Comparative studies of gloss development in electrophotography and offset printing

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Abstract

The difference between the formation processes of the printed surface topography in offset printing and electrophotography is clarified. Understanding the formation processes is important because the printed surface topography is closely related to the print gloss. Furthermore, the formation process in offset printing is applied to electrophotography. The experiments are carried out using matte-coated paper.
From the results, the key difference between the surface topography formation in offset printing and electrophotography was found to lie in the different behaviors of the ink and toner, respectively, on the paper surfaces. We, therefore, imitated the offset printing process in electrophotography by maintaining a low toner viscosity so that the toner could flow on the paper surface. This resulted in a printed surface topography that was more consistent with the paper surface topography; subsequently, the printed surface gloss became more consistent with the paper gloss.

Keywords Electrophotography; Gloss; Matte-coated paper; Offset printing; Paper surface topography, Printed surface topography.

INTRODUCTION

In recent years, many color printers possessing the qualities of high speed and high image quality have been commercially introduced[1–3]. These printers allow easy and fast printing, and they can also adapt to the digitalization of the printing procedure easily. Due to these features, these printers are used for small volume print jobs in the printing market. However, the correlation between print gloss and paper gloss in electrophotographic products has been known to be inferior to that in offset printing products[4]. In other words, electrophotography produces high print gloss even on low-gloss matte-coated paper, which results in a texture quite different from offset printing products and may yield an unnatural impression. It is desirable, therefore, that print gloss changes according to the paper gloss in electrophotographic products, similar to offset printing products, so that the prints appear more natural.

In offset printing, studies have been carried out mainly on the mechanism of gloss development on high-gloss paper. For example, it has been shown that when ink is transferred to paper, topographical unevenness, called split patterns, forms on the deposited ink surface[5]. Some of these split patterns persist on the printed surface even after the ink dries, and this is known to affect the print gloss. Furthermore, changing the ink vehicle absorbency of the coated paper by altering its surface and internal structure has also been found to affect the print gloss[6]. Another study showed through cross-sectional observations of printed samples that the amount of absorbed ink affects the formation of the printed surface topography[7]. In these studies, however, there has been little clarification about the mechanism of gloss development on low-gloss paper.

With regard to electrophotography, several studies have attempted to develop fusing technologies that provide high print gloss[8]. Pettersson and Fogden clarified that the amount of toner that is transferred has a significant influence on the printed surface topography[9]. Ide and Kurimoto reported that uniformity in print gloss was obtained by using a clear toner[10]. Kurimoto and Watanabe demonstrated through cross-sectional observations how the height and uniformity of the toner layer are different between the outputs of electrophotography and offset printing[11]. Very few attempts have been made, however, to study how print gloss changes according to paper gloss in electrophotography.

This study was intended to clarify gloss development mechanisms in offset printing and how these mechanisms are different from those in electrophotography. In our previous studies, we showed how paper and printed surface topographies differ in offset printing and electrophotography. In one of these studies, Pearson's correlation coefficient was used to examine the relationship between the surface topographies of a coated paper surface and its printed surface at the same location[4]. Four kinds of coated papers possessing different glosses were used. In offset printing, the correlation coefficient was high for every kind of coated paper except the cast-coated paper. In electrophotography, however, the correlation coefficient was low for all the four kinds of papers. This result implies that in order to change the print gloss in accordance with the paper gloss, the printed surface topography should follow the paper surface topography. The present work examines the formation process of printed surface topography in offset printing and electrophotography and the reason for the gloss development being different between these two printing technologies. We also attempted to apply the formation process of the printed surface topography in offset printing to electrophotography. This experiment was carried out using matte-coated paper, whose surface topography was expected to have a significant influence on the formation of the printed surface topography.

EXPERIMENTAL DETAILS

Printing Trials

Offset printing was performed using the universal printability tester（KRK, Tokyo, MPT6000）, and dampening water was not applied. The printing speed was 2.8 m/s and the printing pressure was 11.8 kN/m. The ink kneading temperature was 25 °C and the ambient temperature was 20 °C–25 °C. The ink used in the printing trials was cyan ink (Toyo Ink Manufacturing, Tokyo, TK high-unity MZ). These printing conditions and the ink type were based on those employed in common-sheet-fed offset printing presses. The amount of ink supplied to the kneader was 0.1 mL, which was the volume required to reproduce Japan Color 2001[12] standards. Under this condition, 1.2 g/m^2 of ink was transferred to the matte-coated paper to cover the entire surface, and the thickness of the ink layer after drying was approximately 0.8 μm when printed on cast-coated paper.

Electrophotographical printing was performed using a color laser printer (Fuji Xerox, Tokyo, DC1250). This printer has a hot roll fusing system containing two metal rolls covered with silicon rubber and heated by halogen lamps inside the rolls. As the standard printing condition, the printing speed was set to 130 mm/s; the printing load, 1275 N; and the printing temperature, 160 °C. The cyan toner was used in the printing trials; its amount was adjusted so that the average thickness of the toner layer was approximately 4.0 μm when printed on cast-coated paper.

The commercial matte-coated paper (Oji Paper, Tokyo, OK matte coat) of a basis weight of 127.5 g/m^2 was used. In the experiment for evaluating the paper surface topography and the ink distribution on the printed surface, the ink layer was solidified using liquid nitrogen at given intervals. The samples were then dried for two days in a freeze dryer (Tokyo Rikakikai, Tokyo, EYELA FDU-830).

In the experiment for examining the relationship between the fusing parameters and the printed surface topography in electrophotography, the printing load and temperature were considered to be variable fusing parameters. One of the two parameters was changed at a time, while the other parameter was maintained at the standard level mentioned above. Printed samples were obtained for three levels of every parameter. The values employed were as follows: printing loads of 981, 1275 (standard level), and 1569 N and printing temperatures of 150 °C, 160 °C (standard level), and 170 °C.

In the experiment to study the formation process of printed surface topography in offset printing and to apply it in electrophotography, printed samples were heated in an oven at 160 °C for 30 s so that the toner on the paper recovered its viscosity. The fusing parameters were set to a printing load of 981 N and a printing temperature of 150 °C.

Printed Sample Characterization

Three-dimensional profiles of the paper surface and its printed surface at the same location were examined using a laser microscope (Keyence, Osaka, VK-8500). The sampling pitch in the height direction was 0.02 μm. The specular gloss of the paper and printed samples at 60° was measured using the gloss meter (Nippon Denshoku, Tokyo, VG2000).

Immediately after printing, the printed surface was observed using a laser microscope (Keyence, Osaka, VF-7500). The analog image output from the laser microscope was transferred via a digital video camera into a computer so that the topographical changes in the printed surface could be observed. From these images, the reflected light distribution was calculated using image processing software (Media Cybernetics, Washington DC, Image-Pro Plus).

For the examination of the relationship between paper surface topography and lightness images of the prints, the paper surface topography and color images of the prints were observed using a laser microscope (Keyence, Osaka, VK-8500). The intensity of illumination was set to be constant for all the color images available as RGB data. These data were assumed to be sRGB and converted to L*a*b* images.

For the quantification of the similarity between the paper and printed surface topographies, Pearson's correlation coefficients were calculated from the data of five sets of locations using the image processing software. The results were averaged for each kind of sample.

To determine the extent to which the paper surface topography was maintained after printing, Fourier transform was carried out for the topographical images of the specified areas of the paper surface and for those of the corresponding areas of the printed surface of the identical paper. Using the radially averaged power spectrum (RAPS) [13], the gain defined by the following transfer function (Eq. (1)) was calculated.

$$Gain(dB) = 20\log\left(\frac{\text{RAPS(Printed surface topography)}}{\text{RAPS(Paper surface topography)}}\right) \qquad (1)$$

If the gain is 0 dB, the surface topographies before and after printing are completely identical. The gains larger and smaller than 0 dB imply that the printed surfaces are rougher and smoother than the paper surfaces, respectively. The gain was calculated for five locations on the paper and printed surfaces.

RESULTS AND DISCUSSION

Surface Topography and Initial Gloss Dynamics for Matte-coated Paper

Topographical images of the paper and printed surfaces for the standard printing condition are shown in Figure 1. In offset printing, the paper surface topography has a significant influence on the printed surface topography. In electrophotography, the large-scale roughness is preserved on the printed surface. The small-scale roughness, however, is hidden by the toner, causing the printed surface to be considerably smoother than the paper surface.

Figure 2 shows the gloss dynamics, that is, changes in the print gloss of the matte-coated paper immediately after printing, in both electrophotography and offset printing. In offset printing, the gloss changed with time; it increased for approximately 10 s immediately after printing and subsequently decreased for several minutes. In other words, the printed surface topography continued to change during the entire period of time. In electrophotography, the gloss did not change with time. This result shows that in offset printing, the printed surface topography develops during some period of time after the ink has been transferred onto the paper. In electrophotography, on the other hand, the printed surface topography is established during the fusing procedure, that is, in the fusing nip.

Mechanisms of Gloss Development in Offset Printing

In order to clarify the mechanism of gloss development in offset printing, the changes in surface topography during increases and decreases in the gloss were examined[14–15].

Printed Surface Topography during Increase in Print Gloss

Using the laser microscope, the printed surface topography was observed immediately after the ink transfer. As shown in Figure 3, many white spots were visible. This observation indicates that the printed surface was very uneven. This uneven topography was formed by splits in the ink layer occurring at the nip exit.

Figure 4 shows how the white spot area ratio (the ratio of the total area occupied by white spots to the total surface area) and the gloss changed with time. The white spot area ratio decreased for the initial several tens of seconds, reflecting the decrease in the topographical unevenness. After this process, the white spot area ratio barely changed. The print gloss, on the other hand, increased for the first several tens of seconds and then reached an equilibrium state; subsequently, it decreased for several hundreds of seconds. In other words, the time during which the white spot area ratio decreased was consistent with that during which the print gloss increased. This result suggests that the increase in print gloss resulted from the decrease in the unevenness of the printed surface topography.

Printed Surface Topography during Decrease in Print Gloss

In order to examine the process of decrease in the print gloss, the microdynamics of the printed surface topography after the ink transfer was observed using the laser microscope. The light source was positioned so that the direction of light was as close and parallel as possible to the surface plane. This positioning reduced the light incident on the ink layer. The illumination intensity was set so that a sufficient amount of light was reflected from the surface for recording the details of the topography. The result of these observations is shown in Figure 5. The reflected light profiles were measured along the direction of illumination. Therefore, the reflected light profiles represented the printed surface topography to some extent[16]. By closely studying the profiles, the roughness pattern was observed to repeat regularly with a wavelength of several micrometers on the printed surface.

The paper surface and printed surface were observed using SEM, as shown in Figure 6. In some areas of the printed surface, coating pigments of the paper surface were exposed. This result suggests that the pigment coating layer exposed on the printed surface is likely to be observed as high-frequency roughness in the reflected light profile analysis. More specifically, the roughness hidden by the ink layer was revealed as the ink film became thinner with the penetration of the ink vehicle.

Relationship between Printed Surface Topography and Ink Distribution

On the other hand, the paper roughness may cause an ink flow that can lead to uneven ink distribution. It is known that the thickness of an ink layer correlates well with the density of color according to the Kubleka-Munk theory. In other words, the concave areas with more ink are expected to appear densely colored, and the convex areas with less ink are expected to appear lighter. With these assumptions, the time change of the relationship between the paper surface topography and the luminosity distribution on the printed surface was examined. The correlation coefficient between the paper surface topography and the lightness images on the printed surface was calculated, and a quantitative analysis was carried out. For one sheet, eight locations were chosen for the correlation coefficient calculation because the correlation level was expected to vary depending on the choice of the location. The average and variance of the correlation coefficients for the sheet were calculated and compared between the samples, and the results are shown in Figure 7. Although no correlation was apparent between the paper surface topography and the luminosity distribution immediately after the ink transfer, the correlation coefficient increased with time. This result indicates that ink flows according to the paper surface topography and concentrates in the concave areas of the paper surface, thus making those areas appear dark. The driving force for wetting the surfaces of the concave areas is considered to be the surface tension of the ink and not the gravity.

Formation Process of Printed Surface Topography in Offset Printing

From the above results, it is concluded that in offset printing on matte-coated paper, gloss is developed along with the formation of the printed surface topography through the processes described below. When ink is transferred to the paper, topographical unevenness of the printed surface results from inhomogeneous ink layer splits. This unevenness disappears during the initial several tens of seconds. Concurrently, the ink flows along the paper surface, and the printed surface becomes smoother than the paper surface.

For the next several hundred seconds, the ink vehicle penetrates the paper and causes the shape of the printed surface to gradually become increasingly similar to that of the paper surface. In other words, the roughness hidden by the ink layer so far becomes apparent and prominent as a result of the ink vehicle penetration.

Mechanisms of Gloss Development in Electrophotography

In order to clarify the mechanism of gloss development in electrophotography, the relationship between the paper and the printed surface topographies was examined by varying the fusing parameters, namely, the load and temperature of the nip[17].

Relationship between Nip Load and Printed Surface Topography

The paper surface topography and printed surface topography resulting from different nip loads were observed with the laser microscope, and the correlation coefficients between the paper and the printed surface topographical images were calculated; these correlation coefficients are shown in Figure 8. The correlation coefficient shows a tendency to decrease with the nip load. The relationship between the nip load and the print gloss is shown in Figure 8. The print gloss, on the other hand, shows a tendency to increase with a decrease in the nip load. The above result shows that the level of influence of the paper surface topography on the printed surface topography changes with the nip load.

Relationship between Nip Temperature and Printed Surface Topography

The paper surface topography and printed surface topography resulting from different nip temperatures were observed with the laser microscope, and the correlation coefficients between the paper and the printed surface topographical images were calculated; these coefficients are shown in Figure 9. The correlation coefficient between the paper and the printed surface topographical images increases with a decrease in the nip temperature. The relationship between the nip temperature and the print gloss is shown in Figure 9. As the nip temperature decreases, the small-scale roughness becomes apparent on the printed surface and the gloss decreases. The above result shows that the level of influence of the paper surface topography on the printed surface topography changes with the nip temperature.

Relationship between Paper Surface Topography and Unfused Surface Topography

It was shown through the result for all the parameter values, that the lesser the fusing energy applied to the toner, the more was the influence of the paper surface topography on the printed surface topography. This implies that the unfused surface topography follows the paper surface topography to a certain extent, and the printed surface topography becomes different from the paper surface topography when heat and pressure are applied. With this assumption, the relationship between the paper surface topography and the unfused surface topography was examined.

The paper surface topography, unfused surface topography, and printed surface topography were observed using the laser microscope, as shown in Figure 10. The unfused surface was covered with toner particles larger than those covering the fused surface. Two-dimensional Fourier transform was carried out for the images of these surfaces. Using RAPS, it was examined if there were any peak frequencies other than those corresponding to the toner particle size. In this observation, the transform equation was not used because the toner particle diameter on the unfused/printed surface was homogeneous and the gain would have an intense peak of the diameter and apparently interfere with the output (the dividend of the transfer function occupied by the unfused/printed surface topography).

The result of the frequency analysis is shown in Figure 11, and the peak frequencies of the image of each surface are presented in Table 1. As this result indicates, there are no similarities in the peak frequencies in the high-frequency range. This is because it is difficult to reproduce a paper surface roughness smaller than the toner diameter on unfused/printed surfaces. In the low-frequency region, however, the paper and unfused surfaces have some consistent peak frequencies, whereas no consistent frequencies are observed between the paper and the printed surfaces.

This result confirms our hypothesis by suggesting that the influence of the paper surface is maintained, to a certain extent, on the unfused surface topography; the printed surface topography becomes different from the paper surface topography when heat and pressure are applied.

Formation Process of Printed Surface Topography in Electrophotography

From the above results, it is concluded that in electrophotography using matte-coated paper, the printed surface topography is formed through the processes described below.

Before the toner on the surface is fused, the low-frequency roughness, that is, roughness greater than the size of the toner particles distributed over the unfused surface, is characteristically similar to that of the paper surface. The pressure and heat applied to the toner result in a toner layer shape that is different from that of the paper surface topography through processes such as coalescence and flowing. The degree of change in the toner shape is dependent on the amount of applied heat energy and the viscosity of the melted toner. Through this process, the printed surface topography becomes smoother than the paper surface topography.

Application of Formation Process of Printed Surface Topography to Offset Printing in Electrophotography

Formation Process of Printed Surface Topography

The above results indicate that in offset printing, the printed surface topography follows the paper surface topography through the following two steps.

Step 1: Smoothing out the topographical unevenness of the printed surface caused by ink layer splits immediately after printing.

Step 2: Inducing ink flow along the paper surface and causing the ink vehicle to penetrate the paper.

Through these two steps, the printed surface topography is obtained; thus, the printed surface topography is modestly influenced by ink and significantly influenced by the paper surface topography.

It was assumed that the following steps would enable such printed surface topographies to be available in electrophotography by applying the formation mechanisms of the printed surface topography in offset printing. First, a low fuser nip temperature and a low load were applied to reduce the excess smoothing of the toner while maintaining the influence of the paper surface topography. Second, the toner viscosity was kept low to allow the printed surface topography to follow the paper surface topography. Furthermore, one apparent difference between the printed surface topography in the offset printing and the electrophotography outputs pertains to the thickness of the ink/toner layer[11]. Therefore, the amount of toner was adjusted so that the thickness of the toner layer was approximately 2.0 µm on cast-coated paper.

Printed Surface Topography Resulting from Imitated Offset Printing Mechanisms

Using a laser microscope, the topography of the paper surface as well as the topography of the printed surface resulting from imitated the offset printing mechanisms described earlier was observed. The results are shown in Figure 12.

Table 2 shows the correlation coefficient between the paper and the printed surface topographical images with 60° print gloss. The tran sfer function that is calculated when the paper and printed surface topographies are applied as the input and output, respectively, is shown in Figure 13. This result indicates that when the formation process responsible for the surface topography in offset printing is studied and applied to electrophotography, the correlation coefficient increases, print gloss decreases, and gain of the transfer function approaches zero. In other words, the surface topography and print gloss become more consistent with the original paper surface topography.

CONCLUSION

In this research, the difference between the formation processes of printed surface topography in offset printing and electrophotography was clarified using matte-coated paper.

In offset printing, the formation of printed surface topography occurs through the following processes. The ink is transferred to the paper, and the topographical unevenness of the printed surface results from ink layer splits. This unevenness is smoothed out during the initial several tens of seconds. Furthermore, the ink flows along the paper surface, and the printed surface becomes smoother than the paper surface. For the next several hundreds of seconds, the ink vehicle penetrates the paper and causes the printed surface to gradually become increasingly similar to the paper surface. In other words, the roughness initially hidden by the ink layer becomes apparent as a result of the ink vehicle penetration.

In electrophotography, the formation of printed surface topography takes place through the following processes. Before the toner on the surface is fused, low-frequency roughness, that is, roughness greater than the size of the toner particles distributed over the unfused surface, is characteristically similar to that of the paper surface. The pressure and heat applied to the toner provide the toner layer with a shape different from that of the paper surface topography through processes such as coalescence and flow. The change in the toner shape is dependent on the applied heat energy and the viscosity of the melted toner.

The formation process of the printed surface topography in offset printing was studied and applied to electrophotography. It was found that by this application, the printed surface topography became more consistent with the paper surface topography. The results of this research, therefore, have opened the door to a new technology for controlling a print gloss matching the paper gloss.

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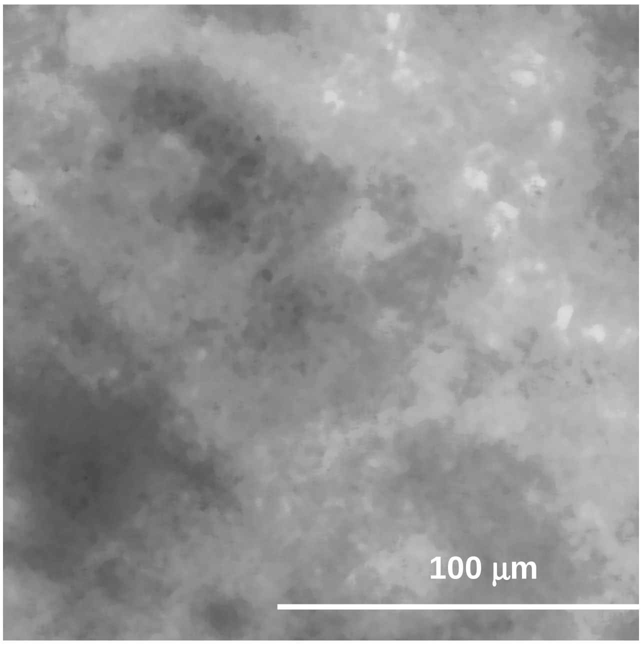
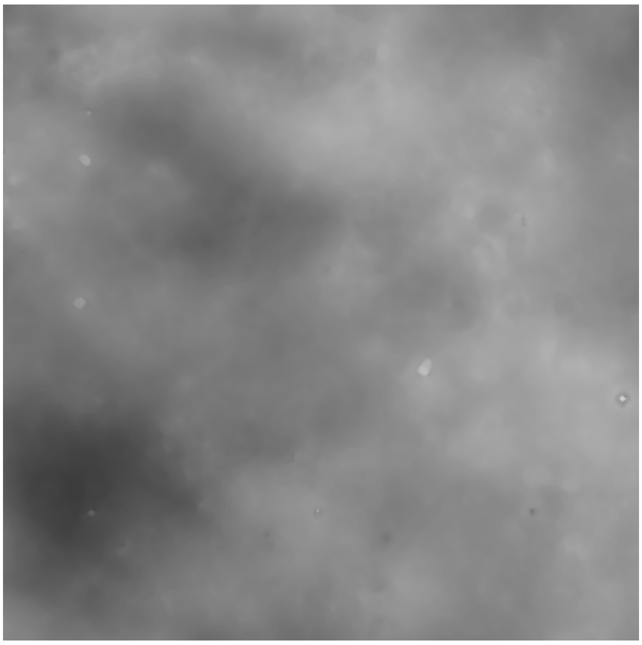
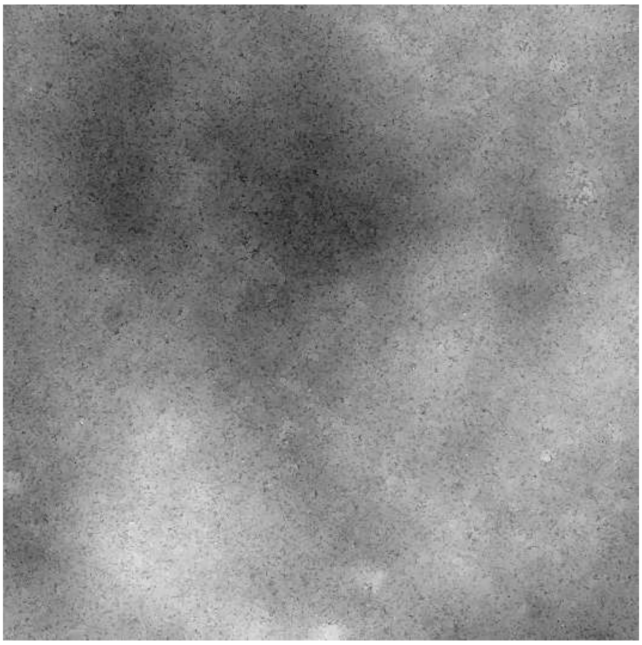


(a) Paper surface



(b) Printed surface



(c) Paper surface

(d) Printed surface

Fig.1 Topographical images of paper surface and printed surface for the standard printing condition taken during offset printing (a and b) and electrophotography (c and d) on a height scale of 10 μm and assigned to 8-bit gray levels.

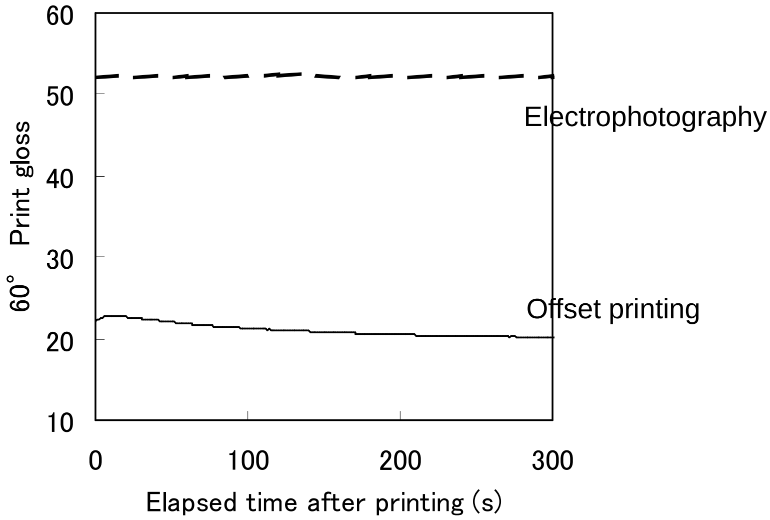


Fig.2 Dynamic print gloss for matte-coated paper.

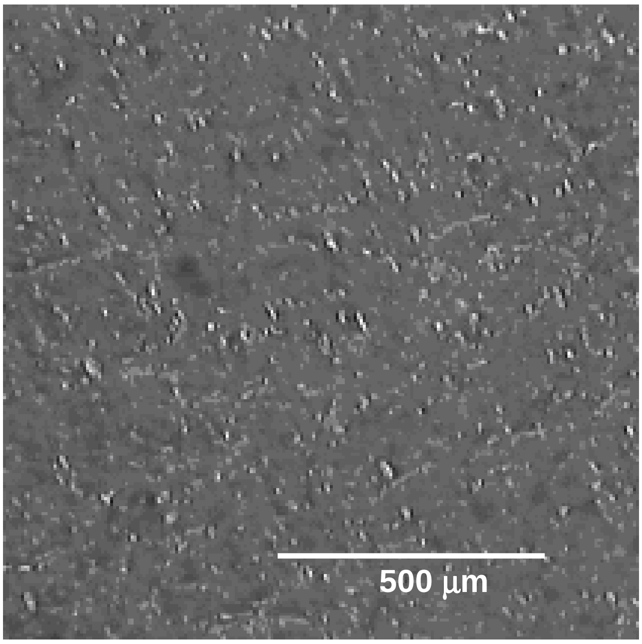


Fig.3 Printed surface topography recorded immediately after ink transfer.

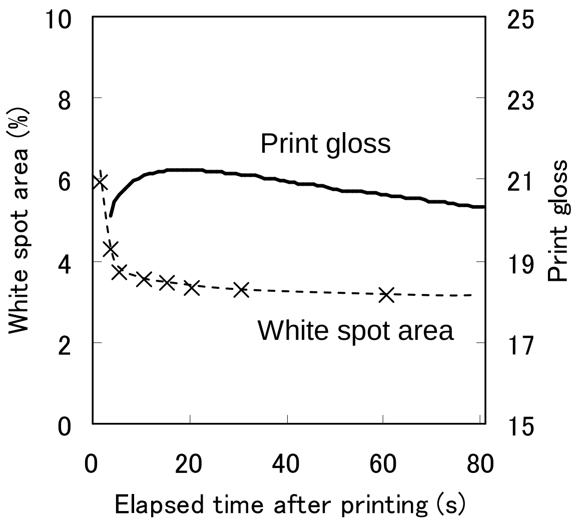
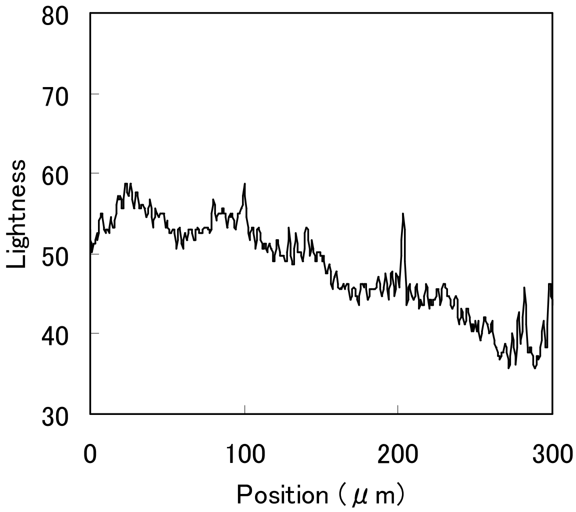
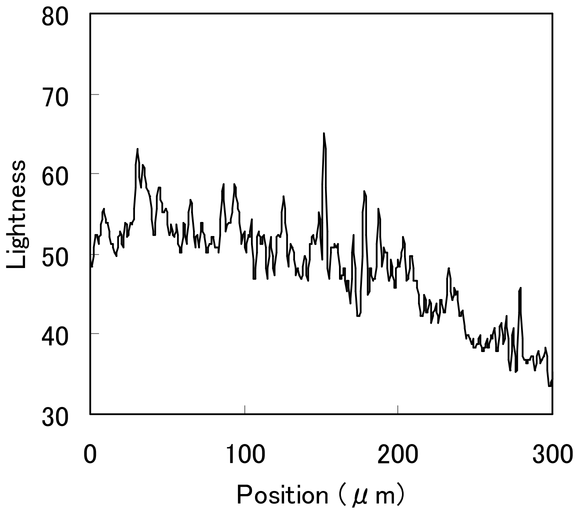


Fig.4 Dynamic print gloss and change in white spot area for matte-coated paper.

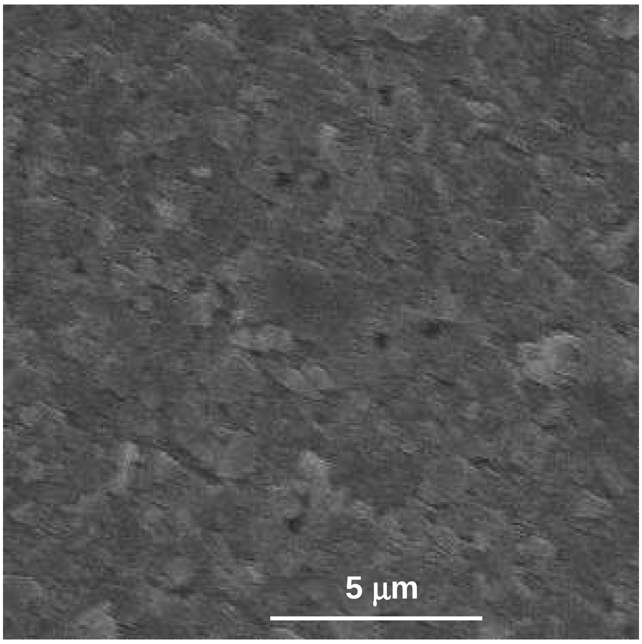


(a) 30 s

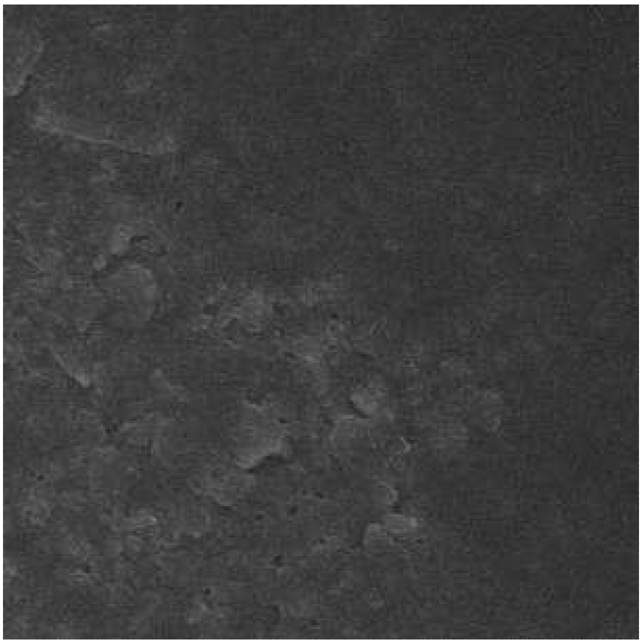


(b) 180 s

Fig.5 Profiles of ink density 30 s (a) and 180 s (b) after printing.



(a) Paper surface



(b) Printed surface

Fig.6 Scanning electron microphotographs of paper (a) and printed (b) surfaces.

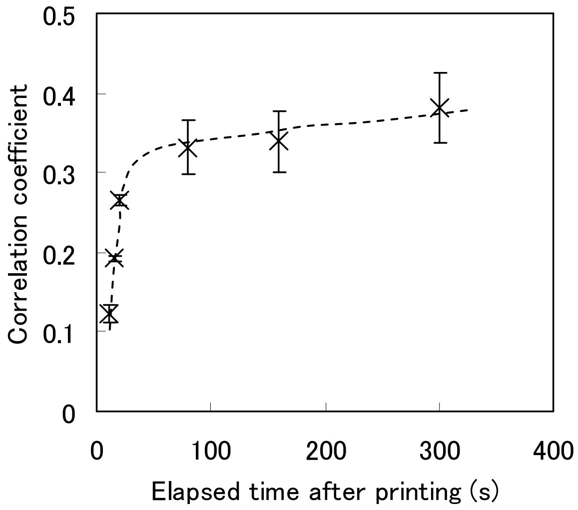


Fig.7 Change in correlation coefficient between images of paper surface profile and distribution of ink lightness.

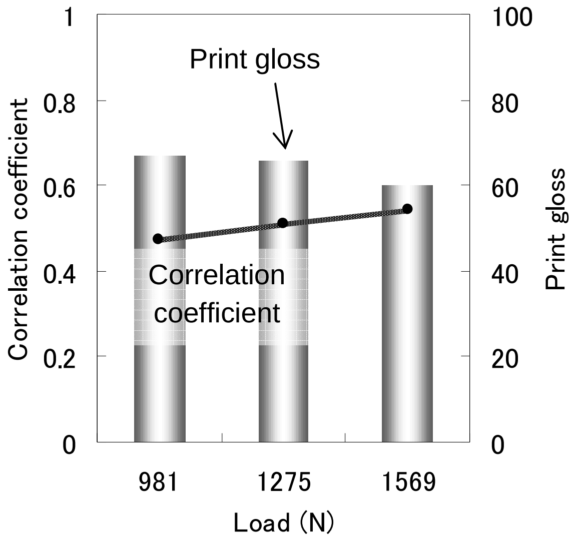
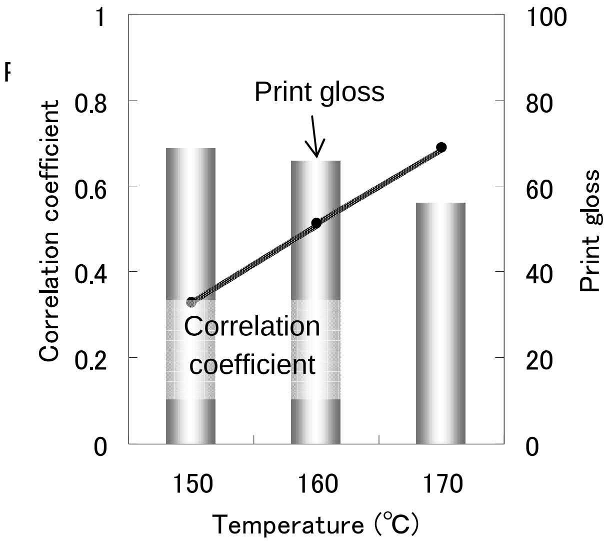
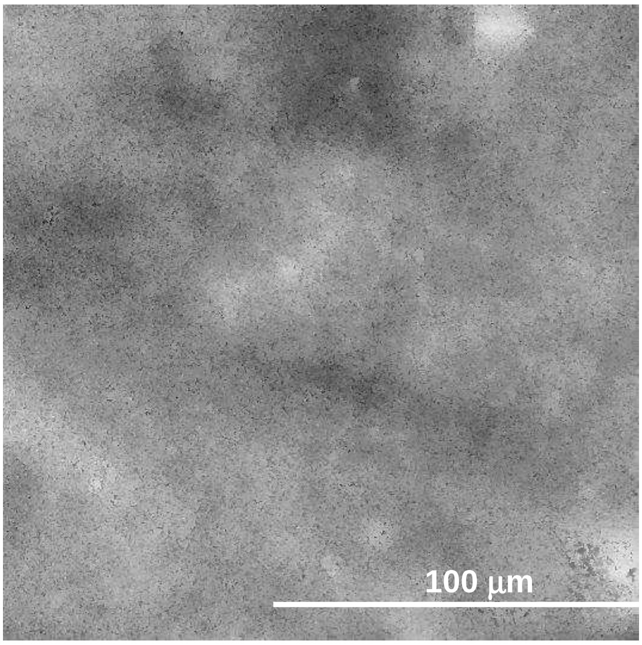


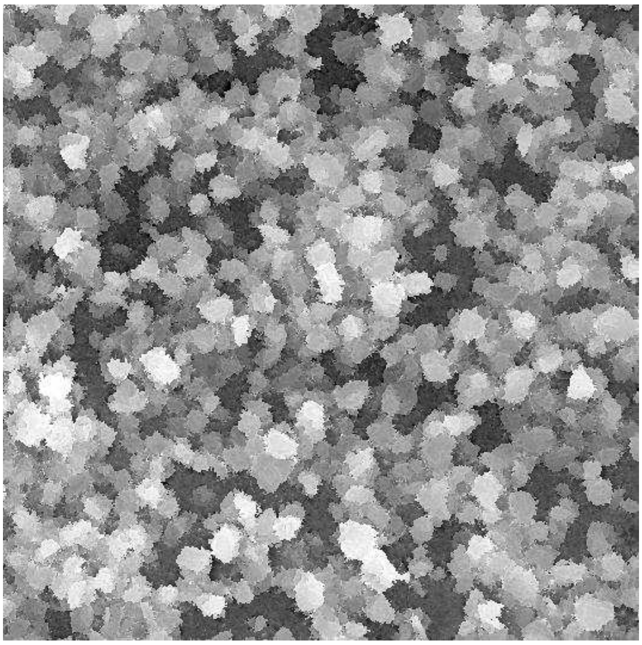
Fig.8 Effect of nip load.



1
0.8
0.6
0.4
0.2
0
Correlation coefficient
100
80
60
40
20
0
Print gloss
Print gloss
Correlation coefficient
150
160
170
Temperature (℃)



(a) Paper surface



(b) Unfused surface

(c) Printed surface

Fig.10 Topographic images of paper, unfused, and printed surfaces on a height scale of 20 μm assigned to 8-bit gray levels.

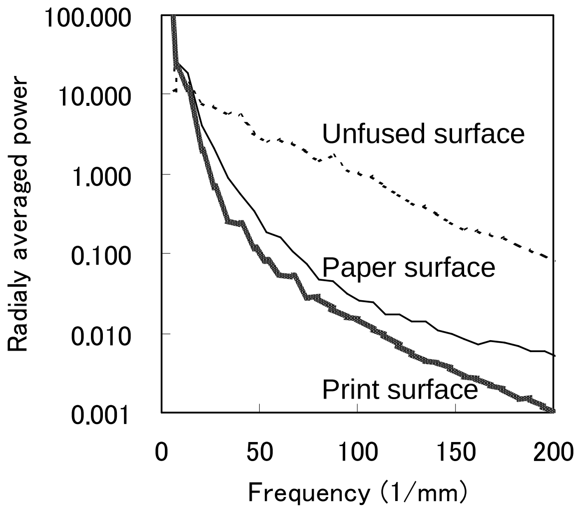
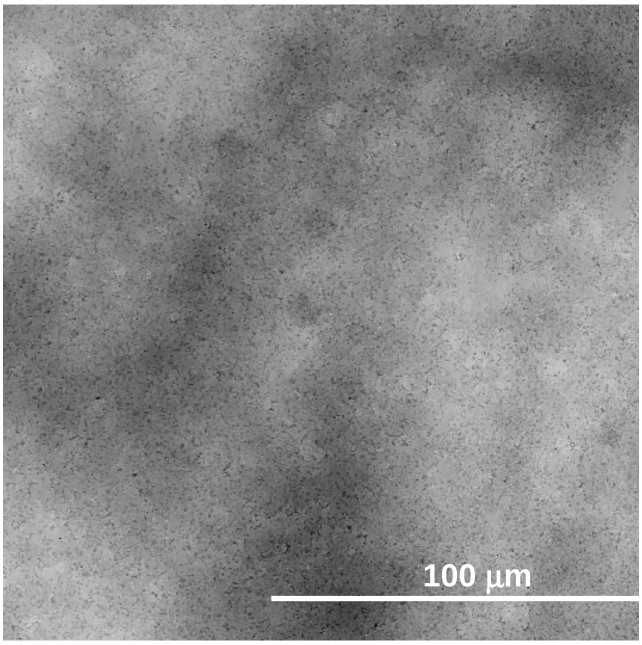
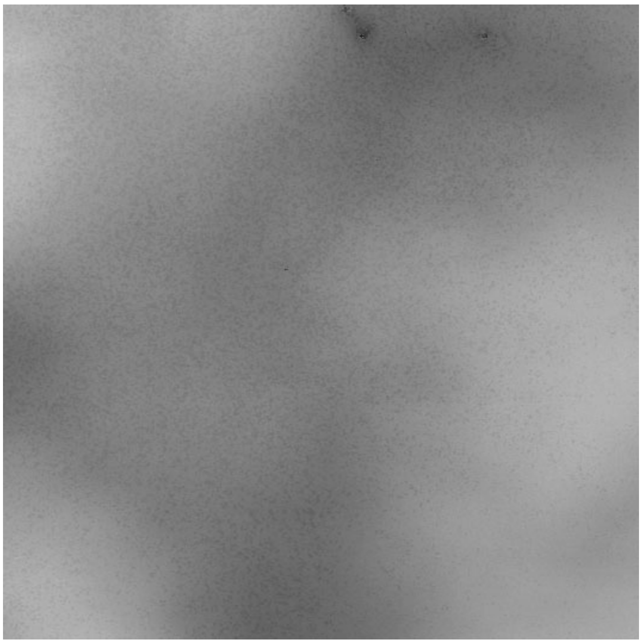


Fig.11 Frequency characteristics of surface topography.



(a) Paper surface



(b) Printed surface

Fig.12 Topographical images of paper surface and printed surface formed in electrophotography following offset printing mechanisms on a height scale of 10 μm and assigned to 8-bit gray levels.

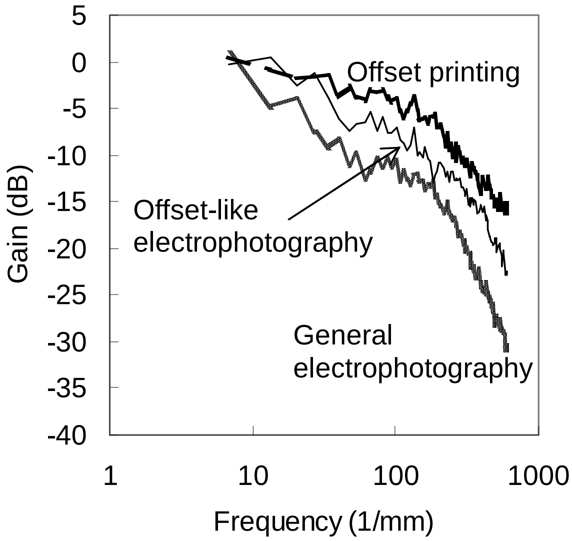


Fig.13 Comparison of transfer functions.

Table 1 Peak frequency of surface topography.

Paper suface (1/mm)	Unfused surface (1/mm)	Printed surface (1/mm)
13.5	13.5	
26.9	26.9	
	40.4	40.4
60.6	60.6	
		67.3
		80.7
87.5	87.5	
107.7	107.7	
121.2		
134.6		
	141.3	141.3
148.1		
	161.5	161.5
168.2		
		188.4
195.2		

Table 2 Comparison of print gloss and correlation coefficients between paper and printed surface topography.

	Offset printing	General electrophotography	Offset-like electrophotography
Print gloss	19.1	51.3	44.2
Correlation coefficient	0.88	0.66	0.78