The Effects of Paper Coating on Gravure Ink Mileage

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Abstract: An ink mileage curve is a plot of the printed optical density of an ink on a substrate as a function of ink film thickness. It is helpful to predict how much ink is needed to achieve target density and has been studied for many years. It was found that it was affected by both paper properties and ink properties. However, most of the previous research was done for offset lithographic printing and little was done for gravure printing, due to the difficulty of measuring gravure ink mileage. In our previous studies, ink mileage was measured using two methods based on the same analytical principle: the tracer method by adding a tracer into the ink, and the direct method utilizing metal ions that already exist in the ink. In this study, both of the two methods were used. The substrates used were pilot coated papers using different coating formulations. The coated papers were printed on a pilot rotogravure web press. The concentrations of copper ions in both cyan liquid ink and ink film were analyzed by atomic absorption spectroscopy (AAS) and used to calculate the amount of ink transferred to the paper. The ink was also doped with a metal ion tracer, and the amount of ink transferred was obtained in the same way. It was found that the transferred amounts of cyan pigments were higher than those of the tracer, thus the direct method is slightly more reliable. The analysis of the obtained ink film coat weight and reflection density data showed that both the Oittinen and Calabro-Savagnone model fitted the experimental data well, with the latter a little better. The relationships between regression coefficients and tested paper properties were studied. Saturation density D_s correlated with all of the tested paper properties, but not strongly. Higher roughness, air permeability, pore size, or porosity resulted in higher saturation density. Density smoothness m was found to correlate very well with roughness and air permeability. Higher roughness and air permeability resulted in lower m, thus lower density. No significant correlations were found between the ink film coat weight exponent n and tested paper properties.

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Introduction

An ink mileage curve is a plot of the printed optical density of an ink on a substrate as a function of ink film thickness. It is helpful to predict how much ink is needed to achieve target density and has been studied for many years (Tollenaar and Ernst, 1962, Kornerup et al., 1964, Oittinen, 1972, Calabro and Mercatucci, 1974, Calabro and Savagnone, 1983, Blom and Conner, 1990, Chou and Harbin, 1991, MacPhee and Lind, 2002). In order to study the ink mileage curve quantitatively, several models for curve fitting have been reported by different researchers. It was found that the ink mileage curve was affected by both paper properties and ink properties.

However, most of the previous research was done for offset lithographic printing and little was done for gravure printing, due to the difficulty of measuring gravure ink mileage. The previous studies were based on the experimental data of prints made on IGT and/or Prüfbau printability testers using offset lithographic inks. The quantity of transferred ink, and hence the amount of ink on paper, was determined by the weight difference of the printing disc before and after printing. This method can not be applied to gravure inks. We used an analytical method in our previous studies. In our earlier study, the inks were doped with tracers, which were analyzed using Atomic Absorption Spectroscopy (AAS) to calculate the mass of the ink transfer, and hence the ink film coat weight (Xu et al., 2005 and 2006). This tracer method can be used in all kinds of ink types including solvent-based gravure and flexographic inks. It can also be applied to commercial printing presses. However, adding a tracer into an ink is not convenient and the effect of the tracer on ink performance was minimal, but still existed in reality. Therefore, a later study used metal ions in ink pigments, more precisely, copper ions in cyan ink, for ink transfer detection (Xu et al., 2007). Copper is part of the cyan pigment, so it does not interfere with ink viscosity, or ink color. This direct method is more convenient and accurate.

Our previous studies found that equation 1 and 2 modified from two of previous models (Oittinen, 1972, Calabro and Savagnone, 1983) fitted the data well, with equation 2 having a little smaller sum of the squares of the residuals.

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

Calabro and Savagnone $$\frac{1}{D} = \frac{1}{D_s} + \left(\frac{1}{mw}\right)^n \qquad (2)$$

where w is the thickness of ink film on the substrate and D is the relative reflection density. D_s, m, and n are regression coefficients. 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 and is called "density smoothness" (Tollenaar and Ernst, 1962). The higher the density smoothness is, the higher the reflection density is. It was found that saturation density D_s had higher correlations with air permeability and pore size than surface roughness. Parameter m correlated well with paper roughness measured by the profilometer, and at a less significant level, with air permeability. Parameter n correlated well with both roughness measured by the profilometer and air permeability.

In this work, we printed papers coated using formulations with different latex binders. Both the tracer and direct method were applied and compared. The effects of paper properties on gravure ink mileage curves were studied.

Experimental

Paper Coating

A series of coating trials were run with a 32# base paper. Coating formulations are shown in Table 1. The ratio between delaminated clay and fine clay was 80:20, which was the same for all the samples. The latex binder type used was different but the same concentration for sample 1 to 5. The coating formulation for sample 6 contained the same latex as sample 2 but at a lower level.

Table 1. Coating formulations

Sample ID	1	2	3	4	5	6
Delaminated clay, Astraplate	80	80	80	80	80	80
No. 1 clay, KCS	20	20	20	20	20	20
Latex, XL 3005	6					
Latex, XL 2457		6				4.5
Latex, XL 2373			6			
Latex, XL 411-16				6		
Latex, XL 411-09					6	
Lubricant, Dispex N40	0.1	0.1	0.1	0.1	0.1	0.1

Paper Testing

A Parker Print-Surf (PPS) Model 90 (Messmer Instrument) was used to measure roughness at 490 kPa with soft backing, according to TAPPI standards. Air permeability coefficient as determined by PPS porosity (Pal et. al., 2006) was measured at 980 kPa clamping pressure. An Electronic Microgage Model 210 from EMVECO Inc. (now Lorentzen & Wettre USA, Inc.) with a spherical steel stylus having a radius of 0.001 inch was also used for roughness measurement. Average pore sizes and porosity were determined by mercury intrusion porosimetry. Measurements were carried out using an Autopore IV 9500 (Micromeritics Instrument).

Printing

The coated papers were printed on a pilot rotogravure web press (Cerutti Model 118, Italy) located at Western Michigan University (WMU) Printing Pilot Plant. Commercial toluene-based coated cyan ink for rotogravure (Flint Group) was used. It was doped with a selected tracer. The ink efflux time with Shell cup #2 was kept at 25 ± 0.5 seconds. Printing was done at 600 ft/min with electrostatic assist (ESA) on. The cyan cylinder has compressed cells. The print layout contains different tonal values from 10% to 100 %.

Ink Film Coat Weight

A known amount of liquid ink samples and certain areas of unprinted paper samples and printed paper samples with different tonal values were digested in a mixture of nitric acid and hydrogen peroxide (1:1) by slow boiling for at least 3 hours. The copper (Cu) and tracer concentrations were analyzed quantitatively using a Varian Atomic Absorption (AA) Spectrometer Model AA240. The ink film coat weights at different tonal values were calculated using the equation:

$$w = \frac{c_1 - c_2}{c_3} \qquad (3)$$

where w is ink film coat weight (gram per square meter, or gsm). c_1, c_2, and c_3 are metal concentrations in printed paper (gsm), unprinted paper (gsm), and liquid ink (wt %), respectively.

Relative Reflection Density

The reflection densities at different tonal values were measured with reference to the reflection density of unprinted paper using an X-Rite 530 SpectroDensitometer.

Results and Discussion

The characteristics of the papers are reported in Table 2. Less latex content in sample 6 than that in sample 2 resulted rougher and more porous coating surface.

Table 2. Characteristics of papers

ID	Grammage (g/m^2)	PPS Roughness (micron)	Profilometer Roughness (micron)	Permeability Coefficient ($micron^2$)	Pore Size (nm)	Porosity (%)
1	48.7	1.73	2.03	2.02E-5	239.2	64.98
2	48.8	1.74	2.02	2.22E-5	204.2	63.41
3	48.7	1.62	1.94	1.90E-5	208.8	62.10
4	48.0	1.69	2.04	2.27E-5	188.6	56.50
5	48.2	1.62	1.99	2.10E-5	231.6	60.87
6	48.5	1.78	2.09	2.53E-5	250.1	65.99

Table 3. Relative reflection density and ink film coat weight results

ID	Tone (%)	Relative Reflection Density	Ink Film Coat Weight, gsm (Direct Method)	Ink Film Coat Weight, gsm (Tracer Method)
1	25	0.28	1.34	1.01
	50	0.56	2.70	1.96
	70	0.84	4.56	3.46
	80	1.01	5.84	4.64
	90	1.19	7.29	6.03
	100	1.30	8.28	7.02
2	25	0.27	1.40	1.01
	50	0.55	2.76	2.02
	70	0.83	4.67	3.61
	80	1.01	5.96	4.78
	90	1.19	7.45	6.05
	100	1.30	8.45	7.06
3	25	0.28	1.35	0.95
	50	0.56	2.71	1.89
	70	0.83	4.36	3.26
	80	1.01	5.69	3.79
	90	1.18	6.88	5.43
	100	1.30	8.06	6.20
4	25	0.27	1.43	1.12
	50	0.55	2.85	2.30
	70	0.83	4.66	3.89
	80	1.00	5.98	5.16
	90	1.18	7.57	6.53
	100	1.30	8.56	7.67
5	25	0.27	1.40	1.05
	50	0.56	2.77	2.18
	70	0.83	4.55	3.71
	80	1.01	5.85	4.86
	90	1.18	7.27	6.23
	100	1.30	8.32	7.24
6	25	0.26	1.36	1.14
	50	0.54	2.71	2.16
	70	0.81	4.50	3.96
	80	0.99	5.78	5.24
	90	1.16	7.20	6.70
	100	1.28	8.03	7.81

The measured results of relative reflection density and ink film coat weight obtained from both direct copper and tracer method are shown in Table 3. The ink film coat weight values obtained from direct copper method are higher than those from tracer method, which means that the transfer amount of the tracer was lower than that of cyan pigments. The correlation between these two sets of data is 0.987, which eliminates the possibility of measurement errors. The possible reason could be the ESA system had different effects on the pigments and on the tracer, which resulted in their different transfer amounts. Pigments, as a part of ink film, play important role on reflection density; therefore the results obtained from the direct copper method are slightly more reliable.

The ink film coat weight data obtained from direct copper method and the relative reflection density data were analyzed using appropriate OriginPro 7.5 nonlinear fitting routines. Equations 1 and 2 were examined. D_s, m, and n were treated as regression variables. One example of the ink mileage curves is shown in Fig. 1. The solid dots are experimental data of cyan ink on paper sample 5. The solid line is the non-linear fitting result using the Oittinen model, while the dotted line using the Calabro-Savagnone model. These two curves were indistinguishable in our data range and began to separate with increasing ink film coat weight. The ink mileage curve obtained using the Calabro-Savagnone model is above that using the Oittinen model; therefore, the saturation density obtained from the Calabro-Savagnone model is higher than that from the Oittinen model. The hollow dots are residual values. The residual is equal to the experimental value minus the value calculated from the fitting model. Residual values can be used to tell how good the fit is. The smaller the absolute values of the residuals are, the better the curve fit is.

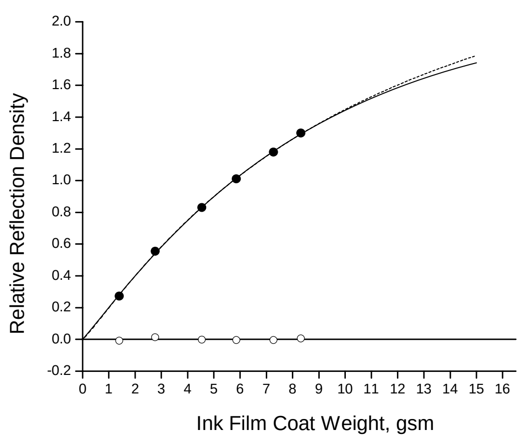

Figure 1. Ink mileage curve of sample 5 (the solid line is the curve fitting using the Oittinen model and the dotted line using the Calabro-Savagnone model)

The residual values obtained from curve fitting of all samples were plotted against ink film coat weight. The degree of fit of an equation to the experimental data can be determined by the sum of the squares of residuals and the distribution of residuals around zero. A small sum of the squares of residuals and an even distribution indicate a good fit. The residual plots of the two models are compared in Fig. 2. The results indicate that both models fitted the experimental data well, with Calabro-Savagnone model a little better. This agrees with the finding in our previous studies (Xu et. al., 2006 and 2007).

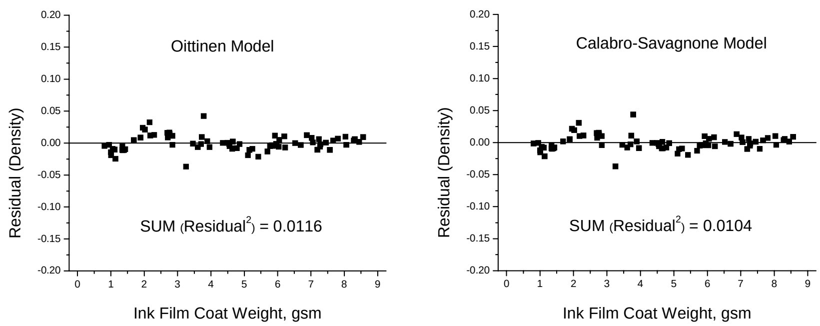

Figure 2. Sum of the squares of reflection density residuals and their distribution

The regression coefficients, D_s, m, n, derived from curve fitting for both models are listed in Table 4. The values for different coated papers are close because of the same clay contents in coating formulations, but there are still significant differences due to the effects of different latex binder types and contents. Saturation density D_s values derived from the Calabro-Savagnone model are higher than those from the Oittinen model, which has been shown in Fig. 1.

Table 4. Regression coefficients of Oittinen and Calabro-Savagnone model

ID	Oittinen Model			Calabro-Savagnone Model		
	D_s	m	n	D_s	m	n
1	2.250	0.101	1.013	3.370	0.245	1.053
2	2.161	0.098	1.046	3.213	0.241	1.089
3	2.181	0.103	1.040	3.276	0.252	1.079
4	2.152	0.097	1.047	3.174	0.239	1.093
5	2.077	0.102	1.065	3.032	0.249	1.116
6	2.374	0.089	1.031	3.608	0.233	1.067

It is difficult to conclude which values are more reliable based on present data. It can only be found out by applying thicker ink film which will fall in the region where the reflection density approaches the saturation density. However, achieving reflection density close to 2 requires relatively thick ink film and makes the gravure printing trials difficult to run.

The correlations between paper characteristics and regression coefficients for both models are shown in Table 5. Saturation density D_s correlated with all of the tested paper properties, but not strongly. Saturation density results from first-surface reflection, which is affected by the smoothness of the ink film surface. Surface roughness of an ink film is related to the ink's leveling, which is mainly determined by the ink's properties, but also is affected by the paper properties. Therefore, the correlations are not very strong, but still exist. Higher roughness, air permeability, pore size, or porosity resulted in higher saturation density. Picollet et. al. (1998) studied gravure ink penetration and spreading on LWC coated papers. They found that rough surface and pores in coating layer facilitated ink spreading and penetration, respectively, and thus improved ink leveling.

Table 5. Correlation matrix of regression coefficients of Oittinen and Calabro-Savagnone model

	Oittinen Model			Calabro-Savagnone Model		
	D_s	m	n	D_s	m	n
PPS Roughness	0.77	-0.81	-0.59	0.74	-0.86	-0.61
Profilometer Roughness	0.64	-0.87	-0.36	0.58	-0.94	-0.35
Permeability Coefficient	0.55	-0.96	0.01	0.50	-0.95	-0.04
Pore Size	0.59	-0.34	-0.38	0.57	-0.17	-0.40
Porosity	0.69	-0.32	-0.58	0.70	-0.18	-0.63

Parameter m, also called density smoothness, determines the steepness of density curve in the region of very thin film. It was found to correlate very well with roughness and air permeability. Higher roughness resulted in lower m because the ink film was too thin to cover the rough surface, thus the corresponding reflection density was low. Higher air permeability also resulted in lower m because the solvent was absorbed so fast that the ink did not have time to level, thus the reflection density was also low.

No significant correlations were found between the ink film coat weight exponent n and tested properties. It was more likely affected by the ink properties. Calabro and Savagnone (1983) found that parameter n had a better correlation with ink rheological variables, such as viscosity, yield value and tack, and its optical properties, such as the absorption coefficient and the fineness of grind of the pigment.

Conclusions

Two methods based on the same analytical principle were tested: the tracer method by adding a tracer into the ink, and the direct method utilizing metal ions that already exist in the ink. It was found that the transferred amounts of cyan pigment were higher than those of the tracer, thus the direct method is slightly more reliable. The analysis of the obtained ink film coat weight and reflection density data showed that both the Oittinen and Calabro-Savagnone model fitted the experimental data well, with the latter a little better, as evidenced by smaller sum of the squares of residuals. The saturation densities obtained from the Calabro-Savagnone model were higher than those from the Oittinen model, which needs further investigation by applying very thick ink film. The relationships between regression coefficients and tested paper properties were studied. Saturation density D_s correlated with all of the tested paper properties, but not strongly. Higher roughness, air permeability, pore size, or porosity resulted in higher saturation density. Density smoothness m was found to correlate very well with roughness and air permeability. Higher roughness or air permeability resulted in lower m, thus lower density. No significant correlations were found between the ink film coat weight exponent n and tested paper properties.

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