The Relationship Between Paper Properties and Fuser Oil Uptake in High-Speed Digital Xerographic Printing

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Abstract

Fusing plays a vital role in achieving high resolution print quality in high-speed digital xerographic printing. The fuser roll is typically coated with a release agent so as to facilitate clean splitting of the fused image and paper as it exits the fusing nip. If oil uptake by paper is excessive, a fuser oil depletion problem will develop with time and the fuser roll will become insufficiently coated with oil. In this study, the oil uptake performance of a wide range of commercial papers was evaluated using a prototype high-speed xerographic fuser. The key paper properties that control oil uptake are identified using a partial least squares regression model. A mechanistic view of how these paper properties interact to affect oil uptake is explored in terms of the wetting of oil on paper and in terms of a contact area index (CI). Surface free energy of paper was found to be the dominant property in describing the wetting of oil on paper. CI, based on theory from contact mechanics, is used to describe the degree of contact between paper and the fuser roll at the nip. A positive correlation between CI and oil uptake suggests that roughness and bending stiffness have significant influences on oil uptake.

Introduction

Xerography is an electrostatic printing process which uses dry powder or toner, heat and pressure to fuse images onto a substrate. High-speed digital xerographic printing presses are versatile with the capability to produce high resolution prints on a variety of media at high speeds. The focus of this study is on the fusing section where the image is fixed onto paper. Hot roll fusing is the most common fixing method for these printers where toner is fused onto the substrate by heat and pressure within a nip formed by two rotating rolls, a fuser roll and a pressure roll (Figure 1) [1].

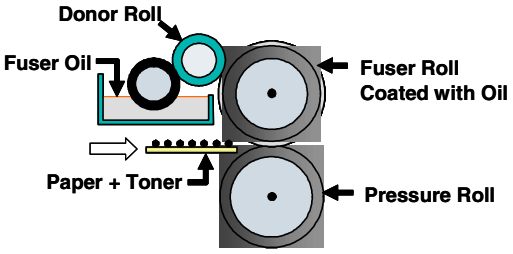

Figure 1: *Fusing section in a high-speed xerographic printing press*

Clean splitting between the fuser roll and paper with a toner image must be achieved so as to produce a sharp image without offset at high reproduction speeds. To facilitate this, the fuser roll is lubricated with a release agent, which in most cases is a silicon-based oil that is applied continuously using a donor roll. However, at the fusing nip the paper substrate sorbs oil, and over time with high volume production, excessive oil uptake will occur resulting in oil depletion within the system. Consequently, the fuser roll will become insufficiently coated with oil, resulting in toner offset and poor print quality. As well, the fuser roll life will be reduced and/or terminated. It has been observed that the oil depletion rate varies with different types of papers, but the specific paper properties that control the oil depletion rate are not clear. An understanding of the interactions between fuser oil and paper is fundamental in improving fuser roll life and print quality. Meanwhile, understanding these interactions will help papermakers develop new types of papers that will have a minimal impact on fuser oil consumption and eliminate downstream problems, such as oil streaks on the printed copy.

Over the years, extensive research in the area of xerographic printing has looked into the interaction between toner and paper in terms of the effect of paper properties, toner properties and operational conditions on fusing fix [2-4]. However, an important aspect in the fusing process that has been overlooked is the effect of fuser roll lubrication on print quality. This study aims to investigate this gap in literature by identifying the key paper properties that control fuser oil uptake and by obtaining a mechanistic understanding of the interactions between oil, paper and the fuser roll.

Materials and Methods

The test paper set consisted of sixteen commercial papers (sample #1- 16), five of which were uncoated papers (sample # 1, 4, 5, 7, 8) and the remaining were coated papers with varying coating compositions All samples were tested for their physical properties as listed in Table 1.

A commercial silicon-based fuser oil was used in this investigation. Viscosity was 575cSt at 25°C and surface tension of the oil was 20.6 mJ/m^2 at 25°C [13].

The oil uptake performance of all blank paper samples were evaluated using a prototype high-speed xerographic fusing system and inductively coupled plasma mass spectroscopy (ICP-MS). The detailed experimental procedure is described in [5].

Partial Least Squares Regression Modelling

Partial least squares (PLS) regression was used to correlate the oil uptake data with paper properties in order to identify the key factors that predict oil uptake. In this investigation, the model predicts oil uptake (y-variable) from the paper properties (x-variables). To assess the PLS model performance, the loading plot and the R^2Y and Q^2 values were observed. R^2Y is a multiple correlation coefficient between the measured response (y) and the predicted response (y_{PRED}) values. The Q^2 parameter denotes the model's ability to predict the response. An ideal model has R^2Y and Q^2 values greater than 0.5 while minimizing Δ, the difference between R^2Y and Q^2 [6]. Further details of the PLS regression method used in this study are given in [5].

Determining Surface Free Energy of Paper

Wu's geometric mean method was used to determine the surface free energy of the paper samples [7]. This method is based on Fowkes' theory and requires contact angle measurements of two liquids, one polar and one non-polar, on the test substrate. The liquids must be well characterized for their surface tension (γ) and polar (γ^P) and dispersive (γ^D) surface energy components. Diiodomethane and water were the test liquids utilized in determining the surface free energy of all the paper samples. Literature values for the surface tension and dispersive and polar components for diiodomethane (γ_D =50.8 mJ/m^2; γ_D^D =49.5 mJ/m^2; γ_D^P =1.3 mJ/m^2) and water (γ_W = 72.2 mJ/m^2; γ_W^D = 22 mJ/m^2; γ_W^P = 50.2 mJ/m^2) were used [7].

Results and Discussion

Test Paper Set

All paper samples were tested for their physical properties as listed in Table 1. It is clear that these samples cover a broad range for each property.

Table 1: Properties measured for all paper samples

Property	Range
Basis Weight	76-269 g/m^2
Caliper	0.10-0.24 mm
Porosity	12-3500 Gurley Seconds
Roughness (RMS)	1.20-5.83 µm
Bending Stiffness (MD)	0.84-32.6 mN
Coefficient of Friction	0.29-0.61
$CaCO_3$ Content	14-26%
Starch Content	1.9-8.3%

Oil Uptake Data

Oil uptake data was collected for all paper samples and the data is summarized in Figure 3. It is important to note that the experimental technique to quantify oil uptake is known to result in higher values for oil uptake than when printing on a commercial press. Therefore, the results are relative oil uptake amounts among paper samples.

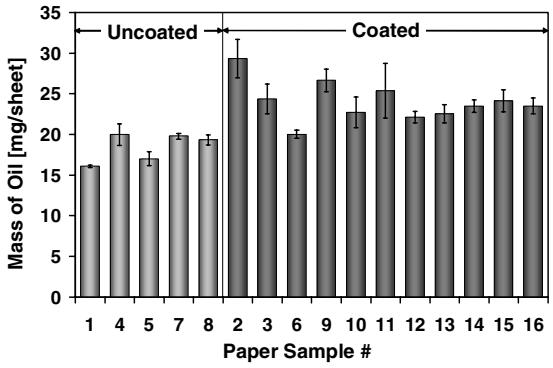

Figure 3: Oil uptake amounts for all paper samples. Sheet size is 8.5"x11".

Partial Least Squares Regression Model

PLS regression was applied and one principal component was fit to the experimental data sets. The R^2Y and Q^2 values are 0.72 and 0.61 respectively. Key parameters that have strong correlations with oil uptake are identified in the loading plot (Figure 4). RMS roughness and contact angle measurements of oil on paper (CA) are furthest from zero in the negative direction and have strong negative correlations with oil uptake. Basis weight, bending stiffness, caliper and surface free energy (SFE) are furthest from zero in the positive direction and have strong positive correlations with oil uptake. With the lowest PLS weight, porosity based on Gurley seconds has the weakest positive correlation with oil uptake.

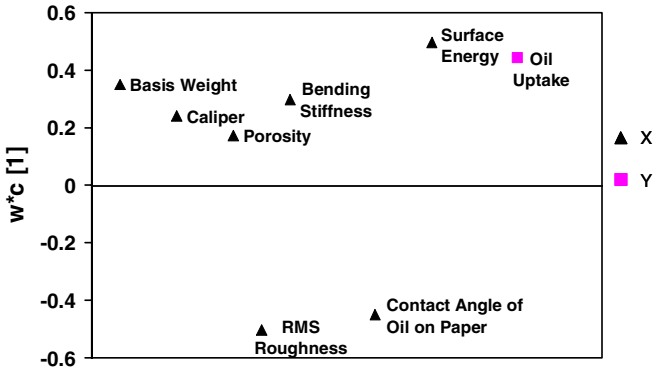

Figure 4: The loading plot describes the relationships between X and Y variables.

R^2Y and Q^2 are both greater than 0.5 with $\Delta = R^2Y - Q^2 = 0.11$ at a minimum. This indicates that the model predicts oil uptake well from the identified key paper properties.

After identifying the key paper properties that are statistically correlated with oil uptake, it is important to gain a mechanistic understanding of how these interacting paper properties affect the oil uptake process. Wetting of oil on paper and a contact area index (CI) are used to explain how oil is physically transferred to paper within the fusing nip. Wetting and the contact area index are examined in relation to the identified key paper properties.

Wetting of Fuser Oil on Paper

From the PLS model, the positive correlation between oil uptake and SFE can be explained in terms of the wetting behaviour of oil on paper. The surface tension of the fuser oil at room temperature is low (20.6 mJ/m^2), and the oil will preferentially wet papers that exhibit higher surface energy. As the surface energy of paper increases, wetting of oil on paper will increase; hence, oil uptake will increase. A linear regression of oil uptake as a function of surface free energy of paper also illustrates this positive correlation (Figure 5).

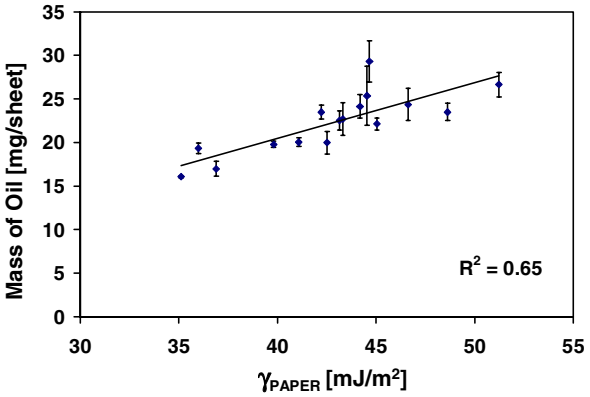

Figure 5: Oil uptake versus surface free energy of paper. R^2=0.65.

Moreover, the negative correlation between oil uptake and CA from the PLS model helps to establish the correlation between wetting and oil uptake. As the contact angle of oil on paper decreases, wetting increases and an increase in oil uptake results. Therefore, contact angle measurements of oil on paper at ambient conditions can be used to predict the wetting behaviour of oil on paper during the oil uptake process.

Relative Contact Area Between Paper and the Fuser Roll at the nip

At the microscopic scale, surfaces are rough exhibiting asperity peaks and valleys, and as a result, when two rough surfaces come into contact, the real contact area is less than the nominal contact area. The relative contact area between paper and the fuser roll at the nip is modelled using theory from contact mechanics and in relation to the basis weight, caliper, stiffness and roughness of the paper samples. The transfer of oil from the fuser roll to paper is then examined as a function of this relative contact area at the nip.

Greenwood and Williamson developed a theory for the elastic contact of rough surfaces that takes into account surface topography and elastic deformation based on Hertz theory [8]. The model assumed that contact occurs at the asperity peaks of the surface, and that the total contact area is the sum of the contact area of each contacting peak. According to Greenwood and Williamson, for a negative exponentially distributed rough surface, the relative contact area parameter, A_{re}, is given as,

$$Are = \sqrt{\frac{\pi}{\sigma k}}\left(\frac{P}{E'}\right) \tag{1}$$

where σ is the root-mean-squared (RMS) roughness value; k is the RMS value of the peak curvature and is defined in Equation 3 [9]; E' is a complex modulus defined in Equation 2.

$$\frac{1}{E'} = \frac{\left(1-\nu^2_{paper}\right)}{E_{paper}} + \frac{\left(1-\nu^2_{roll}\right)}{E_{roll}} \tag{2}$$

A_{re} is a dimensionless parameter describing the relative contact area between two rough surfaces or the ratio of real contact area to nominal contact area. This parameter describes the contact area between surfaces as a function of surface texture and compressibility of the substrate. Surface texture parameter was also defined as a dimensionless parameter, $R_f = \sigma k$, by Yan and Aspler [9]. σ and k are obtained from surface profile measurement data using Equation 3,

$$k = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\frac{\left(z_{i+1} - 2z_i + z_{i-1}\right)}{h^2}\right]^2} \tag{3}$$

where z_{i-1}, z_i and z_{i+1} are three consecutive height measurements; h is the horizontal step interval between the height measurements; and n is the total number of peaks measured.

For each paper sample, surface profile measurement data was collected using WYKO, a non-contact optical surface profiler system that can measure a wide range of surface heights [10]. Surface profile measurement data was analyzed using Matlab to calculate k. RMS roughness was given by WYKO analysis software.

Based on the work by Greenwood and Williamson, as well as, Yan and Aspler, a contact area index (CI) was developed to describe the degree of contact between paper and the fuser roll at the nip (Equation 4). This index represents the relative contact area as a function of RMS roughness (σ), asperity peak curvature (k) and complex modulus (E'). σ and k were obtained from WYKO surface profile measurements of each paper sample. E' combined the modulus of paper and that of the fuser roll. In this study, the fuser roll was estimated to be silicon rubber and for Equation 2, E_{roll} = 2 MPa and ν_{roll} = 0.5 [13] were used as estimate values for the fuser roll at fusing temperature. These values remained constant throughout the study. E_{paper} was calculated using the bending stiffness of paper (S) and Equation 5 [14]. Changes in the Poisson's ratio among the paper samples were assumed to be negligible and a constant Poisson's ratio of ν_{paper}=0.4 was used [12]. Pressure (P) within the fusing nip was estimated as a function of caliper (C), where $P = \beta C$ and β is a constant, which depends on the spring constant of the nip.

$$CI = \frac{A_{re}}{\beta\sqrt{\pi}} = \frac{1}{\sqrt{R_f}}\frac{C}{E'} \tag{4}$$

$$E_{Paper} = \frac{12S}{h^3} \tag{5}$$

While CI is not an absolute measurement for the contact area between paper and the fuser roll at the nip, it is an indication for the degree of contact that would result when paper contacts the fuser roll. A paper sample with a lower CI value indicates that the asperity peak surface area available to contact the fuser roll is less than that of a paper with a higher CI value.

For each paper sample, a contact area index (CI) is calculated using Equation 4. Calculating a CI value for each sample allows for a relative comparison among papers for their degree of contact with the fuser roll. A positive correlation between oil uptake and CI is shown in Figure 6. This indicates that surface texture and stiffness of paper (which encompasses effects from basis weight and caliper) play a significant role in understanding the relative contact area between paper and the fuser roll in the nip. Hence, with a higher degree of contact between paper and the fuser roll, oil uptake will increase.

Simplified Model for Oil Uptake

Surface chemistry of paper and the degree of contact that occurs between paper and the fuser roll at the nip are shown to be significant parameters in predicting and understanding oil uptake. SFE characterizes the dominant surface chemistry effect of paper on oil uptake, and CI accounts for the effects of physical paper properties on oil uptake. A multiple linear regression (MLR) model is developed with oil uptake as a function of the independent parameters, CI and SFE. After scaling CI and SFE to unit variance, the MLR model is

$$y_{OIL} = 1.27x_{CI} + 2.25x_{SFE} - 1.65 \quad (6)$$

with $R^2 = 0.8$. Therefore the two parameters, CI and SFE, account for 80% of the variance in the oil uptake data. This indicates that CI and SFE are key parameters in predicting oil uptake by the test set of papers in high-speed xerographic printing. A 3-D contour plot of oil uptake as a function of SFE and CI is shown in Figure 6.

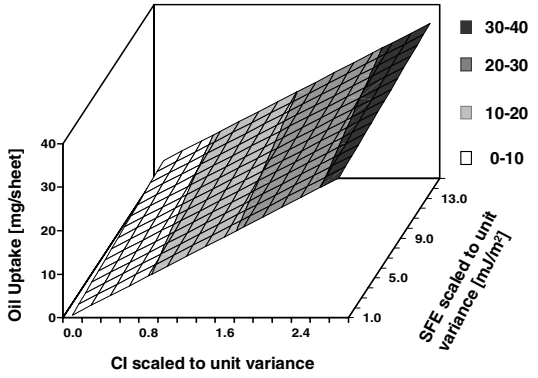

Figure 6: 3-D contour plot of oil uptake as a function of SFE and CI.

With the lowest PLS weight, porosity has the weakest positive correlation with oil uptake. However, this weak correlation between oil uptake and porosity does not imply that there is no effect of porosity on oil uptake, but rather the bulk porosity measurements included in this model does not sufficiently predict the oil uptake data. It is possible that paper surface porosity has a greater effect on oil uptake than bulk porosity; hence, a surface porosity measurement may improve the statistical correlation between porosity and oil uptake.

Conclusions

A partial least squares regression model is developed and it identifies key parameters significantly correlated with oil uptake. Roughness and contact angle measurements have strong negative correlations with oil uptake, while caliper, basis weight, stiffness and surface free energy have strong positive correlations with oil uptake.

The oil uptake process can be described in terms of wetting of oil on paper and in terms of a contact area index (CI). SFE of paper is the dominant property that describes the wetting behaviour of oil on paper. CI is developed to compare the degree of contact between paper and the fuser roll at the nip. CI and oil uptake have a positive correlation, suggesting that surface texture and stiffness of paper have significant influences on oil uptake.

A multiple linear regression model is developed for oil uptake as a function of CI and SFE. This model accounts for 80% of the variance in the oil uptake data indicating that CI and SFE are dominant parameters in predicting oil uptake by paper in high-speed digital xerographic printing.

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References

[1] L. Leroy, et al. "Electrophotography: Effects of Printer Parameters on Fusing Quality". Proc. 11th International Printing and Graphic Arts Conference. Bordeaux, France. (2002).

[2] J.S. Aspler, et al., "Interactions of ink and water with the paper surface in printing", Nordic Pulp and Paper Research Journal, 8, 10 (1993).

[3] D. J. Sanders, D. F. Rutland, "Effect of Paper Properties on Fusing Fix", Journal of Imaging Science and Technology, 40, 2 (1996).

[4] Prime, R.B. Relationships between Toner Properties, Fuser Parameters, and Fixing of Electrophotographic Images. Society of Photographic Scientists and Engineers, 27(1), 19-25, (1983).

[5] Lai, P. and Yan, N. "The Relationship Between Paper Properties and Fuser Oil Uptake in High-Speed Xerographic Printing". Proc. 92nd PAPTAC, 2006.

[6] L. Eriksson, et al., "Multi- and Megavariate Data Analysis: Principles and Applications". (Umetrics Academy).

[7] Wu, S. Polymer Interface and Adhesion. New York, NY: Marcel Dekker, Inc., (1982).

[8] Greenwood, J.A. and Williamson, J.B.P., "Contact of Nominally Flat Surfaces", Proc. Roy. Soc., London, UK, Series A, Math. Phys. Sci, A295:300 (1966).

[9] Yan, N. and Aspler, J. "Surface Texture Controlling Speckle-Type Print Defects in a Hard Printing Nip", Journal of Pulp and Paper Science, 29, 11 (2003).

[10] WYKO CORPORATION, "WYKO™ NT-2000", WYKO Surface Profiles Technical Reference Manual, (May 1996).

[11] Migwi, C.M., et al. "A method of determining the shear modulus and Poisson's ratio of polymer materials". Journal of Materials Science, 29 (1994)

[12] Stenberg, N., et al. "Out-of-plane Poisson's ratios of paper and paperboard". Nordic Pulp and Paper Research Journal, 17, 4 (2002).

[13] Private Communication with Xerox Research Centre of Canada.

[14] Levlin, J., Söderbjelm, L. Pulp and paper Testing. Papermaking Science and Technology, Book 17. Finland: Fapet Oy (1999).

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