Estimating ink mileage of dry toners in electrophotography

RENMEI XU AND CELESTE M. CALKINS

ABSTRACT: This work investigates the ink mileage of dry toners in electrophotography (EP). Four different substrates were printed on a dry-toner color production Xerox iGen3 EP press. The print layout contained patches with different cyan, magenta, yellow, and black tonal values from 10% to 100%. Toner amounts on cyan patches were measured using an analytical method. Printed patches and unprinted paper samples, as well as dry toners, were dissolved in concentrated nitric acid. The copper concentrations in the dissolved solutions were analyzed by a Zeeman graphite furnace atomic absorption spectrometer. Analytical results were calculated to determine the toner amounts on paper for different tonal values. Their corresponding reflection densities were also measured. All data were plotted with OriginPro® 8 software, and four mathematical models were used for curve fitting. It was found that the C-S model fitted the experimental data of the two uncoated papers better than the other three models. None of the four models fitted the experimental data of the two coated papers, while the linear model was found to fit the data well. Linear fitting was the best in the practical density region for the two coated papers. Ink mileage curves obtained from curve fitting were used to estimate how much ink was required to achieve a target density for each paper; hence, the ink mileage was calculated. The highest ink mileage was 3.39 times the lowest ink mileage. The rougher the paper surface, the higher the requirement for ink film weight, and the lower ink mileage. No correlation was found between ink mileage and paper porosity.

Application: Paper mills and printers can estimate ink mileages of EP papers and toners, which can aid in improving paper properties for higher ink mileage and help printers reduce printing costs.

The environment and human health can benefit from good manufacturing practices (e.g., less ink usage during printing), which can be achieved by choosing ink or paper with high ink mileage. Studies found that ink mileage was affected by paper surface roughness, air permeability, pore size, and ink properties such as viscosity, yield value, tack, absorption coefficient, and fineness of pigment grind [1-12]. However, previous research was done for liquid inks used in conventional printing processes, such as offset and gravure printing. Nonimpact printing (NIP) technologies have grown rapidly in the last several decades. Electrophotography (EP), one of the major NIP technologies, mostly uses dry toners. Whether ink mileage behaviors of dry toners would be similar to those of liquid inks needs to be studied.

An ink mileage curve is a plot of the reflection density of an ink film, printed on a substrate, as a function of the ink film thickness. Reflection density increases with the increase of ink film thickness until it approaches a value called saturation density, D_s. In practice, ink film thickness is difficult to measure. Therefore, ink film weight, as the mass of ink film per square meter, has been used to represent ink film thickness, and its unit is gram per square meter, or g/m². Ink film weight has been measured by the weight difference of a substrate before and after printing [1-8]. Recently, an analytical method was developed to measure it more accurately [9-12].

Four mathematical models of ink mileage curves proposed by previous researchers [1, 3-5] were used in this study. Modifications were made so that the regression coefficients had the same meaning. Parameter D_s is the saturation density of an ink film at infinite ink film thickness. Parameter m determines the steepness of density curve in the region of very thin film; this was called density smoothness by Tollenaar and Ernst [1]. Parameter n is the ink film weight exponent and was added to improve curve fitting. These models are expressed in Eqs. (1)-(4):

T-E $$D = D_s(1 - e^{-mw}) \quad (1)$$

Oittinen $$D = D_s(1 - e^{-mw^n}) \quad (2)$$

C-M $$\frac{1}{D} = \frac{1}{D_s} + \frac{1}{mw} \quad (3)$$

C-S $$\frac{1}{D} = \frac{1}{D_s} + \frac{1}{mw^n} \quad (4)$$

where w = ink film weight
D = relative reflection density
D_s, m, n = regression coefficients

Ink mileage studies have been done for liquid inks used in conventional printing processes, such as offset lithography [1-8] and gravure printing [9-12]. Calabro and Mercatucci [4] found that saturation density (D_s) depended on the characteristics of the ink and the paper. However, in a later study, Calabro and Savagnone [5] found that D_s showed very poor correlation with measured ink characteristics. Our previous studies [9-12] found that saturation density correlated with paper air permeability, pore size, and surface roughness.

Parameter *m* determines how fast the ink mileage curve approaches the saturation density by the increase in ink film thickness. Tollenaar and Ernst [1] reported that *m* correlated with the degree of contact between the ink film and the paper. Calabro and Savagnone [5] found that *m* was correlated mainly with the smoothness, gloss, and absorption values. Our previous studies [9-12] showed that *m* was correlated well with paper roughness and air permeability. Calabro and Savagnone [5] found that the ink film weight exponent *n* had a better correlation with ink rheological variables (e.g., viscosity, yield value and tack) and its optical properties (e.g., the absorption coefficient and the fineness of the pigment grind). In our previous studies [9-12], *n* was correlated with paper roughness and air permeability.

Nonimpact printing technologies have grown rapidly in the past several decades. Electrophotography is one of the major NIP technologies and has been used for commercial production printing. Electrophotography presses mostly use dry toners instead of liquid inks. In conventional printing processes, such as offset lithography and gravure, liquid inks set on paper by absorption first. In the EP process, dry toners are fused onto the paper surface by heat and pressure.

Higher ink mileage means less toner consumption. According to a white paper from Preton Ltd. [13], the manufacturing process, pollution, and disposal of toners have a huge impact on the health of the environment and humans. Each year, more than 350 million toner cartridges are used, and fossil oil and energy are used to produce them. Toner cartridges also contain toxic ingredients and volatile organic compounds (VOCs). Toxic ingredients are plastic, metal, and small amounts of rubber, paper, foam, and toner that will take up to 450–1000 years to decompose. Wikina et al. [14] studied economic considerations and environmental sustainability of printing processes and found that printing processes that used toner were harmful to the environment. He et al. [15] found that the average particle number concentration in an office during working time was 5 times higher than that during non-working time and the main submicrometer particles were mainly caused by office printers. Wang et al. [16] also reported that a large concentration of carbon-based nanoparticle emission that might threaten human health was detected from an HP4100 LaserJet printer. Recent studies by Betha et al. [17] investigated emission characteristics of ultrafine particles (UFPs) and VOCs in a commercial printing center and found that UFP concentration increased during peak printing activity. Nuclei-mode particles increased several times and were likely the source of reactions between ozone and VOCs emitted from printers. In summary, environmental and human health will benefit from environmentally friendly business practices such as less ink and toner usage.

The goal of this study was to print different substrates on a dry-toner EP press, measure their ink film weights and reflection densities, use different models to fit the experimental data to find the best one, and study the effects of paper properties on ink mileage.

EXPERIMENTAL

Substrates

In this study, four commercial paper substrates from Xerox were selected. Two of them were uncoated (24-lb Glatfelter [GL] and 28-lb Navigator [NV]) and two were coated (80-lb Elite Gloss [EG] and 10-pt. Supreme Gloss [SG]). A Mitutoyo Surface Roughness Tester Model 211 (Mitutoyo America; Aurora, IL, USA), which is a stylus profilometer, was used to measure surface roughness. The arithmetic mean deviation of the roughness profile, *Ra*, was obtained with an evaluation length of 2.5 cm. Gloss at 75° was measured using a Gardco Novo-Gloss glossmeter (Paul M. Gardner; Pompano Beach, FL, USA). Parker Print Surf (PPS) roughness and porosity at 980 KPa were measured at Western Michigan University, Kalamazoo, MI, USA.

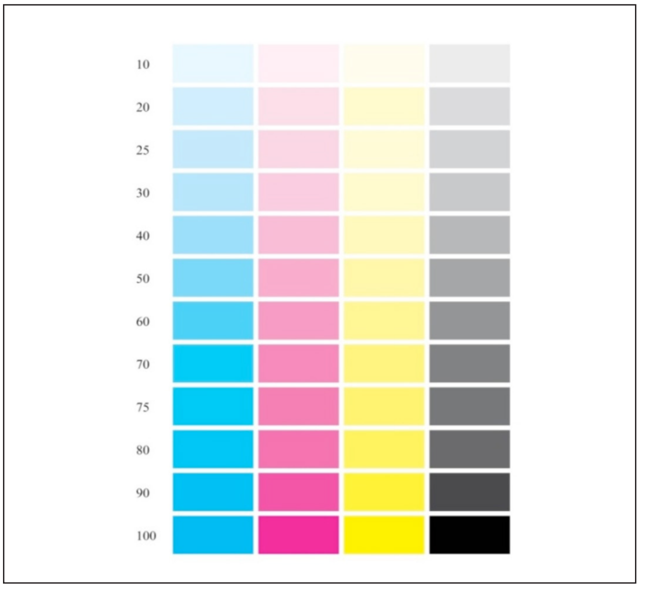
Printing

The substrates were printed on a Xerox iGen3 110 with an EFI Fiery Color Server, located at Muncie Novelty in Muncie, IN, USA. Xerox dry inks were used. Line screen was 175 lines per inch. Printing speed was 40 images per min.

The print layout contained patches with different cyan, magenta, yellow, and black (CMYK) tonal values from 10% to 100%, as shown in **Fig. 1**.

Ink film measurement

Toner amounts on cyan patches of different tonal values were measured using an analytical method. Samples of unprinted papers, printed patches, and dry toners were dissolved in concentrated nitric acid by slow boiling. The copper concentrations of all obtained solutions were analyzed by a Model 4110



1. Print layout.

Paper	Basis Weight (g/m²)	Roughness Ra (µm)	PPS Roughness (µm)	PPS Porosity (mL/min)	Gloss at 75° (%)
Glatfelter (GL)	105	2.959	5.656	942.63	12.3
Navigator (NV)	90	1.976	4.067	1335.50	9.4
Elite Gloss (EG)	120	0.534	1.057	2.87	70.0
Supreme Gloss (SG)	219	0.334	1.016	3.95	82.1

I. Paper properties.

ZL Zeeman graphite furnace atomic absorption (AA) spectrometer with AA WinLab Analyst Version 2.5 software (Perkin Elmer; Waltham, MA, USA). Analytical results were calculated using Eq. (5) to determine the transferred toner amounts for different tonal values.

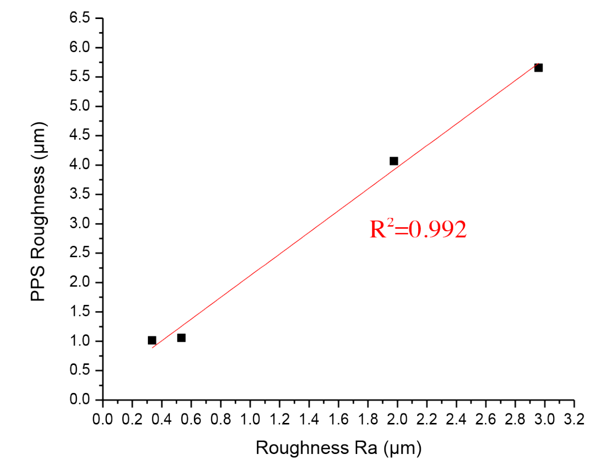
$$w = \frac{c_1 - c_2}{c_3} \qquad (5)$$

where w = ink film weight (g/m²)
c_1 = element concentration in printed paper (g/m²)
c_2 = element concentration in unprinted paper (g/m²)
c_3 = element concentration in dry toner (wt%)

The relative reflection densities at different tonal values with reference to unprinted paper were measured using an X-Rite SpectroDensitometer 528 (X-Rite; Grand Rapids, MI, USA).

Curve fitting

All the data were analyzed using OriginPro 8 software (OriginLab; Northampton, MA, USA). The four mathematical models shown in Eqs. (1)-(4) were used for curve fitting. Sum of squares of residuals (SSR) was used to tell how good the curve fitting was (i.e., the residual was equal to the experimental value minus the value calculated from the fitting model). The smaller the SSR value, the better the curve fitting.



2. Relationship between two paper roughness values.

Model	GV	NV
T-E	0.03174	0.00811
Oittinen	0.02886	0.00799
C-M	0.03316	0.00734
C-S	0.02611	0.00657

II. Sum of squares of residuals.

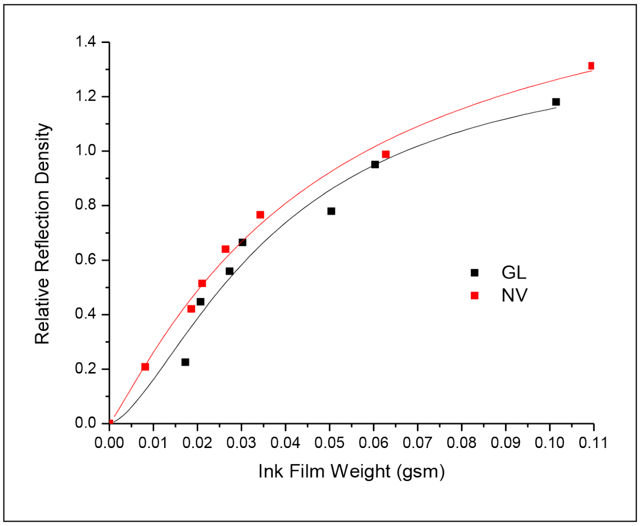
RESULTS AND DISCUSSION

Results of the measured paper properties are listed in **Table I**. The two roughness values measured with a stylus profilometer and a PPS instrument had high correlation with the R^2 value of 0.992, as shown in **Fig. 2**. The GL paper was the roughest, followed by NV, EG, and SG papers. The NV paper had the highest porosity, followed by GL, SG, and EG papers. Coated EG and SG papers were smoother than uncoated GL and NV papers; therefore, they had higher gloss values.

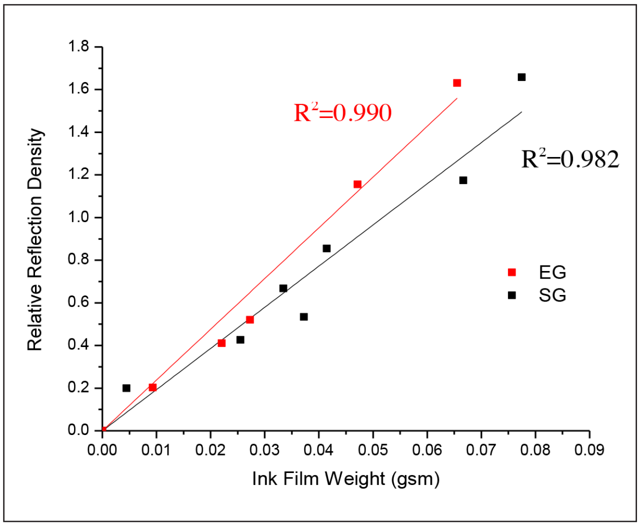
For the two uncoated papers, all four models fitted the data well, as evidenced by the small values of SSR shown in **Table II**. When the SSR values were compared, the curve-fitting results obtained using the C-S model were better than those using the other three models. The SSR values for the GL paper were higher than those for the NV paper. Table I shows that the GL paper was much rougher than the NV paper, which introduced higher variation into ink-film weight measurements for the GL paper.

Figure 3 shows a comparison of the curve-fitting results for the uncoated GL and NV papers using the C-S model. Less toner was required for the NV than the GL paper to achieve the same reflection density. The GL paper was rougher than the NV paper, so more toner was needed to fill out the valleys on the surface before an ink film layer with a smooth surface and certain film thickness could be obtained.

None of the four models was found to be able to fit the data of the two coated papers, which didn't occur in previous studies of liquid inks used in offset and gravure [1-12]. The linear regions in the beginning of ink mileage curves of gravure inks on lightweight coated papers were below the density value of 0.4 [9-12]. In this study, the available experimental data up to the density value of 1.7 for coated papers were still located within the linear regions of their ink mileage curves. Linear curve-fitting results showed the R^2 values are 0.990 for the EG paper and 0.982 for the SG paper, respectively. **Figure 4** shows a comparison of the ink mileage curves of the two coated papers obtained from linear curve fitting. Less toner



3. Ink mileage curves of uncoated GL and NV papers with the C-S model.

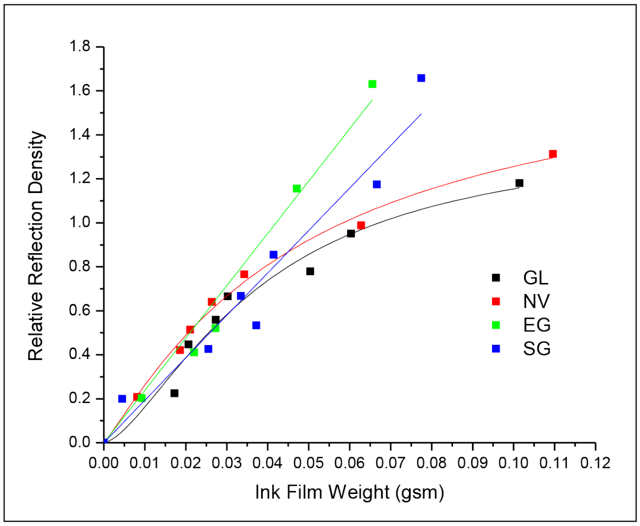


4. Ink mileage curves of coated EG and SG papers with linear fitting.

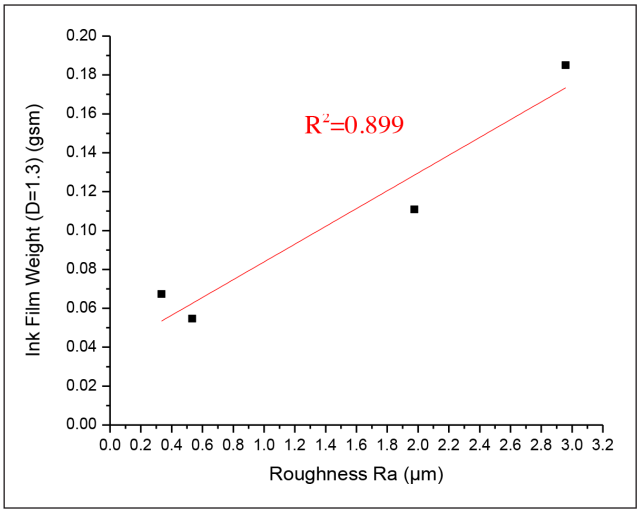
was required for the EG than the SG paper to achieve the same reflection density. The EG paper was rougher than SG paper but had lower porosity. Whether porosity plays a more significant role in ink mileage for coated papers needs further investigation.

The ink mileage curves of all the four papers are compared in **Fig. 5**. In the thin ink film region, ink mileage is similar for all four papers. However, the linear regions of the ink mileage curves of the two coated papers extend to a wide density range, while the ink mileage curves of the two uncoated papers gradually approach their saturation densities.

Ink mileage curves can be used to predict how much ink is required to achieve a target density. For example, if a cyan density of 1.30 is desired, the ink film weight required for a substrate can be obtained from its ink mileage curve; hence, the ink mileage for that substrate can be calculated, as shown in **Table III**. The GL paper demonstrated the lowest



5. Ink mileage curves of all four papers.



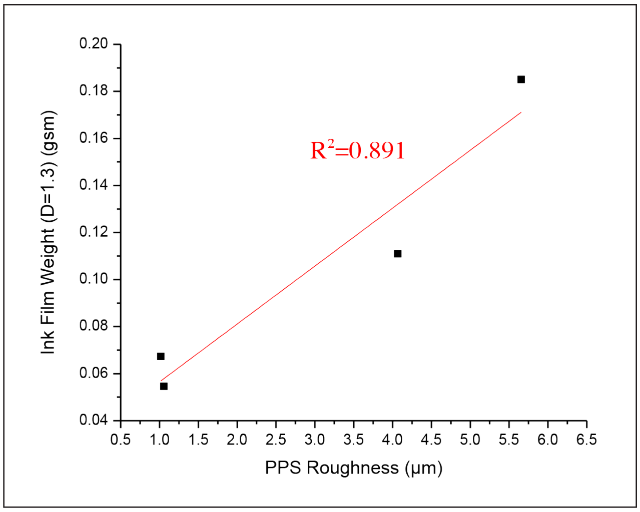
6. The relationship between roughness Ra and ink film weight at cyan density of 1.30.

Substrate	Ink Film Weight (g/m^2)	Ink Mileage (m^2/g)
Glatfelter (GL)	0.1850	5.40
Navigator (NV)	0.1109	9.02
Elite Gloss (EG)	0.0546	18.31
Supreme Gloss (SG)	0.0673	14.85

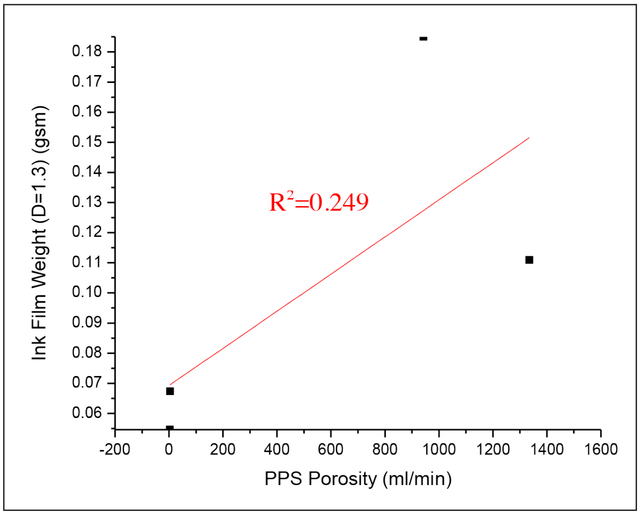
III. Ink mileage prediction at a target cyan density of 1.30.

ink mileage, while the EG paper showed the highest (3.39 times higher).

The relationship between calculated ink film weight and paper roughness *Ra* is shown in **Fig. 6**. The relationship between calculated ink film weight and PPS roughness is shown in **Fig. 7**. Both roughness values have strong correlations with ink film weight. The rougher the paper



7. The relationship between PPS roughness and ink film weight at cyan density of 1.30.



8. The relationship between PPS porosity and ink film weight at cyan density of 1.30.

surface, the higher the requirement for ink film weight and, consequently, the lower the ink mileage.

The relationship between calculated ink film weight and PPS porosity is shown in **Fig. 8**. No correlation was found. In conventional printing processes, such as offset and gravure, liquid ink is absorbed by the paper first when it is in contact. In the dry-toner EP process, toners are transferred from a drum to paper and no absorption occurs. Therefore, porosity has little effect on toner film formation.

CONCLUSIONS

Ink mileage curves of the uncoated papers were obtained by fitting the experimental data with four nonlinear models. The C-S model had a better fit than the other three models. None of the four nonlinear models could fit the experimental data of the coated papers, while the linear model was found to fit the data well. Linear fitting can be used in the practical density region for coated papers. The wide linear regions found for dry toners on coated papers were different from previous findings for liquid inks.

Ink mileage curves obtained from curve fitting can estimate the ink requirement for a target density; hence, the ink mileage can be calculated. Among the paper substrates investigated, the highest ink mileage for a target cyan density of 1.3 could be 3.39 times the lowest ink mileage. It was also found that ink mileage correlated well with paper roughness. High ink film weight is required for a rough paper surface, and therefore ink mileage is low. No correlation was found between ink mileage and paper porosity. **TJ**

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ABOUT THE AUTHORS

Benefits to the environment and human health from good manufacturing practices, such as less ink usage during printing, can be achieved by choosing inks or papers with high ink mileage. We chose this research topic because of the need to provide printers such information so they can choose inks or papers wisely. Previous research was done for liquid inks used in conventional printing processes, such as offset and gravure printing. Our research investigated the ink mileage of dry toners in electrophotography (EP), one of the major nonimpact printing technologies.

The most difficult aspect of this research was chemical analysis. Paper and print samples had to be digested completely in order to get accurate results. It was interesting that the ink mileage curves of the studied coated papers had good linear fit, a finding that differed from previous studies.

Mills can use this method to estimate ink mileages of their EP papers and then make improvements by modifying paper properties. The next step will be to compare different toners and study how toner properties affect ink mileage.

Xu

Calkins

Xu and Calkins are assistant professors in the Department of Technology at Ball State University, Muncie, IN, USA. Email Xu at rxu@bsu.edu.