particles adhered to the latent image. At the postnip region, toner particles separated from the chain and formed a toner cloud in the gap. The toner cloud vibration synchronized with the frequency of the ac voltage, and some portion of the airborne toner adhered to the latent image. The BCO was sometimes observed in this region.

Depletion of toner particles from the tip of some long chains (circles in Fig. 12) was found to occur in the postnip region of the development area. This phenomenon was not observed in the prenip region. The reason for the depletion of the toner particles in the postnip region of the development area was the low toner concentration. Thus, the BCO phenomenon occurred when an insufficient concentration of toner particles was supplied to the development area. Development caused a shortage of toner particles on the brush in the postnip region, and the BCO phenomenon was more likely to occur at the boundary between the image and nonimage areas, as shown in Fig. 5.

CONCLUDING REMARKS

The dynamics of toner and carrier particles in a two-component development system used for electrophotography were investigated to clarify the characteristics of development and to reduce image defects due to the occurrence of the BCO phenomenon. The following features have been clarified:

(1) Developed toner particles on the electrostatic latent image increase linearly with the development voltage above the threshold voltage, and development ceases at high voltages. Development is enhanced at a high toner-to-carrier concentration and at a high-speed ratio between the development sleeve and the photoreceptor drum. Under our standard conditions, toner height is 1–1.5 times as large as the toner diameter. Development occurs not only in the contact area between the carrier brush and the photoreceptor but also in the pre- and postnip regions where the brush does not make contact with the photoreceptor.

(2) The occurrence of BCO is reduced in the image area rather than in the nonimage area under conditions of a low dc development voltage, a high toner concentration, and a high-speed ratio for the development sleeve. A major reason for the reduced occurrence of BCO under these conditions is that the effective voltage at the development gap is reduced by the adhesion of negatively charged toner particles to the latent image. Another reason for the reduced occurrence of BCO at high toner concen-

trations is that the electrical charge at the top of the chain is reduced when the concentration is larger than a particular threshold because nonconductive toner particles disturb electrical conduction in the chain. These conditions cause a reduction in the Coulomb force applied to the top of the chain and reduce the occurrence of the BCO phenomenon.

(3) Depletion of toner particles in the brush occurs in the postnip region of the development area when an insufficient concentration of toner particles is supplied to the development area. This condition is realized when the initial toner concentration and speed ratio of the development sleeve are low and increases the occurrence of the BCO phenomenon.

Because the development physics has not yet been completely clarified, it is necessary to develop a three-dimensional dynamic model that involves mechanical, electrostatic, and magnetic interactions and the charge transfer.

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