Pale Defect in Halftone Area Following Solid Image in Two-Component Magnetic Brush Electrophotographic Development System

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Abstract
We studied the mechanism of and countermeasures against a pale image defect observed in the halftone area following a solid image in a two-component magnetic brush electrophotographic development system. We build a model machine that consisted of a pseudo-photoreceptor drum, development sleeve, and stationary magnetic roller to perform direct observations of the toner and carrier particles in the development area. The image was formed on an insulated film electrode pasted onto the drum. Instead of a digital halftone image, an analog halftone image was formed on the pseudo-photoreceptor. A parameter experiment showed that the image defect was enhanced when the voltage difference between the solid area and halftone area was large, the AC voltage superposed on the DC development voltage was low, the development gap was large, and the ratio of the sleeve speed to the drum speed was low. However, the defect was almost independent of the toner-to-carrier concentration ratio as well as the frequency and waveform of the superposed AC voltage. The dynamic behavior of the toner particles in the development area was directly observed using a high-speed microscope camera, and the cause of the print defect was investigated.

Key words: Electrophotography, Laser Printer, Two-Component Magnetic Brush Development, Halftone, Imaging

1. Introduction

Electrophotography is the technology used in laser printers and virtually all copiers available today. It is a complex process that generally involves six distinct steps, as shown in Fig. 1; the six steps are charge, expose, develop, transfer, fuse, and clean.\(^{1(3)}\) In step 1, electrical gas discharge is used to uniformly charge the photoreceptor film, which is an insulator in the absence of light. In step 2, laser light discharges the normally insulating photoreceptor, producing a charge pattern on the photoreceptor (latent image). In step 3, toner particles, attracted by the electric field generated by the charges on the photoreceptor, move from the development sleeve and adhere to the latent image, transforming it into a real image. In step 4, the toner particles are transferred to a paper, which is electrically charged to have a polarity opposite to that of the toner particles. In step 5, a permanent image is fixed on the paper by melting the toner on the paper surface. Finally, in step 6, the photoconductor surface is cleaned of any excess toner particles.

The development step usually determines the best image quality that the printer or copier can produce. Although there are several types of development subsystems, such as single-component development systems, a two-component magnetic brush development system is widely used in color and/or high-speed electrophotographic machines.\(^{1(4)}\) In this
type of system, magnetic carrier particles with toner particles that are electrostatically attached are introduced in the development area by 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. In the presence of a magnetic field, the magnetized carrier beads form chain clusters, the so-called brush, on the sleeve.\(^{4}\)-(\(^{9}\)) The ends 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 formed by a laser beam on the photoreceptor to form real images.\(^{10}\)-(\(^{15}\))

Although this system is highly reliable and can achieve relatively high-quality printing compared with other systems such as the nonmagnetic single-component system,\(^{2,3}\) some types of image defects sometimes occur in the system. Bead-carry-out is one image defect that is inherent to the two-component magnetic brush development system.\(^{14,15}\) Pale halftone following a solid image is another inherent defect. As shown in Fig. 2, the halftone image becomes pale over a width of 1–2 mm immediately after the printing of the solid image.

In this study, an experimental investigation was carried out on the pale image defect in the halftone area to clarify the effects of parameters such as the development voltage, development gap (defined as the minimum gap between the development sleeve and photoreceptor drum), ratio of the sleeve speed to the drum speed, and toner-to-carrier concentration ratio. Further, the dynamic behavior of the toner and carrier particles in the development

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**Fig. 1** Schematic drawing of the two-component magnetic brush development system used in electrophotography (left), and an image of the magnetic brush in the development area (right).

**Fig. 2** Example of the pale image defect observed in the halftone area immediately after the printing of a solid image.
area was observed with a high-speed microscope camera to understand the mechanism of defect formation.

2. Experimental

Figure 3 shows a photograph and a schematic of the model machine used to investigate and observe the pale image defect in the development area. The model machine was used instead of a commercial printer in order to conduct a parametric experiment and perform direct observations of the toner and carrier particles in the development area. This machine consisted of a short photoreceptor drum, a development sleeve, a magnetic roller, and driving systems.\(^{(15)}\)

The drum and development sleeve were 30 and 18 mm in diameter, respectively, and the rotational speed of the drum was 150 mm/s. The magnetic flux density normal to the gap at the center of the development area was 120 mT at the surface of the sleeve. The drum, which was made of aluminum, was not coated with a photoreceptor; however, it had a nonconductive acetate tape (thickness: 90 \(\mu\)m; relative permittivity: 2.0) because high-intensity light was used for observing the motion of the carrier and toner particles in the development area.

An electrostatic solid latent image was formed by using a square electrode that was made of aluminum foil (thickness: 10 \(\mu\)m) and insulated with transparent polyimide tape (thickness: 75 \(\mu\)m; relative permittivity: 3.2). Upon the application of a DC voltage \(V_s\) to the electrode, an electrostatic latent image that was similar to a latent image formed on an actual photoreceptor drum was generated.\(^{(15)}\) A DC voltage \(V_d\) was applied between the drum and development sleeve to create an analog halftone, and an AC voltage was superposed on the DC voltage. The development voltage of the solid image is \(V_s - V_d\), and that of the halftone is \(-V_d\). Instead of a digital halftone, an analog halftone image was formed upon applying a DC voltage to the development sleeve.

Before conducting the experiments, the surface of the drum was wiped with a piece of alcohol-soaked tissue paper to neutralize the surface potential. The dynamic behavior of the toner and carrier particles in the development area was observed from the right end of the development gap by means of the high-speed microscope camera (Photron, Fastcam SA1.1), as schematically shown on the right side in Fig. 3. The shooting speed was 20,000 frames/s and the shutter speed was 1/20,000 frames/s. The captured signals were converted to movies, and the motion of particles was then carefully examined on a PC monitor.

Spherical soft magnetic carrier particles and pulverized non-magnetic toner particles were used in the experiment. The magnetic carrier particles consisted of soft ferrite with an average diameter of 40 \(\mu\)m. The toner particles were cyan pigmented and had an average diameter of 6 \(\mu\)m. Figure 4 shows scanning electron microscopy (SEM) images of mixtures of the carrier and toner particles.

![Fig. 3 Apparatus used to model a two-component magnetic brush development system.](image-url)
Fig. 4 SEM images of mixtures of toner (6 µm) and carrier (40 µm) particles.

Fig. 5 Surface of the pseudo-photoreceptor drum before development (left) and after development (middle) and the end edge of a solid image after development (right).

Fig. 6 Circumferential distribution of blue bits at the boundary between the trailing edge of the solid image and the halftone image.

After the drum was rotated by one cycle to conduct the development of image, a still photograph of the edge of the solid image was taken with the digital still camera (Fig. 5). The blue bits, a signal intensity of RBG signal components, in the still image in the processing direction were then counted and averaged in the axial direction. Blue bits were used because cyan-pigmented toner particles were used for the experiment.

Figure 6 shows an example of the circumferential distribution of blue bits. A large undershoot corresponding to the pale image defect can be seen in the halftone area immediately outside the border of the solid image; thus, the actual image defect was reproduced. The bit depth of the undershoot, defined as the bit difference between the saturated bit in the halftone area and the minimum bit in the pale image defect, is used as an index of the pale image defect. Optical conditions such as the position of the camera were fixed throughout
all experiments to ensure that all measurements could be compared. The experiments were repeated five times under the same experimental conditions and the mean value was determined. The standard experimental conditions were as listed in Table 1, unless otherwise specified.

Table 1. Standard experimental conditions

<table>
<thead>
<tr>
<th>item</th>
<th>value</th>
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<tbody>
<tr>
<td>development voltage (solid)</td>
<td>700 V</td>
<td></td>
</tr>
<tr>
<td>development voltage (halftone)</td>
<td>400 V</td>
<td></td>
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<tr>
<td>superposed AC voltage</td>
<td>1.5 kVp-p, 6 kHz</td>
<td>sine wave</td>
</tr>
<tr>
<td>development gap</td>
<td>400 µm</td>
<td></td>
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<tr>
<td>ratio of sleeve speed to drum speed</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>ratio of toner concentration to carrier concentration</td>
<td>6 wt%</td>
<td>Refer to Fig. 4</td>
</tr>
</tbody>
</table>

3. Results and Discussion

Figure 7 shows the experimental results, which indicate how the system parameters affected the pale image defect and image density in the halftone area. The left-hand-side figures in Fig. 7 show the undershoot bit, which is an index of the pale image defect. On the other hand, the right-hand-side figures show the bit depth in saturated halftone areas, which is an index of the image density in the halftone area. The voltage difference between the solid and halftone areas, the development voltage of the halftone area, the amplitude and frequency of the AC voltage, the development gap, the speed ratio (sleeve speed to drum speed), and the toner/carrier concentration were selected as the parameters to be examined. We also conducted experiments to investigate the effect of the AC voltage waveform on the pale image defect and image density. The results provided information on the following aspects of defect formation.

3.1 Effect of applied voltage

As shown in Fig. 7 (a, left), the pale image defect was enhanced when the voltage difference between the solid and halftone areas was large. It is thought that the toner particles moved circumferentially from the halftone area to the edge of the solid image because of the circumferential electrostatic field when the voltage difference was high, resulting in the generation of the pale image defect in the halftone image adjacent to the solid image. As discussed in the next section, this assumption was supported by direct observation of the toner motion in this area. On the other hand, as shown in Fig. 7 (a, right), while the bit depth in the halftone area increased with the development voltage in the halftone area, it was almost independent of the voltage in the solid area.

The application of a high AC voltage reduced the intensity of the pale image defect as shown in Fig. 7 (b, left). The reduction was a result of the AC voltage causing the reciprocating motion of the toner particles at the development gap and agitating the developed toner particles in the halftone area. This assumption was also supported by direct observations of toner motion in the post-nip region. Another reason for the reduction of the defect was that a relatively large amount of toner particles were supplied from the wide area of the brush upon the application of a high AC voltage. On the other hand, the pale image defect was almost completely unaffected by the frequency and waveform (sine or rectangular) of the AC voltage in the frequency range of 1 to 18 kHz, as shown in Fig. 7 (c, left). It is also natural for the bit depth in the halftone area to be almost independent of the magnitude and frequency of the AC voltage (see Fig. 7 (b, right) and Fig. 7 (c, right)).
3.2 Effect of development gap, ratio of sleeve speed to drum speed, and toner/carrier concentration

Figure 7 (d, left) shows the effect of the development gap. The pale image defect was enhanced when the gap was large. Because the number of toner particles supplied from the brush on the solid area was insufficient for a large gap (i.e., low electric field), which led to the latent image in the solid area being poorly neutralized, it is likely that toner particles were transferred from the adjacent halftone area to the solid area, leading to the pale image defect being enhanced. The bit depth in the halftone area decreased slightly when the gap increased (Fig. 7 (d, right)), because the effective electric field decreased.
The pale image defect was reduced at a high speed ratio (ratio of the sleeve speed to the drum speed), as shown in Fig. 7 (e, left). Because a sufficient number of toner particles were supplied to the solid area at a high speed ratio, additional toner particles were not likely to be transferred from the adjacent halftone area, unlike the case of high development voltage and small gap. In addition to this effect, the sufficient supply of toner particles to the halftone area might also reduce the pale image defect. This assumption is supported by the experimental result that the bit depth in the halftone area increased with the increase of the speed ratio (Fig. 7 (e, right)).

Figure 7 (f) shows the effect of the toner/carrier concentration. The bit depth in the halftone area increased with the toner/carrier concentration (Fig. 7 (f, right)) simply because a sufficient number of toner particles were supplied. However, the effect of toner/carrier concentration on the pale image defect is not clear (Fig. 7 (f, left)).

4. Direct Observation

Figure 8 (a) shows a snapshot of the pre-nip region observed with the high-speed microscope camera. Because the dynamic motion of particles cannot be captured with still images, a schematic diagram has been added to Fig. 8 (b). The overall particle behavior was the same as that previously observed. At the beginning of brush formation, chains of magnetic carrier particles were formed almost parallel to the magnetic flux lines and leaned against the sleeve. However, they assumed an upright position as they approached the development gap. The brush then came into contact with the drum and was 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 were aligned along the magnetic flux lines.

The development, that is, the adhesion of toner particles to the latent image on the drum, occurred not only in the contact area between the carrier brush and drum, but also in the pre- and post-nip regions where the carrier brush did not come into contact with the drum. In the pre-nip region, carrier chains vibrated in the lateral direction when the leaning chains were upright, owing to the abrupt change in the magnetic flux line; at the same time,
toner particles were forced to separate from the chain. Some of the separated airborne toner particles adhered to the latent image. In the post-nip region, toner particles separated from the chain and formed a toner cloud in the gap. The toner cloud vibrated at the frequency of the AC voltage, and some of the airborne toner particles adhered to the latent image.

The movement of toner particles from the halftone area to the edge of the solid image was observed on the pseudo-photoreceptor drum in the pre-nip region (schematically shown in Fig. 8 (b) with the movement indicated by solid-line arrows). The region that was depleted of toner particles in the halftone area adjacent to the solid image was not well filled in the nip region and post-nip region. This was clearly the cause of the pale image defect in the halftone image adjacent to the solid image. The electrostatic field between the halftone area and solid area was the driving force of the toner motion. Because the field was high when the voltage difference between the solid and halftone areas was high, the pale image defect was enhanced under this condition, as discussed in the preceding section.

In addition, it was observed that airborne toner particles were likely to adhere to the edge of the solid area, where the electrostatic field was concentrated, rather than to the adjacent halftone area in the vicinity of the boundary between the halftone area and solid area (indicated by broken-line arrows in Fig. 8 (b)). This also caused the depletion of toner particles in the halftone area following a solid image.

5. Conclusion

We have investigated the formation of a pale image defect in the halftone area following a solid image in a two-component magnetic brush electrophotographic development system.

The pale image defect was caused by the movement of toner particles from the halftone area to the edge of the solid image on the photoreceptor drum in the pre-nip region. The circumferential electrostatic field between the halftone area and solid area on the photoreceptor drum was the driving force of the toner motion. The local concentration of airborne toner particles at the edge of the solid image was another factor affecting the pale image defect.

Preferred methods for reducing the pale image defect include the application of high AC voltage, the use of a high value of the ratio of the sleeve speed to the drum speed, and the use of a small development gap.
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References