Analysis of Imaging Density Degradation by Dynamics of Toner Charging and Mass Transfer in the Toner Development Process

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In the monocomponent non-magnetic toner developing system, optimum toner charging and mass transfer are important factors to produce high quality images. Also the uniformity of the image is one of the most important properties in electrophotography. One major type of nonuniformity is the problem of image density degradation also known as ghosting. In this article this phenomenon is discussed in terms of the toner charging and mass transfer characteristics during the first and subsequent roller revolutions. It was found that although the toner charge and toner mass on the development roller surface are very important parameters they are not the only causes of the imaging density difference. It was also found that the relationship between roller surface properties and toner development efficiency are closely related to the uniformity of the printed image. It is demonstrated that the optimum development roller requires low charge retention on the roller surface and low current leakage between the supply and the development rollers. Finally the design features of a two-layered development roller are described, that provides significant improvement of image density uniformities in continuous development.

Journal of Imaging Science and Technology 49: 196–203 (2005)

Introduction

Uniformity of the image is one of the most important properties in the electrophotographic development system. It is observed occasionally that the image density (*ID*) decreases continuously along the paper feed direction. Many authors have discussed this phenomenon, known as ghost imaging, but it is still a significant issue to clarify how the dynamics of toner charging and toner development affect image uniformity. Ni et al. proposed that the ghosting was related to toner charge density and the process bias.[1] Takaya et al. reported the mechanism of ghost formation by discussing the diameter of the toner particles.[2] Iwamatsu et al. also discussed the ghosting mechanism using a numerical method.[3] In addition, there are some reports that analyze the properties of the ghost image.[4,5] However, there are few reports which focus on the properties of the development roller and the effect of the dynamics of toner charging, toner mass transfer and the charge transport mechanism on the uniformity of printing images.

We have previously investigated the dynamics of toner charging using a microscopic current measurement technique.[6–11] It was confirmed that current flows through each part of the development system, i.e., the development roller, blade, and supply roller, only during roller rotation with toner attached on its surface. This current is strongly affected by the properties of the development roller surface. We discussed the correlations among the toner charging, toner mass transfer, observed currents and development roller properties. Finally it was proposed that the toner remove/supply efficiency of the supply roller is one of the most important processes to determine the uniformity of the imaging density.

The study in this article is a sequel to one that we presented previously.[11] In the previous study, we have already discussed the imaging density degradation mechanism using a statistical method. It was shown that the uniformity of the printed image is related both to the toner charge and roller surface properties. In this continuation, we report on measurements of the toner charging and toner mass on the development roller surface and the organic photoconductor (OPC) drum surface directly, and discuss the dynamic mechanisms causing imaging density differences as the roller rotates. Also using the results of the current measurements, we clarify the charge transport mechanism in the toner development process. The experimental results reconfirm the important roles of the properties of the development roller surface as well as the toner movement in the development system as required for high image quality.

Experimental

Development Rollers

Development rollers consisting of an elastic polyurethane base coated with a thin resin layer (alkyd-melamine type) were prepared for this study. The fundamental characteristics of the rollers are given in Table I, some of which are the same rollers we used in the previous report, the rest were newly prepared for this study.[11] The rollers N2 to N4 are arranged in the order of the thickness of the highly resistive surface

Original manuscript received September 24, 2004

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TABLE I. Fundamental Characteristics of Rollers Used in this Study

	surface layer				
	resin concentration	CB contents	roller resistance [log Ω]	surface roughness Rz [μm]	residual voltage [V]
N2	15%	—	7.4	8.2	22
N3	20%	—	7.5	5.4	78
N4	25%	—	8.0	1.4	428
C1	20%	10%	7.5	4.5	27
C2	20%	20%	7.0	3.3	10
C3	20%	30%	6.2	4.2	6

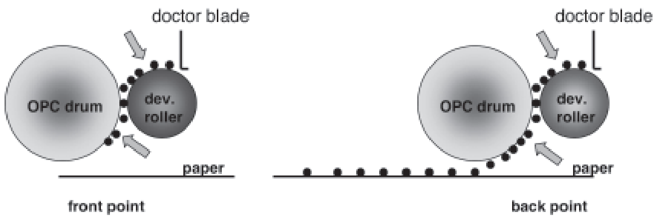


Figure 1. Schematic drawing of measuring points for toner charge and toner mass transfer.

layer. (The roller N4 has the thickest surface layer.) The rollers C1 to C3 have similar surface layer thickness but the resisitivity of the surface layer was controlled by changing the concentration of carbon black (CB). Thus the surface conductivity of C3 roller is very high.

Toners

We used a non-magnetic, monocomponent and negative charging type toner. It is a polymerized toner and the shape is spherical. The mean particle size based on weight was 6.7 μm.

Measurements of Charge Relaxation and Residual Voltage

The charge relaxation on the bare development roller surface was observed using a surface potential meter (QEA Inc.: CRT-2000), and the time constant for charge relaxation was obtained using a method described previously.[12] In these tests the roller surface was charged by a corona charger (supplying DC 8 kV), and the surface voltage relaxation was measured by the surface potential meter as a function of elapsed time after corona charging. We defined the value of the surface potential at 0.35 s, the time for one roller rotation, as “residual voltage” in this study. The results for all rollers are included in Table I.

Development System and Measurements of Imaging Density

We used a commercial laser beam printer (hereafter LBP) and toner cartridge for this study. The doctor blade and the supply roller of the machine were made of stainless steel and polyurethane foam, respectively. The bias voltage was applied on each part of the toner cartridge, –300 V for blade and development roller, and –580 V for the supply roller. Each roller and OPC was rotated several times with the applied voltage bias before start of printing. In this article the term “front” refers to the start of the printed image on the OPC and the “back” refers to end point on the OPC as the paper is fed through the printer, i.e., the top and bottom of the page. An all black, solid image was printed in each of the tests and the image density (*ID*) was measured by a photodensitometer (Macbeth RD918). The *ID* at five points each of the front and back of the printed image was measured and the data were averaged.

Measurement of Toner Charge

We measured the toner charge and its mass on both the OPC drum and the development roller at both the front point and the back point of a printed page. These measurement points are defined in the direction of printing and are indicated by the arrows in Fig. 1. During the measurements all normal voltage biases were applied to the cartridge and the OPC was charged for black development. The printing process was stopped during toner development to the OPC drum for the toner charge measurement. That is to say, as an all black solid image was being printed the drum was stopped at the front image printing point (a) and the toner charges were measured. A new printing test was then run and as the black solid image was being printed it was stopped at the back image printing point (b) and the toner charges were measured as well. A suction type Faraday cage was used to measure the toner charge and its mass (q/m) on the development roller surface. Toner mass/area ratio (m/a) was calculated from the toner mass collected in the Faraday cage and area of the development roller or OPC drum from where toner was removed.

Measurements of Current at Each Part in Development Process

Three electrometers were connected between each development unit part (blade, development roller and toner supply roller) and the power supplies used for applying the external bias voltages. The external bias voltages applied on each part were the same as the LBP machine specification (see above). We measured the development process currents during printing of the all black solid image. The currents were monitored by the three electrometers and the current data were transferred to a personal computer through a GP-IB bus.

Experimental Results

Image Density of Black Printing

The results of image density (*ID*) for each roller are shown in Fig. 2, which includes standard deviation error bars for each roller. The *ID* difference between front and back point generally increases with an increase of insulating surface layer thickness or an increase of surface layer conductivity. The *ID* difference of N3 roller is slightly lower than the N2 roller, but this will be discussed later.

Toner Charging in the LBP System

The toner charging and its mass transfer characteristics for each roller are shown in Figs. 3(a) and 3(b). The toner charge to mass (q/m) is shown in Fig. 3(a), and Fig. 3(b) shows the toner mass transfer (m/a). As shown

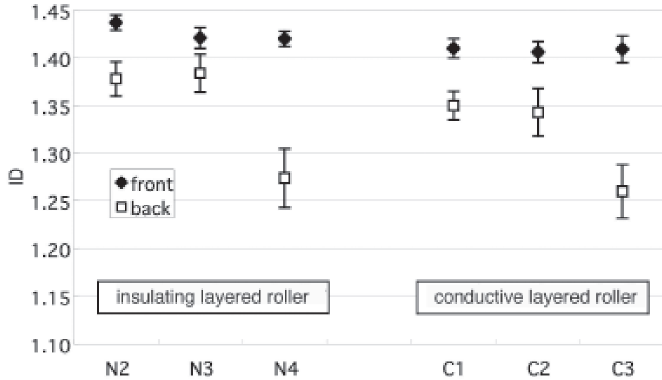


Figure 2. Image density at front and back points of the printing image.

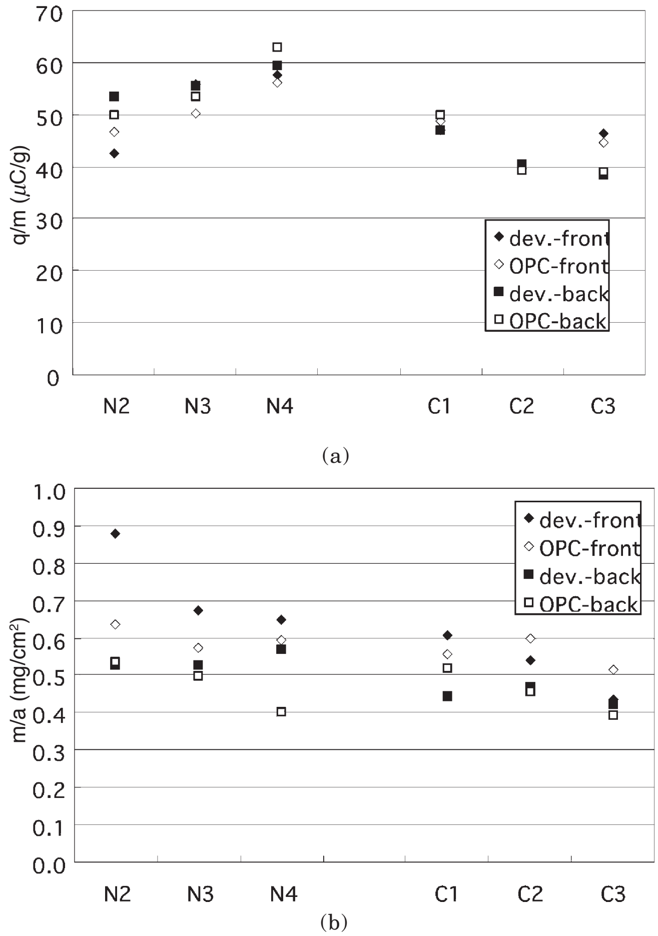


Figure 3. Toner charge and toner mass transfer at each measuring point: (a) toner charge (q/m); and (b) toner mass transfer (m/a).

in Fig. 1, the toner charge and its mass were measured on the development roller and the OPC drum when printing at the front point and the back point. In general terms, toner charge increases with an increase of resistive layer thickness and it decreases slightly with an increase of conductivity of surface layer. The surface roughness of the N2 roller is larger than the other rollers. Thus the toner mass on the development roller surface at the front point is also larger in this case. It is considered that this is one of the reasons why the *ID* difference of N2 roller is slightly larger than the N3 roller.

Current Measurements

The currents at each part (*Id*: through development roller, *Ib*: through blade, *Is*: through supply roller, *It*: total current) were measured during the printing of a solid black image in the development process. Figure 4 shows an example of the results of the current measurements for the N2 roller. The current was observed when the roller started to rotate and the direction of the electron flow is indicated in Fig. 4. As shown in our previous studies[7–9] when the OPC drum was removed and was not contacted to the development roller, the total current was always zero. In this experiment, the total current is around $-2\ \mu$A when the roller is rotated but before the development bias is applied and toner development is started. It is clear that this total current is related to the interaction between the OPC drum and the development roller. We assumed that this current originated from the charge transport from the OPC drum surface (the OPC surface is highly charged since it is not light exposed) to the development roller. When toner development is started, the total current rapidly increases, and the development roller current and the supply roller current changes. A slightly larger current was observed in the development roller during the initial and later part of the toner development process. It is understood that this is because of the time lag from the geometric position of each part. As shown in Fig. 4, slight current differences are observed between the front part and back part of the toner development process. From these results, we calculated the value for the total values of the "front current" and the "back current".

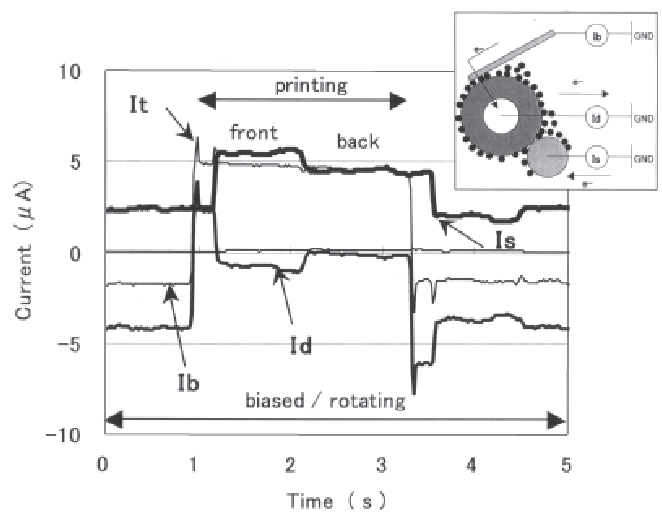


Figure 4. Currents through each part for roller N2 during solid black image printing.

Discussion

Relationship between Toner Mass and Image Density

Figure 5 shows the relationship between the toner mass on the OPC drum and solid black image density for both the front printing part and back printing part. These plots have a fairly linear relationship. To measure the nonuniformity of the image, *ID-Diff* is defined as the difference between the imaging density of the front part and back part. The ratio of front and back part toner mass was calculated and plotted against *ID-Diff* in Fig.

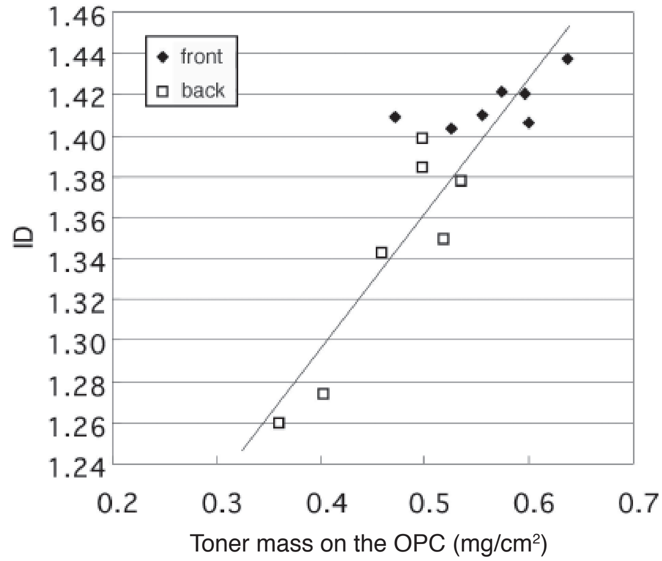


Figure 5. Relationship between imaging density and toner mass on the OPC at front and back points.

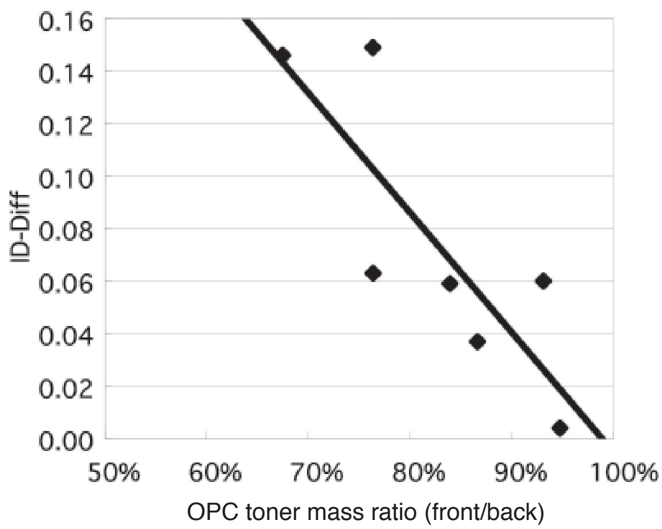


Figure 6. Relationship between image density difference (*ID-Diff*) and the OPC toner mass ratio (back/front).

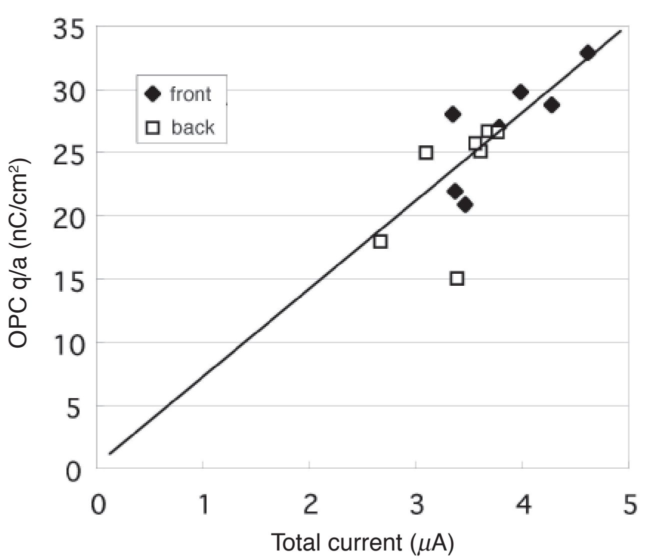


Figure 7. Relationship between toner charge on the OPC drum and the total current at front and back points.

6. The best-fit line for these results was determined (correlation coefficient 0.83) and is also shown in Fig. 6. Thus image density is directly related to the toner mass on the OPC drum.

Relationship between Total Current and Toner Charge Density

Figure 7 shows the relationship between the total current during image printing and toner charge density (q/a) at the front and back points. The line in Fig. 7 is the best-fit line and has a correlation coefficient of 0.85. Note that this line passes through zero, confirming that the current is zero for a charge extrapolated to zero. Thus it is clear that the total current is strongly related to the toner mass transfer from the development roller to the OPC drum. The one isolated point is for the C3 roller, and we will discuss the reason for this later.

Discussion of the Mechanism of Causing Imaging Density Difference

For comparing the toner development at the front and back points, it is realized that the toner charge and toner mass are different either on the development roller surface or on the OPC drum surface. At the front point, the toner is agitated by several rotations and the toner charge and mass reach the saturation steady state value. While at the back point, the saturation charged toner has already been developed to the OPC drum, so new toner must be attached to the development roller surface. The majority of the toner developed here has been newly attached by the supply roller and doctored by the doctor blade. In this combined process the toner is charged, and then it is developed to the OPC drum. Thus it is suggested that imaging density difference is determined by the difference of toner charge and mass and/or the development roller condition (residual voltage) between the front and back points. To clarify the proposed mechanism causing the imaging density difference (*ID-Diff*), we will discuss the insulating-surface-layered rollers (N2,3,4) and conductive-surface-layered rollers (C1,2,3) separately.

(1) Insulating Surface Layered Rollers (N2, 3, 4 Rollers)

As shown in Fig. 2, the *ID* of the back point decreases with an increase of surface layer thickness within experimental error. From the results in Fig. 3(a), it is observed that the toner charges (q/m) increase at every point when the surface layer thickness increases. The toner charge at the OPC back point is slightly higher than that at the OPC front point. In particular the toner charge at the OPC back point of the N4 roller is very high, and it is around 20% higher than that of the toner charge at OPC front point. Thus it is understood that the *ID-Diff* is not caused by a lower toner charge at the back point. Further, it is understood that highly charged toner is developed at the back point. Considering the toner mass condition, the toner mass (m/a) on the development roller surface and the OPC drum is smaller at the back point than the front part as shown in Fig. 3(b). Comparing the results in each roller, N2 roller has a significantly larger toner mass on the development roller surface at the front point. It can be realized that the larger surface roughness causes this larger toner mass for N2 roller.

The most remarkable result is the toner mass on the development roller surface at the back point. The toner mass on the development roller surface for each roller is approximately at the same level although the imaging density of the back point is different. The results show that the toner mass on the OPC drum at the back point

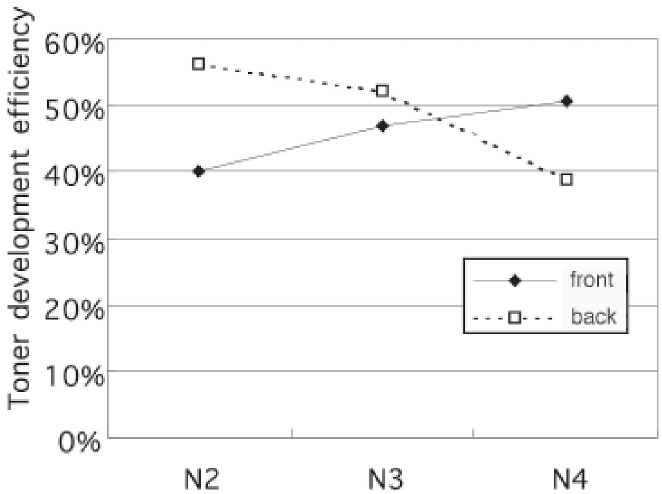


Figure 8. Toner development efficiency of insulating layered rollers.

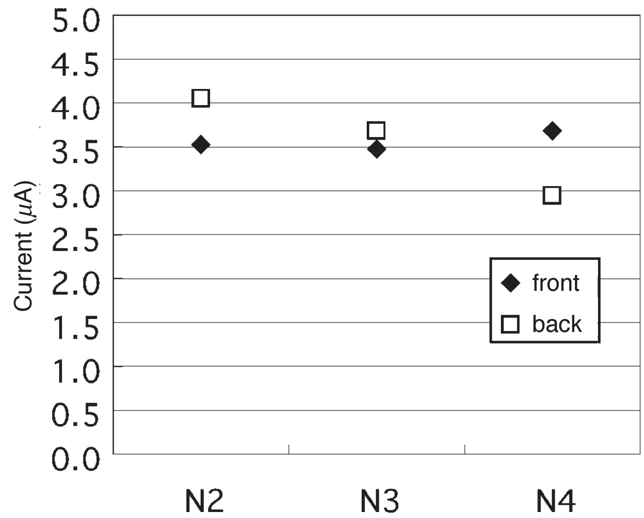
decreases with an increase of the surface layer thickness. This result conforms to the *ID-Diff* results. Also as shown in Fig. 3(a), the difference in q/m between the N3 and N4 rollers is around 5%. But the difference in m/a of OPC back point is over 30%. This means that the *ID-Diff* cannot be attributable to the toner charge alone.

From the results of Fig. 3(b) and the ratio of the rotation rate of the OPC drum to that of development roller, the toner development efficiency was calculated and plotted in Fig. 8. The peripheral velocity ratio of the OPC drum to the development roller is 84:152. Thus the toner development efficiency is defined here as

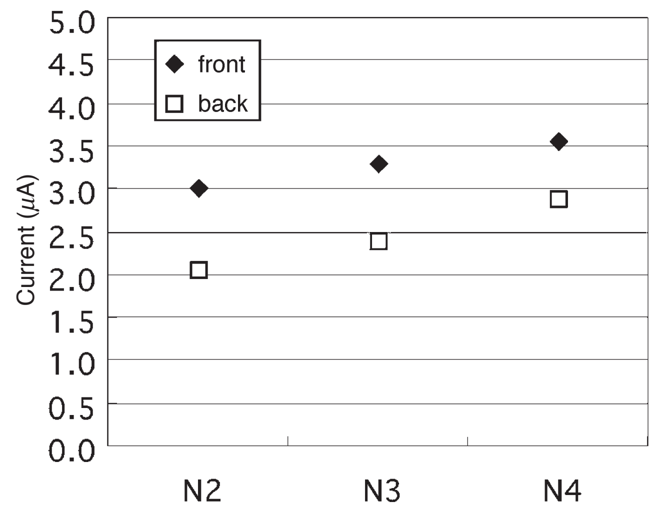
$$\text{(toner development efficiency)} = \frac{\text{(toner mass on the OPC drum)}}{\text{(toner mass on the development roller)}} \times \frac{84}{152}$$

The toner development efficiency ranges from 40% to 60%, indicating that approximately half of the toner on the development roller surface is developed to the OPC drum and the other half of the toner remains on the development roller surface. From the results in Fig. 8, it is observed that the slope of the graph is reversed between the front and the back points. At the front point, the toner mass on the development roller decreases with an increase of the surface layer thickness (N2 to N4 roller) as shown in Fig. 3. Since only a limited amount of toner can be developed to the OPC drum, thus the development efficiency is lower in the case of a thinner surface layer roller. At the back point, conversely the toner development efficiency decreases with an increase of the surface layer thickness. The toner mass on the development roller at the back point is approximately the same value for each roller. This indicates that only a small amount of highly charged toner was developed at the back point. It can be concluded that the *ID-Diff* is strongly related to the toner development efficiency.

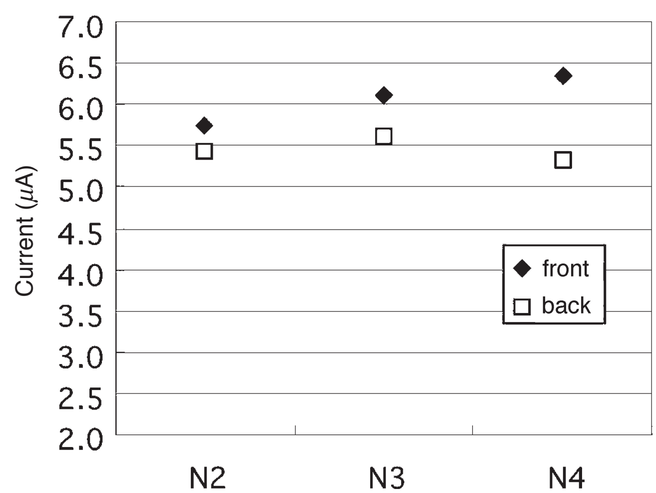
Now we discuss the mechanism from a different point of view in terms of the current measurement results. Figures 9(a), 9(b) and 9(c) show current measurement results at front and back points for each roller while they are in the toner development process. Figure 9(a) is development roller current, Fig. 9(b) is supply roller



(a)



(b)



(c)

Figure 9. Currents though each part for insulating layered rollers: (a) development roller (Id); (b) supply roller (Is); and (c) total current (It).

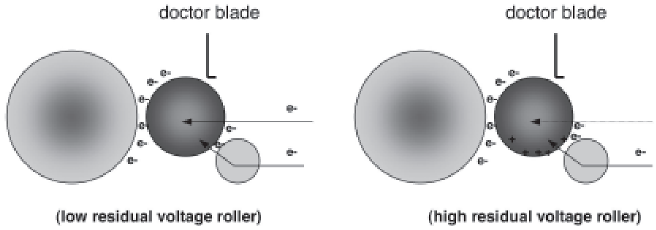


Figure 10. Schematic drawing of negative charge transfer.

current and Fig. 9(c) is total current. As shown in Fig. 9(a), the back point current through the development roller decreases with an increase in thickness of the surface layer. Conversely the back point current through the supply roller increases with an increase in thickness of surface layer as shown in Fig. 9(b). As a result the total current at back point is almost the same for each roller as shown in Fig. 9(c).

In discussing these results, the schematic drawing of negative charge transfer is shown in Figs. 10(a) and 10(b). As shown in Fig. 10(a), the negatively charged toner is developed to the OPC drum, and the negative charge is replenished from the development roller. The new toner is attached to the development roller surface from the supply roller, thus the negative charge is transferred in the direction shown in Fig. 10(a). This scheme is considered to be in agreement with the case of the roller with a thin insulating surface layer (N2 roller).

On the other hand, when the surface layer thickness is largest (N4 roller), the residual voltage increases by a factor of more than twenty as shown in Table I. This means that the charge retaining ability at the surface of the roller N4 is larger than for the other rollers. In this case, after the negatively charged toner is developed to the OPC drum, the counter positive charge remains at the development roller surface, because the roller has a high charge retaining ability. Thus the negative charge transfer through the development roller decreases as shown in Fig. 9(a). The supply roller then resets some part of this counter positive charge, thus the negative charge transfer at the supply roller increases as shown in Fig. 9(b). This charge inducing/reset mechanism in the development process was discussed in detail in previous articles.[6–11] The results observed in this study are fully consistent with these previous reports. The difference of the total current between front and back points is larger when the surface layer thickness is largest as shown in Fig. 9(c). As shown in Fig. 2, the *ID-Diff* is largest in the case of N4 roller, whereas in the N2 and N3 cases the differences are less marked. These results can also be explained by comparing the residual voltages. The residual voltages of the N2 and N3 rollers are similar with each other (22 and 78 V, respectively) whereas the value for the N4 roller is more than 20 times larger than the N2 roller. Thus it is understood that the *ID-Diff* is strongly related to the value of residual voltage.

In summary, the mechanism causing the image density difference for the insulating surface layered rollers can be assumed as follows.

(i) The residual voltage increases with an increase of the surface layer thickness, which means an increase of charge retaining ability at the roller surface.
(ii) Accompanied with this, toner charge density (q/m) increases and the toner adhesion force to the development roller surface increases.
(iii) The counter positive charge remains on the development roller surface after the toner is developed onto the OPC drum.
(iv) The toner adhesion force at the back point increases. The toner removal/attachment efficiency at the supply roller decreases, and some of the same toner remains on the development roller surface.
(v) The same toner passes through the doctor blade again, and the toner charge increases.
(vi) A smaller amount of the more highly charged toner is developed at the back point, and the toner development efficiency decreases.
(vii) The difference in the toner mass developed appears as the imaging density difference.

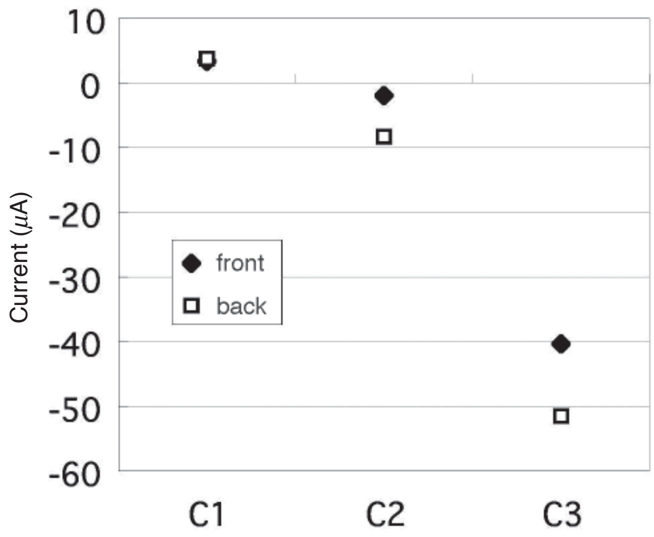
(2) Conductive Layered Rollers (C1, 2, 3 Rollers)

For the conductive layered rollers *ID-Diff* increases with an increase of surface layer conductivity as shown in Fig. 2. As shown in Figs. 3(a) and 3(b), toner charge (q/m) and toner mass transfer (m/a) decrease with an increase of surface layer conductivity. Figures 11(a), 11(b) and 11(c) show the results of the current measurements of C1, C2 and C3 rollers, respectively. Figure 11(a) is development roller current, Fig. 11(b) is supply roller current and Fig. 11(c) is total current. As shown in Figs. 11(b) and 11(c), the development roller current and the supply roller current increased drastically with an increase of the conductivity of the roller surface compared with Fig. 9. The current measurement results of the C1 roller are shown in Fig. 12. Comparing with the results obtained for the N2 roller (Fig. 4), we note that these two results are very similar. The residual voltages of N2 and C1 rollers are 22 V and 27 V, respectively, and the value of *ID-Diff* are also very similar (see Fig. 2). This reaffirms the previous observation of the importance of the residual voltage. Figure 13 shows the current measurement results of the C2 roller. It is observed that the development roller and the supply roller currents increase significantly in magnitude as the toner development is continuing. The external voltage bias is applied between the development roller and the supply roller, and thus it is suggested that some current leakage occurs in the case of the highly conductive surface rollers. This is presumably the reason why the data C3 roller falls off the regression line in Fig. 7.

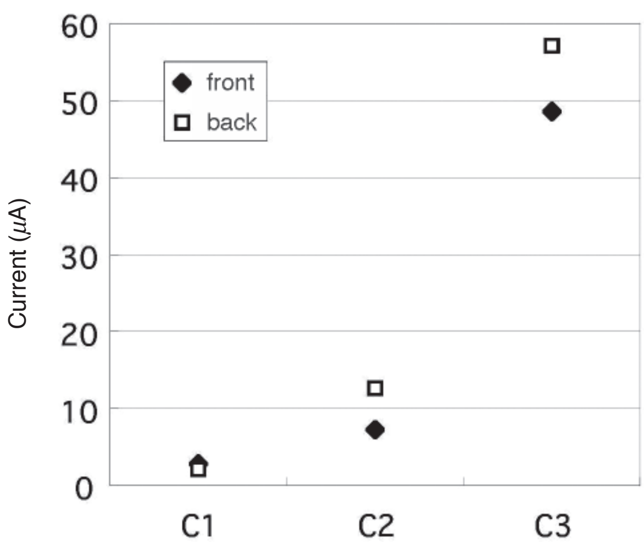
As the toner development is continuing (which is to say at the back point), it becomes easier to contact the development roller surface and the supply roller surface directly because the toner layer is getting thinner. As a result, the current leakage between the development roller and the supply roller becomes larger as shown in Fig. 13. In effect, this reduces the bias between the development roller and the supply roller to a level below the proper condition for development. Also the effective bias of the toner development becomes unstable. Thus proper toner mass transfer and toner development cannot be achieved. These phenomena are different from those at the front point, resulting in the image density difference.

(3) Design of a Development Roller of High Uniformity of Imaging Density

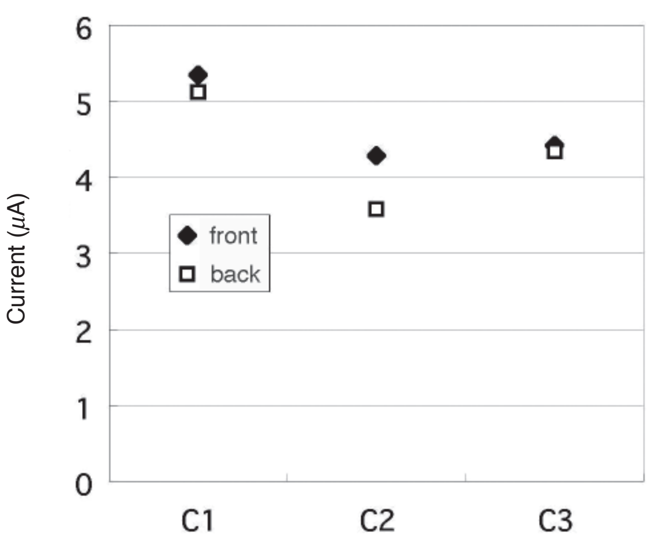
To reduce the ghosting problem, we designed a two-layered surface roller. This roller has a conductive layer upon the base elastic roller, which is then covered over by an insulating surface layer. Thus the surface is very insulating but the bulk roller resistance is relatively low. The important considerations for the design of this two-layered roller are both to restrain the residual volt-



(a)



(b)



(c)

Figure 11. Currents though each part for conductive layered rollers: (a) development roller (*Id*); (b) supply roller (*Is*); and (c) total current (*It*).

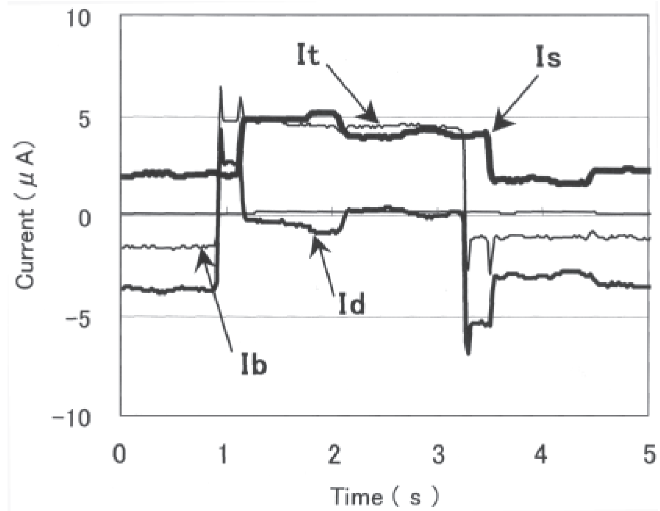


Figure 12. Currents though each part for conductive layered rollers C1 during solid black image printing.

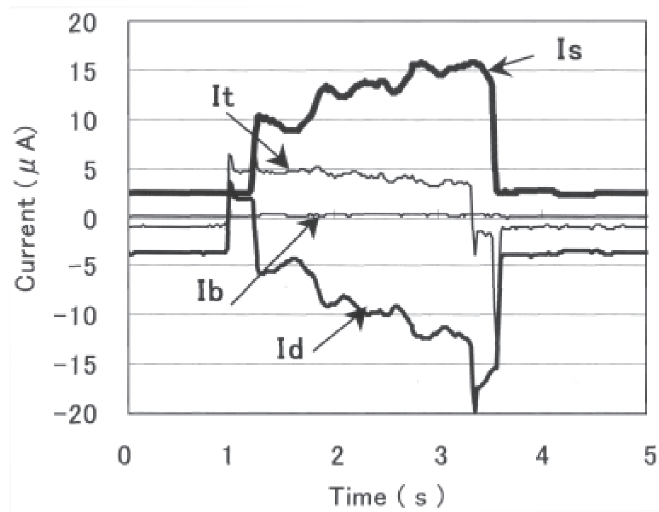


Figure 13. Currents though each part for conductive layered rollers C2 during solid black image printing.

age and to minimize the current leakage between the supply roller and the development roller. When the thickness of the insulating top layer increases, the current leakage is reduced although the residual voltage increases. Conversely in the case of a thinner insulating layer, the residual voltage is reduced, but the current leakage increases. Table II shows the fundamental characteristics of the optimum design for a two-layered roller. The residual voltage is 17 V, this value is less than for the N2 roller. The current measurement results are shown in Fig. 14, and current leakage was not observed in this case. The result for *ID-Diff* of the two-layered roller is shown in Fig. 15, compared with the insulating layered rollers. The resulting *ID-Diff* for this roller is negligibly small (ca. 0.004), indicating complete uniformity of the image. Thus this two-layer roller design can produce a major improvement in the uniformity of the imaging density. More details on the improvement obtained with two-layered rollers are reported in the previous article.[11]

Conclusions

To clarify the problem of ghosting, the mechanisms of monocomponent non-magnetic toner charging and the

TABLE II. Fundamental Characteristics of Two Layered Roller

	first layer		surface layer		roller resistance [log Ω]	surface roughness	residual voltage
	resin concentration	CB contents	resin concentration	CB contents	(applied voltage) 100V	Rz [μm]	[V]
T3	20%	20%	20%	20%	6.7	4.5	17

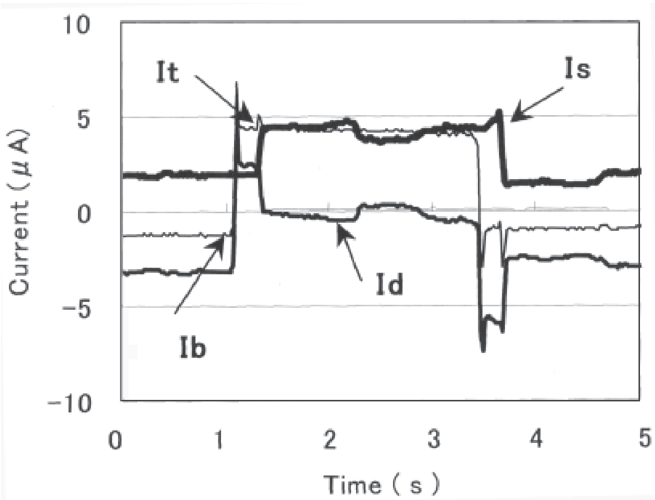


Figure 14. Currents though each part for two-layered roller during solid black image printing.

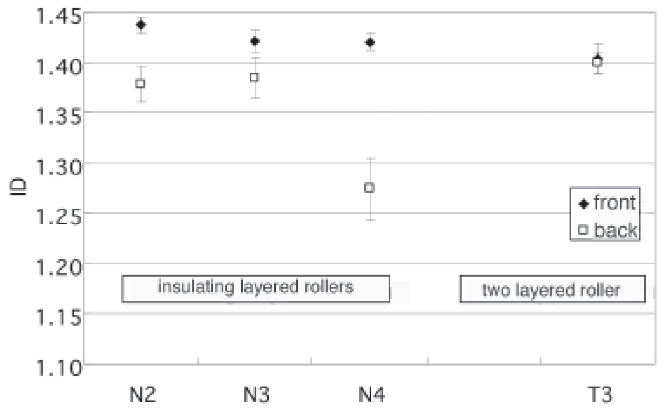


Figure 15. Image density at front and back points of the printing image for insulating layered rollers and two-layered roller.

toner development in the electrophotographic system have been studied as a function of the roller properties. The following conclusions have been drawn.

1. In the case of the insulating surface roller, it was confirmed that the decrease of imaging density at the back print point was the result of a reduction of the toner development efficiency from the development roller surface to the OPC drum.
2. The toner development efficiency strongly depends on the charge retaining ability of the development roller surface, described as the "residual voltage".
3. In the case of the conductive surface layered roller, when the conductivity of the roller surface increases, current leakage occurs between the supply roller and the development roller, due to the voltage bias between them.
4. In this situation the toner charging, mass transfer and the effective development bias are not stable as the roller rotates, thus leading to a larger image density difference.
5. A two-layered surface roller was designed to minimize the residual voltage and limit the current leakage. As a result, the uniformity of the imaging density was highly improved.

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