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Effect of Roughness of Low-Grammage Coated Papers on Print Quality in Color Electrophotography

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Abstract. *The demands for high electrophotographic color print quality emphasize the importance of the paper surface. This work demonstrates the effects of the surface roughness and coating layer characteristics of low grammage coated papers on print mottle. Samples were prepared using different coating techniques, different coating formulations and different coat weights and by changing the calendering conditions to give different surface morphological properties. Print mottle was strongly dependent on substrate roughness. The impact of the surface topography was further demonstrated at different transfer voltages, and when the moisture content or resitivity of the paper was changed, where significant differences were found in print mottle especially when the paper was rough. Surface topography can be optimized by a suitable combination of surface treatment and finishing parameters to give a surface texture with good toner-recipient properties. © 2008 Society for Imaging Science and Technology.*
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INTRODUCTION

Electrophotographic dry toner color printers have developed significantly during recent years. Paper path, fuser and toner transfer system developments in high-end machines have made production color printing possible on a wide selection of substrates. Especially in graphic printing applications, print quality has to be high with low print mottle. Experimental studies of the effect of substrate roughness on print mottle with conventional printing methods have frequently been reported.[1–4] This has been addressed to a lesser extent in dry toner electrophotography, although the negative effect that substrate roughness has on the quality of electrophotographic color prints, especially in high-speed printing, is well known in the industry. Several investigations reported in the literature describe the inhibiting effects on toner transfer of air gaps present in the electrophotographic toner transfer nip. The mechanisms referred to are the Paschen discharge-related field collapse, the effects of air gaps on the dielectric thickness of the material stack present in the transfer nip, and the insufficiency of the net force to transfer the particle due to a lack of sufficient contact and adhesion between the toner particles and the printing substrate.[5–16]

In studies of the influence of substrate roughness on toner transfer, Rimai and Quesnel considered toner transfer to fabrics and to commercial papers and observed a failure in toner transfer in depressions of the substrate with, e.g., xerographic bond paper, ascribed to a lack of toner-paper adhesion.[16] Analogous qualitative observations were reported by Wright et al.[17] Provatas et al.[18] concluded from experimental studies that print density mottle is dependent on filler (PCC) distribution in paper and on thickness variations, but they did not indicate whether there were any differences in roughness among their trial papers. Both quantitative and qualitative effects of paper roughness on edge raggedness,[19] signal-to-noise ratio[20] and print density[21] in monochrome printing have been reported, based on sets of uncoated commercial papers. These results refer mostly to the raggedness of lines and text, and cannot be directly related to print mottle in large uniform tone areas.

The effect of a coating layer on toner transfer has been investigated by Al-Rubaiey et al.,[22] who related the amount of toner transferred to the resistivity of paper and the magnitude of the transfer current. They also compared calendered and uncalendered samples, and found that the former promoted more efficient toner transfer. In their study, this positive influence of calendering on transferred toner amount was explained as being due to an increase in density of the paper, and the possible effect of the smoother paper surface was not discussed.

The effect on the electric field in the toner transfer nip of the dielectric thickness of the materials present, including the air gap due to paper roughness, has been modeled using capacitor models,[10,23–27] where the paper is often considered to be a uniform material. Considering non-uniform paper properties in the transfer nip, Cassidy et al. and Provatas et al.[18,23,24] concluded, based also on their earlier results, that toner print density variations are due to variations in thickness and in filler distribution. Kallunki et al.[25] presented a continuum model and investigated the influence of substrate roughness on the electric field in the toner transfer nip. The field force variations due to paper roughness calculated from

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their model correlated well with the transferred toner layer thickness in cross-sectional studies of a printed sample.[25,28] Tong et al.[27] recently developed a three-dimensional model to calculate the electric field influenced by the simulated paper structure and extended the analytical one-dimensional model by analogy with the models of Yang and Hartmann[29] and Kallunki et al.[25]

There is a lack of quantitative information regarding the influence of paper roughness on toner transfer and on the subsequent print mottle. The impact of different surface treatment techniques combined with different surface finishing conditions on the print quality achieved in different conventional printing presses has been investigated extensively, but to our knowledge no such study has been published with respect to electrophotography.

The aim of the present work was to evaluate the influence of roughness of low grammage single-coated papers on print mottle. Samples with different surface structures were created using different coating techniques, different coating formulations, different coat weights, and different finishing conditions in order to study further the mechanism of print mottle in relation to toner transfer efficiency. Samples were printed on a commercial high-end color printer in a controlled environment [23°C, 50% relative humidity (RH)]. Selected samples were also printed in a bench-scale test system operated at different transfer corona voltages to clarify the role of air breakdown effects in the development of print mottle on this type of material. To gain additional information on the origin of print mottle with rough paper substrates, the same subset of samples was conditioned to six different moisture contents between 24 and 71% RH at 23°C, and printed on the commercial printer.

EXPERIMENTAL

Samples and Printing Trials

Internally sized wood-free 80 and 90 g/m^2 commercial base papers were pilot coated using blade and filmpress coating techniques at a speed of 800 m/min. Different coating formulations were used and their rheologies were adjusted to give differences in coating layer structure. Three basic coating formulations were used: Coating dispersions 1 and 3 consisted of 75 parts of engineered ground calcium carbonate with a narrow particle size distribution and 25 parts of fine Brazilian kaolin with respectively 11 parts of styrene/butadiene and 11 parts of styrene/acrylic latex. Dispersions 1 and 3 differed in latex type. Coating dispersion 2 consisted of 100 parts of engineered ground calcium carbonate with a narrow particle size distribution, and 11 parts of styrene/butadiene latex. In all the coating recipes, the following additives were used: 0.5 parts of sodium carboxymethyl cellulose, 0.5 parts of fully hydrolyzed polyvinyl alcohol, 0.5 parts of calcium stearate, 0.3 parts of synthetic alkali-swellable emulsion, and 1.3 parts of a sulfonated stilbene derivative. Three different coat weights were targeted: 6, 9 and 12 g/m^2 per side, and different roughness levels and different surface structures were obtained by varying the nip pressure in the soft calender which was operated at 150°C, 0 kN/m, 25 kN/m and 150 kN/m nip pressures. In all, 69 different two-sided coated papers were produced. As far as possible, the coat weight was the same on both sides of the paper. This selection of papers showed a Print-surf roughness (1.0 MPa) range from 1.4 to 6.2 μm, a grammage range from 91 to 117 g/m^2 and a thickness range from 93 to 133 μm.

Table I. Papers conditioned to different moisture contents. Each set A…F contains six papers having Print-surf roughness values of 1.3, 2.0, 2.6, 3.1, 3.8 and 4.0 μm, with the same grammage (measured values 103–106 g/m^2), the same coating formulation (dispersion 1) and the same coat weight (12 g/side). Differences in smoothness were created with calendering (none, 25 kN/m, 150 kN/m; nip temperature 150°C), and coating method (blade and filmpress).

Set	Paper RH at 23°C, range [%]	Abs. moisture range [%]
A	24–25	2.6–2.9
B	32–33	3.3–3.5
C	42–43	3.7–4.3
D	49–50	3.8–4.5
E	58–61	4.8–5.4
F	70–71	5.7–6.2

All the samples were printed on a commercial color printer using conventional two-component polyester-based toners. This machine creates the four-color image on an intermediate transfer belt, and transfers the image to the paper substrate in a single transfer step using a biased transfer roller. The printing speed was 60 A4 pages per minute and the printing was carried out under standardized laboratory conditions (23°C and 50% RH).

A sub-set of papers having different moisture contents was also printed on the same machine in order to clarify the effect of surface roughness when the paper resistivity varied. These substrates were, however, printed in a laboratory environment of 23°C and 50% RH, so it is reasonable to assume that some re-conditioning occurred before toner transfer in the printer. In this sub-set, all the samples had the same base paper, the same coating formulation and the same coat weight, so that any differences in print mottle at a given paper moisture content or given resistivity can be related to differences in roughness, coating layer structure or thickness (density) of the paper. Table I shows the relative humidity and moisture levels of these papers immediately before printing.

This same sub-set of samples was further printed in an electrophotographic bench printer (Torrey Pines Research) using different transfer voltages. This device transfers toner layer from the photoconductor drum directly to paper utilizing a corona wire. The trial was carried out to examine line quality and see whether patterns could be observed in the printed samples which would indicate air breakdown discharges occurring at the locations of surface cavities, and to evaluate the possible contribution of this mechanism to print mottle. These prints were made in a 40% RH, 23°C environment at a printing speed of 10 cm/s using a conventionally prepared two-component cyan toner.

Print Quality and Paper Property Measurements

Print mottle was evaluated numerically with a scanner-based mottle measurement system, (TAPIO PapEye, manufactured by TAPIO Technologies). The sample is scanned with 300 dpi resolution in the grayscale mode and wavelet analysis is applied to calculate values for different band widths (0.17, 0.34, 0.67, 1.34, 2.54, 5.1, and 10.2 mm) of the image. From these values, a single mottling value is calculated which is a weighted average of several bandwidths. Weighting is based on the sensitivity of eye to different size defects. The area scanned for each measurement was 9 cm^2. Four printed sheets were measured per trial point. Print mottle was measured from full-tone single toner layer areas (100% C, M, Y and K) and from full-tone areas of two toner layers (200% R, G, B). Print mottle defects were studied with a light microscope. With the commercial printer, a very light raster could be observed due to image processing algorithms of the printer. This did not influence the comparison of print mottle between the trial points. The pattern was very mild and was different in size and type from the typical print mottle defects observed. All samples in each trial series were printed at the same time with identical settings.

Paper surface roughness was characterized using a Print-surf instrument (Lorentzen & Wettre) with 1.0 MPa clamping pressure, in accordance with ISO 8791-4. This measurement provides an average paper roughness, based on the air flow between the measuring head and the substrate. The measurement device converts this airflow into a roughness value and reports the result in microns: the Print-surf roughness $[\mu\text{m}]=kQ^{1/3}$, where k is a geometric constant and Q is the air flow rate between measurement head and sample. Surface profiles of selected samples were obtained using a Rodenstock RM-600 white-light laser profilometer operated at 5 mm lines using 2.5 μm steps and with a depth resolution less than 1 μm. Volume and surface resistivities were measured with a high resistance meter HP 4339B with resistivity cell HP 16008B, in accordance with ASTM D257-78, using a test voltage of 100 V and a charge time of 30 s, with ten replicate measurements.

RESULTS

Effects of Coating Formulation, Structure and Surface Finishing Conditions on Print Mottle

The effects of coating formulation, structure and finishing conditions on the print mottle of the prints produced with the commercial printer under standard conditions (50% RH, 23°C) are shown in Figure 1. In this sample set, the surface roughness had a greater effect on the print mottle, particularly in the 100% areas, than the coating formulation. The small changes in mineral composition did not lead to any substantial differences in print graininess when the paper was smooth. An increase in coat weight, on the other hand, reduced the print mottle since it clearly changed the topography of the substrate. There were also obvious differences at low coat weights, which can mainly be ascribed to effects of coating layer uniformity. The figures also suggest that different roughness regions have different scatters and levels of print mottle. A small linear increase in the print mottle was found up to a print-surf roughness level of 3–3.5 μm, after which the increase was steeper with substantially more scatter. Print mottle at low roughness levels, below approximately Print-surf roughness of 3 μm, was thus at the same level regardless of coating method, coat weight or coating formulation. At higher roughness levels, the characteristics of the coated papers began to have a greater influence on the print quality, where coating method, formulation and particularly coating uniformity played a role.

Figure 1 shows further that, since calendering increased the smoothness and increased the density of the papers, it resulted in a lower print mottle and also less scatter in the print mottle. A comparison of uncalendered and calendered samples indicates that the effect of roughness dominated over the effect of density with these low grammage papers. This is supported by the fact that at a given roughness level no significant effect on print quality was seen when the type of base paper (80 or 90 g/m^2) was changed, except for the few roughest trial points. In those few cases, the 80 g/m^2 base paper gave a lower print mottle.

At higher roughness values, i.e., a Print-surf roughness level higher than 3 μm, the print mottle of higher toner coverage areas (200%) increased and was clearly greater than the print mottle of the 100% toner layer areas. Overall, the scatter in the 200% toner layer print mottle was much greater than that in the 100% areas. In the 200% areas, it was evident, considering the increase in scatter, that the roughness alone cannot fully explain the print mottle. When the toner layer thickness was increased, the print mottle seemed to be more dependent on coating layer uniformity, and thus on the uniformity of the dielectric thickness of paper.

Higher coat weights (12 g/m^2) give a better base paper coverage, which gives a smoother surface and better coating layer continuity and apparently a relatively low print mottle. Substrates with lower coat weights but the same roughness displayed a slightly greater tendency to give print mottle, indicating a dependence on coating layer structure and continuity. The print mottle of the 200% areas seemed also to be slightly more dependent on the coating formulation, which can be an indirect effect of the fact that differences in rheological and consolidation behavior lead to differences in coating layer structure. Filmpress coating gave slightly better print results than blade coating at higher roughness levels, when coating with 9 or 12 g/m^2 per side. This implies that, with those coat weights and coating formulations, the filmpress coating created a structure with more uniform dielectric properties at a given smoothness level, since the dielectric properties of the coating layer and base paper were different. Typically, the filmpress method gives a coating layer with a more uniform thickness following the topography of base paper, while blade coating first fills the voids in the base paper surface with coating dispersion and consequently gives a coating layer with varying thickness.[30,31]

Print mottle defects observed at higher roughness levels were also subjected to qualitative evaluation in photomicrographs of the printed surfaces. Considering the type and

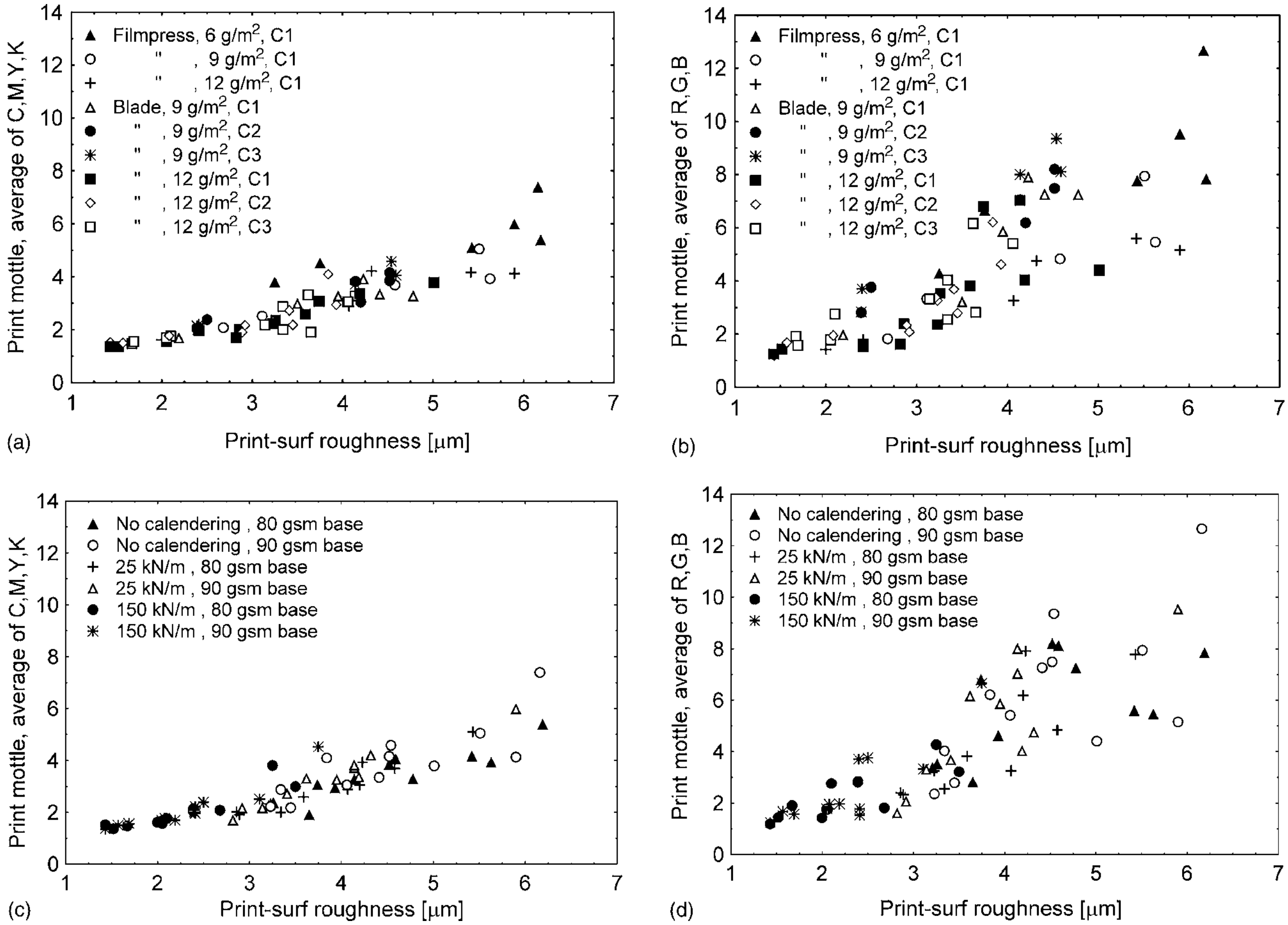

Figure 1. Average print mottle of 100% toner layer areas (left) and 200% toner layer areas (right) vs paper roughness. Filmpress- and blade-coated pilot papers with different coat weights [g/m^2] and different coating dispersions C1, C2 and C3 (top), and effect of base paper grammage and calendering (bottom). Printed at 50% RH, 23°C.

shape of the defects, it was evident that the print mottle defects originated in the toner transfer phase and not in the fusing of the toner. With 100% toner layer areas, toner transfer was incomplete on papers with the highest roughness levels, which had deep cavities on the surface. In such cases, the rough paper showed small areas completely lacking in toner due to incomplete toner transfer. In the case of 200% toner areas, transfer had not been sufficiently efficient with rough papers and the topmost color layer was often missing at locations where there was a valley on the surface of the rough substrate. In most such locations, the 200% toner stack had split but had still transferred partially onto the paper, Figure 2.

Effect of Substrate Roughness on Print Mottle in the Case of Papers Conditioned at Different Humidities

The effect of coated paper roughness on print mottle was investigated when the humidity and thus the resistivity of paper was varied. Six papers with the same base paper and the same coating composition were conditioned to six different moisture levels, Table I. Both the volume and surface resistivities of the paper decreased exponentially with increasing moisture content, which is in agreement with previous findings.[6,32] The surface resistivity declined at a slightly

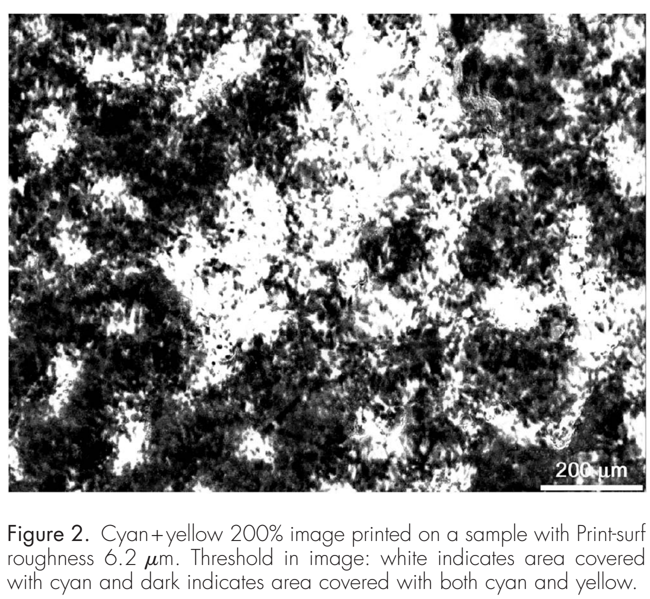

Figure 2. Cyan+yellow 200% image printed on a sample with Print-surf roughness 6.2 μm. Threshold in image: white indicates area covered with cyan and dark indicates area covered with both cyan and yellow.

lower rate than the volume resistivity especially for samples conditioned at 40% RH and above, since fibers in the bulk of the coated sheet absorb most of the moisture available at higher RH levels. The data presented in Figure 3 show that

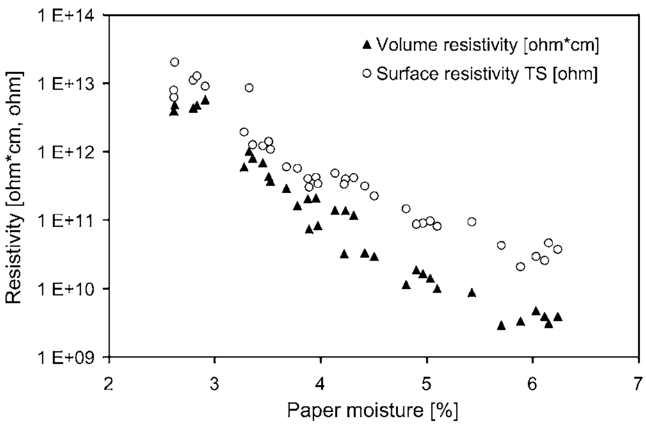

Figure 3. Volume resistivity and top side surface resistivity (100 V, ASTM D257-78 standard) measured on paper samples conditioned to different moisture contents.

the papers in this set cover the resistivity range of papers normally used in electrophotographic printing.[15,33] Since these papers were printed on a commercial printer located in a room with standard conditions (50% RH, 23°C), they were exposed to the printing room environment for as short a time as possible (a few seconds) before printing. Some re-conditioning may have occurred especially at the lowest moisture content trial points, but this was not severe since clear resistivity-related print mottle differences were observed in the print results.

Figure 4 shows the print mottle of 100% and 200% toner layer areas printed on papers with different smoothnesses and different moisture contents. In the 100% toner layers (average of *C*, *M*, *Y* and *K* areas) the effect of paper roughness on print mottle dominates over the effect of moisture content. In the 200% toner layers, the impact of rough paper surface on print mottle is clearly emphasized when the paper has a high resistivity (i.e., when the moisture content is 3.5% or lower). This effect could be seen especially with small band widths, Figure 5, corresponding to the defects observed in microscopy evaluations.

Effect of Transfer Voltage on Print Quality for Substrates with Different Roughness Levels

To study the possible influence of Paschen air breakdown on lines and solid areas, print tests were made at different transfer voltages on a bench printer (Torrey Pines Research). The same samples as used in the previous section were conditioned at 40% RH, 23°C before printing 100% cyan toner areas with different corona wire voltages.

The print mottle of the 100% cyan area (8×8 cm) was in this case lowest with a transfer corona voltage of 3800–3900 V, Figure 6. In the region of optimal transfer voltage, a similar dependence of print mottle on roughness was observed as with the commercial printer. At voltages which were clearly too low there was insufficient toner transfer due to too low (or no) a charge density on the paper surface. At high voltages, the 8×8 cm toner area was destroyed by wide periodical lines due to discharging and mechanical stress or vibrations when the sheet separated from the photoconductor after being strongly adhered to it electrostatically.

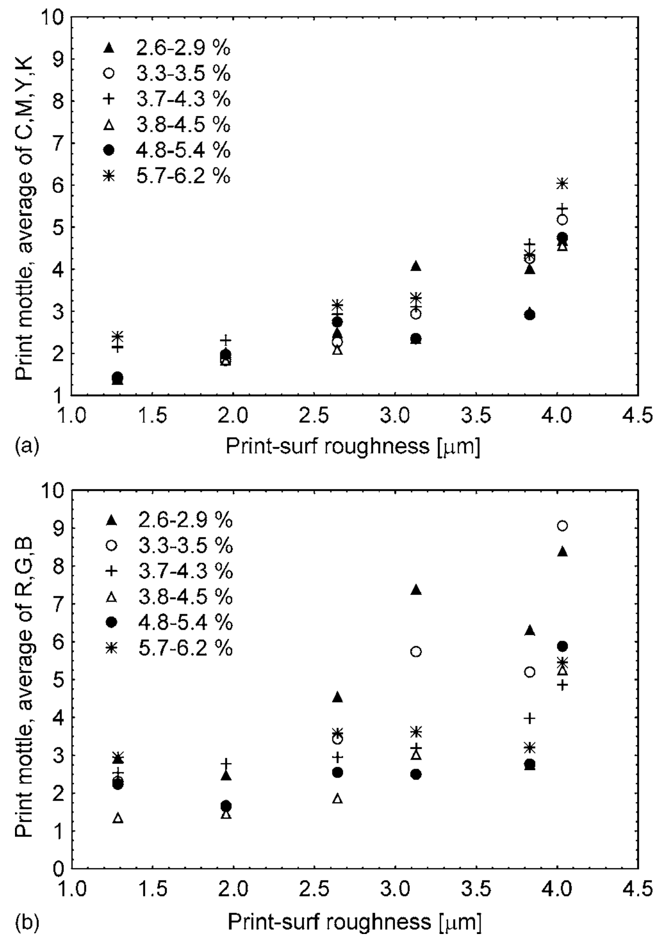

Figure 4. The effect of paper roughness and moisture of paper on average print mottle for 100% toner layer areas (a) and 200% toner layer areas (b).

Figure 7 shows photomicrographs of 1.35 mm wide lines printed on the bench printer using different transfer corona voltages. When the voltage was too high, the trailing edge of the line pattern became ragged. At the nip exit, the Paschen discharge limit is reached and the line edge can become distorted,[19,34] but the defects observed in line edges in Fig. 7 are different from typical Paschen defects shown, e.g., in Ref. 12. It is also interesting that the line edge was more ragged on the smoother paper. One possible explanation could be that charges penetrate through the paper and neutralize the toner charges more easily with a smooth paper which has a higher density. In the middle regions of printed lines, there were no patterns that could be related to an electric field discharge due to too wide an air gap present in the toner transfer nip, even when the transfer corona voltage was so high that lines became ragged.

A topographical analysis with a profilometer on an uncalandered sample having a Print-surf roughness of 5.0 μm showed differences between cavity bottoms and peak tops less than 3 μm, as shown in Figure 8. The maximum thickness of the air layer that such a paper could introduce into the nip is smaller, because the paper is pressed

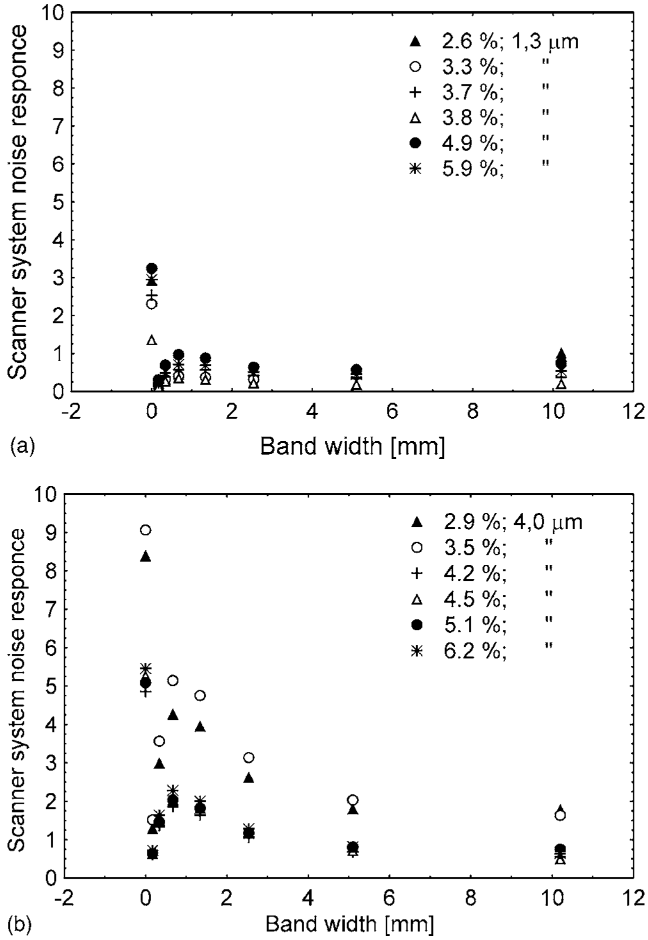

Figure 5. Print mottle measurement system response measured at different bandwidths. Average of 200% toner layer areas, papers with Print-surf roughness 1.3 μm (a) and 4.0 μm (b).

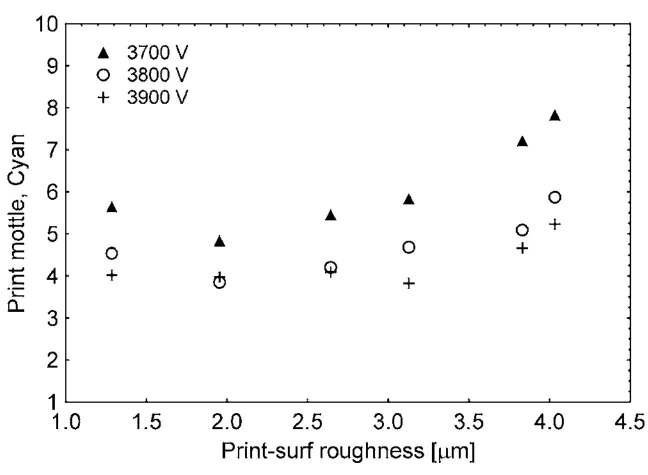

Figure 6. Print mottle of cyan 100% area, printed on a test bench unit with transfer corona voltages 3700, 3800 and 3900 V.

against the toner layer in the nip. The Print-surf roughness, a method widely used in paper industry, agrees fairly well with the R_a-values of the profilometer (the arithmetic mean roughness profile) for rough substrates.[35] However, the correlation between profilometer data and air-flow data depends on the wavelength of variations of the surface topography.[36] The topography information in Fig. 8 can be compared with the Paschen air breakdown curve. If air breakdown were the cause of the print mottle occurring with such coated samples, even when taking into account the air in the toner layer, the electric field would need to be much higher than that normally used in printers. Typical fields used in a toner transfer nip mean that the gap needs to be less than 8–10 μm to avoid air breakdown.[37] Similar topography observations were made with other substrates indicating that, with this type of coated substrate, the distance between peaks in the surface topography is more important for print mottle defects than the maximum depth of the surface depressions.

DISCUSSION

The results demonstrate the impact of coating and finishing conditions on print mottle. The low-grammage coated papers, made of the same finish and with relatively similar coating formulations, enabled the effects of substrate roughness and coating layer structure to be studied. The thickness of both coating layer and base paper, the density and the coating coverage were altered by changing the coating and finishing conditions. The main emphasis in this study was, however, on the influence of paper surface roughness, coating layer topography and structure on print mottle.

In this set of low-grammage coated papers, the print mottle in the 100% and 200% areas correlated strongly with paper roughness but not with small changes in grammage or in surface resistivity. In the 200% areas, roughness alone could not explain print mottle to the same extent as in the 100% areas. The correlation coefficients between print mottle in the 100% areas and roughness, density, grammage and surface resistivity at 50% RH, 23°C were 0.90, −0.71, −0.26 and 0.04, respectively, and the corresponding correlation coefficients in the 200% areas were 0.83, −0.79, −0.29 and 0.05, respectively. There was also a correlation between print mottle and the density of the paper, since the density correlates with the roughness (correlation coefficient between these properties was −0.81). A regression analysis showed, however, that in the 100% areas, the roughness gave the greatest contribution to the print mottle and not the density of the paper. In a linear regression analysis of the above properties where the dependent variable was print mottle in the 100% areas ($R^2=0.86$), the regression coefficient for roughness was 0.98 and for density only 0.08. In the case of the 200% areas ($R^2=0.79$), the regression coefficient for roughness was 0.56 and for density −0.35.

Since it was concluded that a Paschen discharge was not the mechanism behind the unevenness of printed areas, a possible cause of print mottle is that the electrical field in the toner layer is insufficient for complete toner transfer due to air gaps present in the nip and/or a lack of toner-paper contact.[13–16] In this case, it is necessary to evaluate the distances between peaks, or the width of the cavities, and not only the depth of cavities when investigating the causes of the print mottle. These distances predict the area and volume of cavities in paper surface and thus the probability in

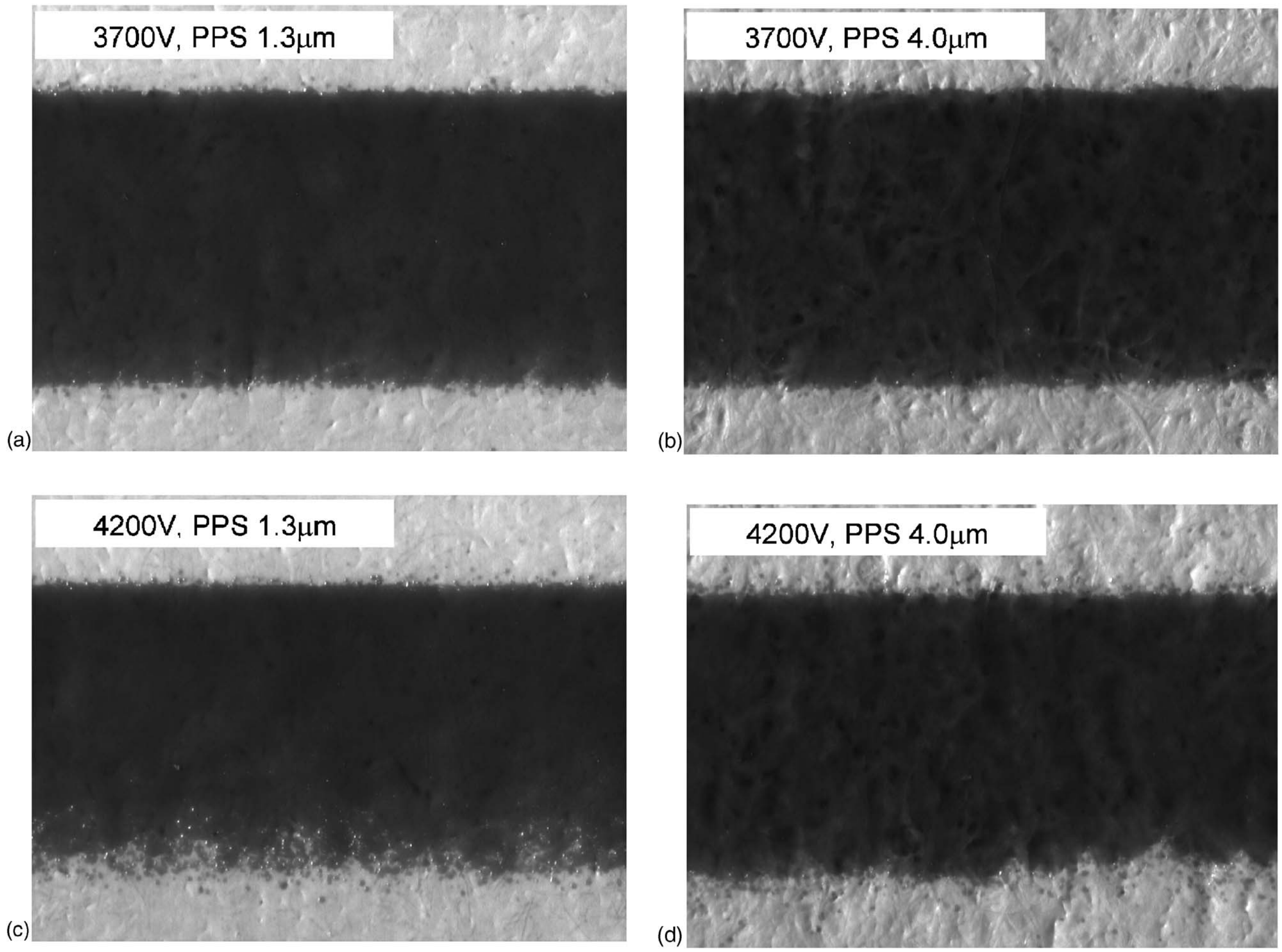

Figure 7. Cyan line (width 1.35 mm), printed with transfer corona voltages 3700 and 4200 V. Top edges of lines have been transferred first. Paper samples with Print-surf roughness 1.3 and 4.0 μm.

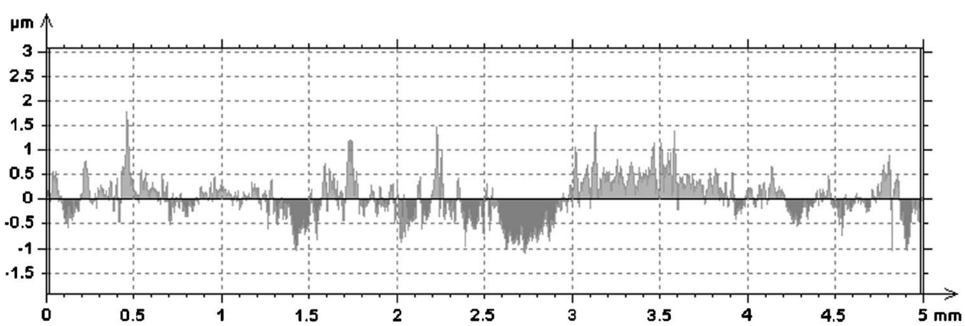

Figure 8. Profilometer data of blade coated (11 g/m^2) uncalandered sample with Print-surf roughness 5.0 μm.

a particular case that there is an air gap between toner layer and paper surface in the transfer nip. Profilometer data in Fig. 8 present several locations in which the distances between peaks correspond to typical defects seen in the microscopy analysis and to data presented in Fig. 5, where most of the print mottle defects caused by an increase in roughness were detected in band widths of 0.17–0.67 mm. The number and frequency of this type of topographical texture is thus significant for print mottle.

Since the correlation between print mottle and roughness was stronger for 100% areas than for 200% areas, and since in 100% areas toner had not transferred at all to the deepest cavities in the paper surface, paper contact and adhesion are critical for transfer, as reported by Rimai and Quesnel.[16] When there are fewer toner particles, it is more probable that these are unable to conform to a rough substrate surface in the transfer nip and air gaps will thus remain between the toner particles and the paper. The necessity of toner layer-paper contact is supported by the fact that changes in moisture content (resistivity) of the substrate and variations in material parameters which locally influence the dielectric evenness of substrate had less influence on print mottle in the 100% than in the 200% areas. These air gaps also reduce the electric field.[25]

In the 200% areas, the toner particles nearest to the paper were normally also transferred in regions of depression in the paper surface, indicating the importance of adhesion and contact. In addition to toner-paper adhesion, contact also causes movement of particles in the toner layer, which reduces adhesion forces between the particles[38] and facilitates transfer. When toner-paper contact exists, the electrical field in the toner layer determines the location from which the toner layer separates in case of an incomplete transfer. In this case, variations in the electric field influenced by local variations in substrate properties affect more directly the amount of toner transferred.

The effects of air gaps in toner transfer may also be approached by using a continuum model and the Maxwell equations.[10,23–27] This approach has limitations in the case of paper in a dynamic transfer nip, since paper has a time-dependent charge development and contains charge carriers with a certain mobility. Paper has a complex, non-uniform structure, the complexity of which cannot be taken fully into account in a relative simple continuum model. Conduction in paper is assumed to be ionic and the mobility of these ions is dependent on the moisture content of paper,[39–43] so there is normally a density of free charges in paper. Also, since the dielectric properties of paper depend on the frequency and moisture,[44] the time available may be insufficient for a complete dielectric orientation during toner transfer, at least in the fastest color printers. It can thus be assumed that a static one-dimensional model approximation could best be used to describe dry paper or a paper with a minimum concentration of ions (salts) in a sufficiently slow transfer process. Since the continuum models are often utilized to describe the fields in the toner transfer nip, it is of interest to test this approach also in the present case, especially since the samples included dry papers with a reduced ion mobility. For simplicity, one-side coated paper is considered here.

The following one-dimensional continuum model is considered: four stacked uniform layers: base paper (thickness d_b, dielectric constant ε_b), coating (d_c, ε_c), air (d_a, ε_a) and toner layer (d_t, ε_t). The charge density ρ is zero in all layers other than the toner layer. The Poisson equation for toner layer can be written as

$$\frac{\partial^2 \phi_t(z)}{\partial z^2} = -\frac{\rho_t}{\varepsilon_t}. \tag{1}$$

The boundary conditions for potential ϕ are V_0 at $z=0$ (the lower surface of paper, which is not printed on) and zero at the top of the toner layer ($z=d_b+d_c+d_a+d_t$). Then, by analogy with Kallunki et al.[25] but including the coating layer, the field component in the toner layer perpendicular to the paper surface (i.e., in the z direction) is

$$E_t = \frac{1}{\varepsilon_t\left(\frac{d_b}{\varepsilon_b}+\frac{d_c}{\varepsilon_c}+\frac{d_a}{\varepsilon_a}+\frac{d_t}{\varepsilon_t}\right)}\left(V_0-\frac{\rho_t d_t^2}{2\varepsilon_t}\right) + \frac{\rho_t}{\varepsilon_t}(z-d_b-d_c-d_a). \tag{2}$$

The field can be approximated by inserting values[45–47] of transfer voltage and negatively charged toner in Eq. (2), $V_0=3000$ V, $\rho_t=-10$ C/m^3, $\varepsilon_t=2$, and using toner layer thickness $d_t=10$ μm. The relative permittivity of the base paper (ε_b) is in this case approximately 3 at 100 Hz frequency. The data of Simula et al. indicate that the relative permittivity of the pigment coating layer is significantly higher than that of the base paper.[44] In this numerical evaluation, a rough estimate is used, $\varepsilon_c=5$.

We can now estimate electric fields for some extreme cases in this work, keeping in mind the assumptions made. Such cases are a smooth paper with 12 g/m^2 coating and 80 g/m^2 base paper, and a rough, slightly coated 90 g/m^2 base paper with an uneven coating distribution. At a location on a 90 g/m^2 base paper ($d_b=108$ μm) which has a 9-μm-deep cavity covered with 3 μm coating (6 μm air in the transfer nip due to paper), the calculated field in the middle of a 10 μm toner layer is 29 V/μm. For an 80 g/m^2 base paper which has a thickness of 96 μm, a 12 μm coating layer and no air gap, the corresponding value is 36 V/μm. Such differences can be used in part to describe the influence of different papers on the electric field. To estimate the amount of toner transferred onto a rough substrate, it is, however, necessary to consider also the adhesion forces between materials in the transfer nip.

CONCLUSIONS

The surface topography and texture of low-grammage coated papers had a strong impact on the print mottle obtained with printers utilizing conventional toners, where smooth papers gave high-quality print results. Blade coating creates smoother surfaces than filmpress-treated papers, but it is possible in the case of a filmpress application to create synergistic effects with calendering, to give an optimized surface or toner-receiving layer. Since print mottle defects on rough substrates were not in this case caused by electrical discharges, it was more important to characterize the distances between peaks in the surface topography rather than the depths of cavities. Toner-paper contact was shown to be important for efficient toner transfer. Parameters having a local influence on the electric field became increasingly important with higher toner coverage.

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