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Relationship between Paper Properties and Fuser Oil Uptake in a High-speed Digital Xerographic Printing Fuser

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Abstract. *The fuser roll in high-speed xerographic printers is typically coated with a silicon-based oil to facilitate clean splitting of the fused image and paper as it exits the fusing nip. If oil uptake by paper is excessive, the fuser roll will become insufficiently coated with oil. Consequently, both image quality and fuser roll life will be negatively impacted. A variety of commercial papers were characterized and evaluated for their oil uptake performance. Using partial least-squares regression, key paper properties correlated with oil uptake were identified. Surface energy of paper was found to have the strongest correlation with oil uptake. Furthermore, based on contact mechanic theories, a contact area index (CI) was used to describe the degree of contact between paper and the fuser roll at the nip. A positive correlation between oil uptake and CI suggests that roughness and stiffness also have significant influences on oil uptake.* © *2007 Society for Imaging Science and Technology.*
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INTRODUCTION

High-speed digital xerographic printing presses are versatile with the capability to produce high resolution prints on a variety of media at rapid 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, which are typically a fuser roll and a pressure roll[1] (Figure 1).

Clean splitting between the fuser roll and paper with a toner image must be achieved to produce a sharp image without offset at high reproduction speeds. To facilitate this, the fuser roll is typically lubricated with a release agent, in most cases a silicon-based oil, that is applied continuously using a donor roll. The printing media takes away oil at the fusing nip and over time, with high volume production, excessive oil uptake may occur, resulting in oil depletion within the system. Consequently, the fuser roll will become insufficiently coated, resulting in toner offset, poor print quality, and a reduction in fuser roll life.

Over the years, extensive research in the area of fusing in xerographic printing has focused on 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 not been well studied is the effect of fuser roll lubrication on print quality. It has been observed that the oil depletion rate varies with different types of papers in high-speed xerographic printing, but thus far the specific paper properties that control this oil depletion rate are not clear.

This study aims to bridge this gap in the 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 material. An understanding of the interactions between fuser oil and paper is of fundamental importance in improving fuser roll life and print quality. Meanwhile, understanding these interactions will help papermakers optimize paper properties to minimize fuser oil consumption and eliminate downstream problems, such as oil streaks on the printed copy.

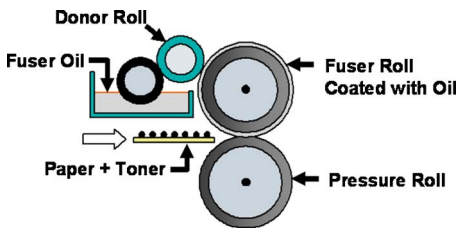

Figure 1. Schematic of the fusing section in a high-speed xerographic printing press.

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Table I. Properties measured for all paper samples.

Property	Range	Test Method
Basis weight	76–269 g/m^2	TAPPI T410
Caliper	0.10–0.24 mm	TAPPI T411
Porosity	12–3500 Gurley sec	TAPPI T460
Bending stiffness (MD)	0.84–32.6 mN	TAPPI T543
rms roughness	1.20–5.83 μm	WYKO™ NT-2000
Surface free energy	35.1–51.2 mJ/m^2	Wu's geometric mean method
Contact angle of oil on paper	57.9°–67.2°	See Materials and Method Section

MATERIALS AND METHODS

Characterizing the Test Paper Set

The test paper set consisted of 16 commercial papers (samples 1–16), five of which were uncoated papers (samples 1, 4, 5, 7, 8), and the remaining were coated papers with varying coating compositions. A typical commercial silicon-based fuser oil with a viscosity of 5.75 cm^2/s (575 cSt) at 25°C and surface tension of 20.6 mJ/m^2 at 25°C was used in this investigation.

All samples were characterized for their physical, topographical and surface chemistry properties. Physical properties (basis weight, porosity, caliper, bending stiffness) were determined for each sample according to the standard test methods listed in Table I.

Surface topography of each sample was evaluated in terms of the root-mean-square (rms) roughness. Measurements were obtained using WYKO™ NT-2000, an optical noncontact surface profiler system. Surface profile measurement data were collected for each sample. The data were median smoothened, and the tilt in the data was removed to ensure that a completely horizontal surface was analyzed.

The surface chemistry of paper was characterized in terms of contact angle measurements of fuser oil on paper, surface free energy of paper, and work of adhesion between paper and oil. Static contact angles of fuser oil on all the papers were measured using the Fibro DAT contact angle machine. All samples were conditioned for at least 24 h in a controlled room at 23°C and 50% relative humidity (T402 TAPPI Standard). The contact angle measurements were also carried out in the conditioned room. For each drop of oil on the paper substrate, the static contact angle was measured as a function of time due to spreading on the substrate. For each paper sample, 16 contact angle-time profiles were obtained and, from these profiles, the contact angles at 1 sec were averaged. This resulted in an average contact angle of oil on paper at 1 sec for each sample.

The surface free energy of paper and the work of adhesion between paper and oil were also determined for all samples. Wu's geometric mean method, with diiodomethane and water as test liquids, was used to determine the surface free energy of the papers.[5] Literature values for the surface tension, 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.[5] The work of adhesion between paper and oil at ambient conditions ($W_{PO,AMB}$) was calculated using the Young–Dupré equation.[6] A $W_{PO,AMB}$ value was calculated for each paper using ambient contact angle measurements of fuser oil on paper at 1 sec. The surface tension of fuser oil at ambient temperature, $\gamma_{OIL,AMB}$ =20.6 mJ/m^2, was used.[7]

Evaluating the Oil Uptake Performance of the Test Paper Set

All paper samples were evaluated for their oil uptake performance by quantifying the amount of oil that each paper sorbed in the fusing nip. The amount of oil uptake for all blank paper samples was obtained using a prototype high-speed xerographic fusing system and inductively coupled plasma mass spectroscopy (ICP-MS). The detailed experimental procedure is described in a previous paper.[8]

Partial Least-Squares Regression Modeling

After characterizing the papers and obtaining oil uptake amounts for each sample, these two data sets were analyzed using partial least-squares (PLS) regression to determine the correlation structure between paper properties (input or x variables) and oil uptake (output or y variable). Partial least-squares (PLS) regression is an established multivariate statistical method that can extract the correlation structure between input and output variables from experimental data.[9] The dimensions of large data sets are reduced by projecting the relevant information onto low-dimension subspaces defined by principal components.[10] Using graphical methods, the data can then be analyzed easily to understand processes and to identify key factors that predict response variables.

In this study, partial least-squares (PLS) regression is used to model the relationship between paper properties (x) and oil uptake (y). Traditionally, multiple linear regression (MLR) is used in relating a response variable (y) to a set of x variables, but PLS is more robust because unlike MLR, PLS can handle large numbers of x variables, highly dependant variables, and noisy data.[10] Simca-P software by Umetrics was used to analyze the data.

The PLS model performance was assessed using the loading plot and the parameters, R^2Y and Q^2. R^2Y is a multiple correlation coefficient between the measured response (y) and the predicted response ($\hat{y}_{PRED}$) values. The Q^2 parameter denotes the model's ability to predict the response. An ideal model[10] has R^2Y and Q^2 values of >0.5 while minimizing Δ, the difference between R^2Y and Q^2. Further details of the PLS regression method used in this study are given in a previous paper.[8]

RESULTS AND DISCUSSION

Test Paper Set

All papers were characterized and the samples cover a broad range of the assessed properties as summarized in Table I. Paper samples range from text weight to cover stock for both coated and uncoated papers.

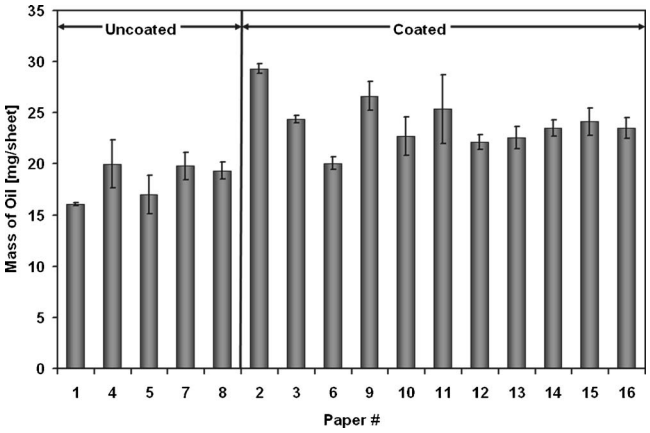


Figure 2. Oil uptake amounts for all paper samples. Sheet size is 8.5 ×11 in.

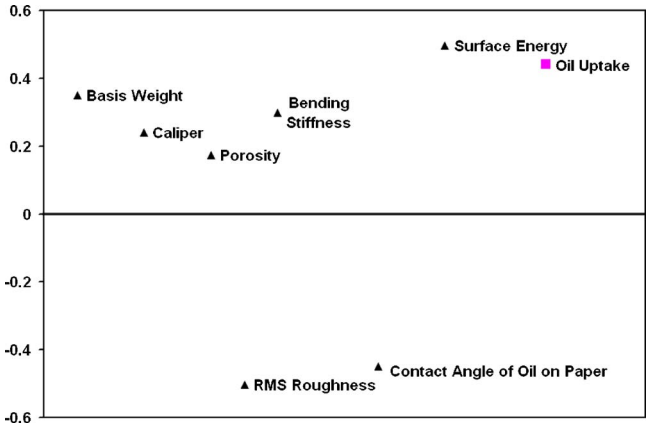


Figure 3. Loading plot for the PLS model. Key paper properties (x) correlated with oil uptake (y) are identified. $R^2Y=0.72$ and $Q^2=0.61$ with $\Delta=R^2Y-Q^2=0.11$.

Oil Uptake Data

Oil uptake data for all paper samples are shown in Figure 2. It is important to note that the experimental technique used to quantify oil uptake results in higher oil uptake values than observed when printing on a commercial press. Therefore, the results should be interpreted in terms of relative oil uptake amounts among the paper samples.

In general, coated papers appear to have higher oil uptake amounts than uncoated papers. However, some coated papers, such as sample 6, have small oil uptake values that are similar to that of uncoated papers. To gain insight into the relationships between paper properties and oil uptake, the oil uptake data are correlated with the properties of all the samples using PLS regression.

Key Paper Properties Identified by the PLS Regression Model

PLS regression was performed on the oil uptake (y) and paper properties (x) data sets. All the paper properties listed in Table I were used as x-variable inputs into the initial PLS regression model. The data were mean centered and scaled to unit variance. One principal component, calculated through cross-validation, was found to sufficiently explain the variance in the data, resulting in R^2Y and Q^2 values of 0.72 and 0.61 respectively with $\Delta=R^2Y-Q^2=0.11$.

The correlation structure between paper properties and oil uptake are identified in the loading plot (Figure 3). Variables with a PLS weighting factor, w^*c, of the same magnitude and sign as that of oil uptake have strong positive correlations, while variables with negative w^*c values have negative correlations with oil uptake. rms roughness and contact angle measurements, for example, are furthest from zero in the negative direction ($w^*c<-0.5$), and thus have a strong negative correlation with oil uptake. Surface free energy has the highest PLS weight ($w^*c>0.5$), and therefore has the strongest positive correlation with oil uptake. Basis weight, bending stiffness, and caliper have moderate positive correlations with oil uptake, with PLS weight values between 0.2 and 0.4. With the lowest PLS weight ($w^*c<0.2$), porosity based on Gurley seconds has the weakest positive correlation with oil uptake. Therefore, the loading plot reveals that papers with high roughness and high surface energy correspond with large oil uptake amounts.

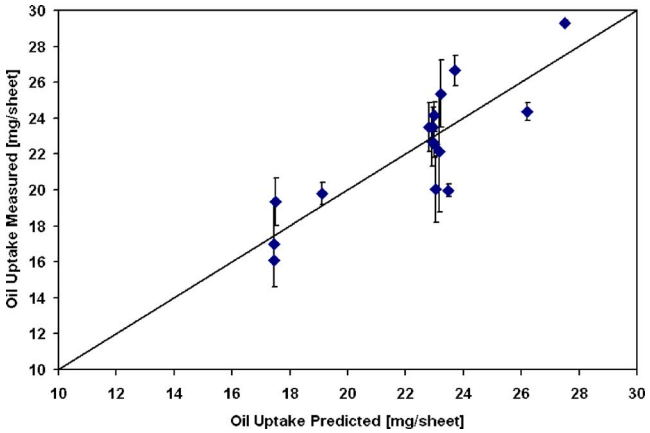


Figure 4. Observed oil uptake data (y_{measured}) vs predicted oil uptake ($\hat{y}_{\text{PLS predicted}}$) values from the PLS model. $R^2Y=0.72$ and $Q^2=0.61$. Each data point represents a different paper sample.

For this PLS regression model, Figure 4 compares the observed (y_{measured}) and the predicted values ($\hat{y}_{\text{PLS predicted}}$) of oil uptake. The model's ability to predict oil uptake well is shown in Fig. 4, where a good scatter of the data points around the 45° line is present.

The equation for the final PLS regression model is

$$\hat{y}_{\text{PLS predicted}} = 0.22x_{\text{SFE}} + 0.16x_{\text{BWT}} + 0.13x_{\text{STF}} + 0.11x_{\text{CAL}} + 0.08x_{\text{POR}} - 0.22x_{\text{RMS}} - 0.20x_{\text{CA}} + 6.4, \quad (1)$$

where SFE=surface free energy of paper, BWT=basis weight, STF=bending stiffness, CAL=caliper, POR=porosity in Gurley seconds, RMS=rms roughness, and CA=ambient contact angle measurements of oil on paper. The coefficients are based on mean centered and unit variance scaled data. To accurately predict absolute values for oil uptake, this model must be validated with an external data set, consisting of a large number of new and well characterized paper samples.

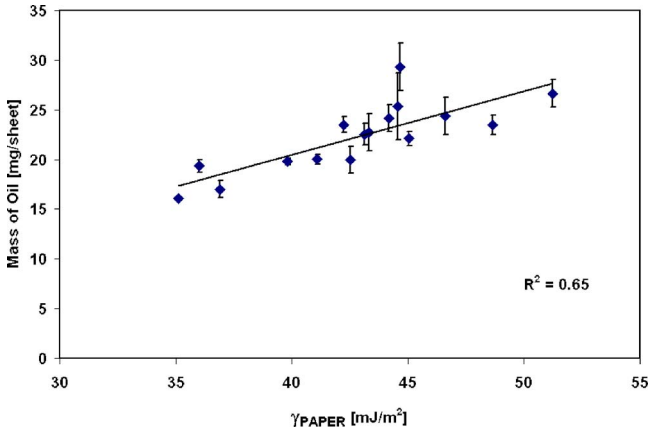


Figure 5. Oil uptake vs surface free energy of paper, R^2=0.65.

Mechanistic Understanding of Fuser Oil-Paper Interactions in the Fusing Nip

Although PLS regression reveals positive and negative correlations between x and y variables, PLS regression does not ascertain cause and effect relationships between the two data sets. Therefore, it is necessary to gain a mechanistic understanding of how these interacting paper properties affect the oil uptake process. The key properties identified by PLS suggest that oil uptake is highly related to two effects: the wetting behavior of oil on paper and the nip contact area between paper and the fuser roll. These two mechanisms are further examined to explain how oil is physically transferred to paper within the fusing nip.

Wetting Behavior of Fuser Oil on Paper

From the PLS regression model, a negative correlation between oil uptake and ambient contact angle measurements of oil on paper was observed. As the contact angle of oil on paper decreases, wetting increases and the result is more oil uptake. Therefore, contact angle measurements of oil on paper at ambient conditions can be used as a tool to predict the wetting behavior of oil on paper during uptake in a fusing nip.

The wetting behavior of oil on paper was further investigated by looking at the effect of surface free energy (SFE) of paper on oil uptake. From the PLS model, a positive correlation between oil uptake and SFE is present. 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 energies. As the surface energy of paper increases, further wetting of oil occurs and the result is an increase in oil uptake. This result follows the same approach by Sanders et al.,[11] where it was found that higher energy surfaces promoted wetting and spreading of molten toner on paper. The positive correlation between oil uptake and SFE can also be seen in the independent linear regression plot of these two variables (Figure 5), where an increase in SFE of paper results in an increase in oil uptake, as the surface tension of oil remains constant. With a good positive correlation (R^2=0.65) between these two variables, SFE of paper is shown to be an important paper property in explaining the effect of wetting on oil uptake; therefore, it is a mechanism by which the oil uptake trend can be partially explained. It is important to note that while the correlation between oil uptake and SFE of paper is determined at ambient conditions, it is expected that the surface energy of the paper will not change significantly with fusing temperature (185°C) due to a short residence time of the paper within the fusing nip (30 ms).

Table II. Ambient work of adhesion between fuser oil and paper for all paper samples.

	Paper Sample No.	$W_{PO,AMB} = \gamma_{OIL}(1+\cos\theta)$ (mJ/m^2)
Uncoated papers	1	28.80
	4	29.58
	5	28.70
	7	29.02
Coated papers	2	31.45
	3	31.40
	6	31.51
	9	30.80
	10	31.15
	11	31.49
	12	31.20
	13	31.56
	14	31.51
	15	31.14
	16	30.01

The surface chemistry effect of paper on oil uptake is also investigated by looking at the ambient work of adhesion between paper and oil ($W_{PO,AMB}$). The calculated values for all paper samples are listed in Table II. In general, the work of adhesion between oil and uncoated papers is slightly lower than the work of adhesion between oil and coated papers. Figure 6 shows a positive correlation between oil uptake and $W_{PO,AMB}$. This indicates that to minimize oil uptake the work necessary to separate oil from paper must be minimized, which is achieved by lowering the surface free energy of the paper surface.

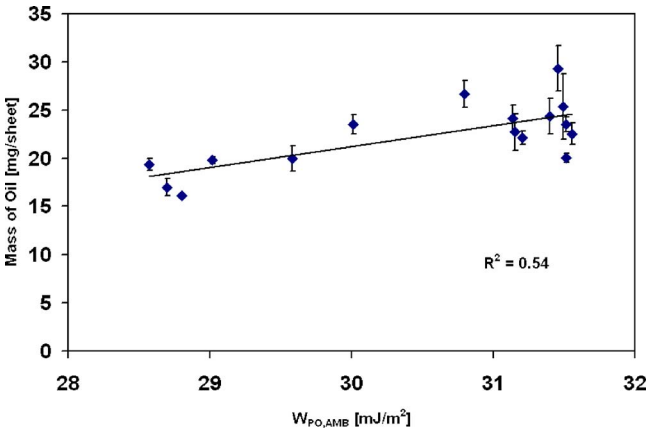


Figure 6. Oil uptake vs ambient work of adhesion between paper and oil, $W_{PO,AMB}$.

Relative Contact Area Between Paper and the Fuser Roll in the Nip

Oil uptake is also examined with respect to the contact area between paper and oil within the fusing nip. This contact area is examined on the microscopic scale, where surfaces exhibit asperity peaks and valleys. As a result, when two surfaces touch, 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 modeled using theory from contact mechanics and in relation to the identified key nonsurface chemistry related properties (basis weight, caliper, stiffness, and rms roughness). The transfer of oil from the fuser roll to paper is then examined as a function of this relative contact area at the nip.

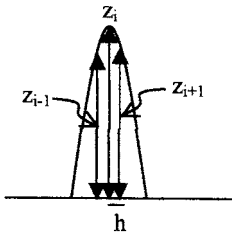
Greenwood and Williamson developed a theory for the elastic contact of rough surfaces that takes into account surface topography and elastic deformation based on Hertz theory.[12] The model assumed that contact occurs at the asperity peaks of the surface, and that the total contact area is the sum of the contacting areas of the peaks. According to Greenwood and Williamson,[12] for a negative exponentially distributed rough surface, the relative contact area parameter, A_{re}, is defined as

$$A_{re} = \sqrt{\frac{\pi}{\sigma k}}\left(\frac{P}{E'}\right), \tag{2}$$

where σ is the root-mean-square (rms) roughness value, E' is a complex modulus defined in Eq. (3), and k is the rms value of the peak curvature and is defined in Eq. (4),[12]

$$\frac{1}{E'} = \frac{(1-\nu_{\text{paper}}^2)}{E_{\text{paper}}} + \frac{(1-\nu_{\text{roll}}^2)}{E_{\text{roll}}}. \tag{3}$$

$$k = \sqrt{\frac{1}{N_A}\sum_{i=1}^{N_A}\left[\frac{(z_{i+1} - 2z_i + z_{i-1})}{h^2}\right]^2} \tag{4}$$



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. The surface texture parameter was also defined as a dimensionless parameter, $R_f=(\sigma)(k)$, by Yan and Aspler[13]; σ and k are obtained from surface profile measurement data using Eq. (4), 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_A is the total number of peaks measured.

The rms roughness and k values for the test paper set are shown in Table III, and these values are in agreement with those published by Yan and Aspler.[13] As expected, rms roughness values for uncoated papers are greater than those of coated papers. Curvature parameters appear to be greater for uncoated papers than for coated papers.

Table III. rms roughness and curvature parameter (k) values for all paper samples.

	Paper Sample No.	rms Roughness (μm)	Standard Deviation for rms Roughness	Average k (1/μm)	Standard Deviation for k
Uncoated papers	1	5.83	0.38	1.35	0.05
	4	3.24	0.11	0.74	0.04
	5	4.84	0.17	1.21	0.03
	7	4.10	0.38	1.02	0.14
	8	4.73	0.05	1.16	0.12
Coated papers	2	1.25	0.01	0.17	0.02
	3	1.20	0.11	0.20	0.02
	6	1.40	0.04	0.20	0.01
	9	1.61	0.11	0.30	0.04
	10	1.44	0.03	0.24	0.01
	11	1.61	0.06	0.25	0.01
	12	1.81	0.13	0.29	0.02
	13	1.80	0.16	0.26	0.01
	14	1.58	0.09	0.24	0.01
	15	1.50	0.02	0.28	0.004
	16	1.26	0.05	0.17	0.01

Based on the work by Greenwood and Williamson[12] as well as Yan and Aspler,[13] a contact area index (CI) is developed to describe the degree of contact between the paper and the fuser roll at the nip [Eq. (5)]. This index represents the relative contact area as a function of rms roughness (σ), asperity peak curvature (k), and complex modulus (E'). E' combines the modulus of paper and that of the fuser roll. In this study, the fuser roll was silicon rubber and for Eq. (3), $E_{\text{roll}}=2$ MPa, and Poisson's ratio, $\nu_{\text{roll}}=0.5$, at 175°C were used[7] as estimated 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 Eq. (6).[14] Changes in Poisson's ratio among the paper samples were assumed to be negligible, and a constant Poisson's ratio of $\nu_{\text{paper}}=0.4$ was used.[15] 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,

$$\text{CI} = \frac{A_{re}}{\beta\sqrt{\pi}} = \frac{1}{\sqrt{\sigma k}}\frac{C}{E'}, \tag{5}$$

$$E_{\text{paper}} = \frac{12S}{C^3}. \tag{6}$$

Although CI is not a measurement for the actual contact area between paper and the fuser roll at the nip, it is an

Table IV. Contact area index, CI, values for all paper samples.

	Paper Sample No.	CI $\times 10^{-7}$	StDev $\times 10^{-7}$
Uncoated papers	1	0.21	0.007
	4	0.36	0.12
	5	0.19	0.08
	7	0.35	0.02
	8	0.17	0.002
Coated papers	2	2.23	0.03
	3	0.96	0.08
	6	1.99	0.01
	9	0.63	0.06
	10	0.86	0.02
	11	0.79	0.03
	12	0.70	0.04
	13	0.73	0.03
	14	0.82	0.04
	15	0.78	0.002
	16	0.90	0.05

indication of the degree of contact that would result when paper contacts the fuser roll. A paper sample with a lower CI value indicates a lower relative contact area with the roll than that of a paper with a higher CI value. A CI value was calculated for each sample, which allowed for a relative comparison among papers for their degree of contact with the fuser roll. The results are summarized in Table IV.

When two surfaces touch, the actual contact is assumed to occur at the tips of the paper surface asperity peaks.[12] In the case of coated or smooth papers, the asperity peaks are broader than the asperity peaks on uncoated or rougher papers. As a result, the peak surface area in contact with the fuser roll is larger for coated papers, and CI will be greater for coated papers. The trend in Table IV, that coated papers have greater CI values than uncoated papers, is in good agreement with this explanation. Furthermore, as peak contact area increases with the fuser roll or as CI increases, further oil uptake by paper is expected. Figure 7 shows a positive linear trend between oil uptake and CI. While R^2 is not too high, the positive trend indicates that surface texture (roughness) and stiffness of paper (which encompasses effects from basis weight and caliper) have an affect on oil uptake.

The approach in applying contact mechanics to examine oil uptake by paper has been simplified, where nip residence time and oil thickness were considered constant due to steady-state conditions in the fusing apparatus. A good basis for understanding oil uptake by paper during fusing has been established, and further study is warranted to investigate the affect of oil rheology on the oil uptake process.

Simplified Model for Oil Uptake

Overall, the 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. These parameters characterize two separate mechanisms by which paper takes up oil from the fuser roll. Surface free energy characterizes the dominant surface chemistry effect of paper within the fusing nip, where wetting of oil on paper is promoted as paper surface energy increases. CI, on the other hand, accounts for the effects of physical paper properties on oil uptake, where an increase in nip contact area between paper asperity peaks and the fuser roll results in an increase in oil uptake. Therefore, with CI and SFE as dominant factors in describing oil uptake by paper, a multiple linear regression (MLR) model is developed using CI and SFE as independent parameters. After scaling CI and SFE to unit variance, the MLR model is

$$\hat{y}_{\text{MLR predicted}} = 2.25x_{\text{SFE}} + 1.27x_{\text{CI}} - 1.65, \qquad (7)$$

with $R^2 = 0.8$. Figure 8 compares y_{measured} with $\hat{y}_{\text{MLR predicted}}$, which shows that SFE and CI describe oil uptake well.

Figure 9 is a three-dimensional (3D) contour plot summarizing the relationship between oil uptake, surface free energy (SFE) of paper, and contact area index (CI). The linear relationship between oil uptake and CI, and between oil uptake and SFE are evident from this plot.

Of the paper properties included in the PLS model, further study is required to ascertain the relationship between

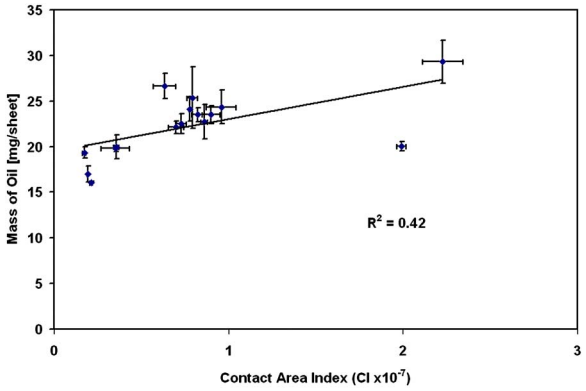


Figure 7. Positive correlation between oil uptake and contact area index (CI) is illustrated.

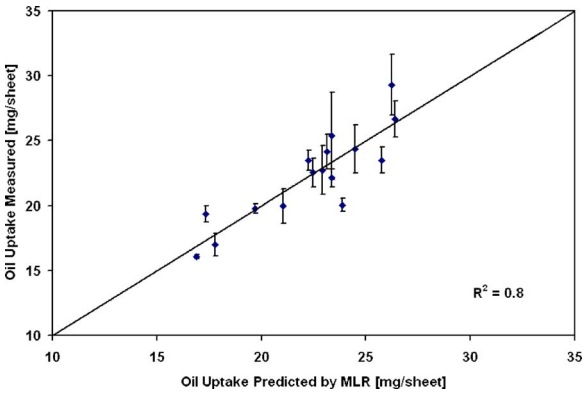


Figure 8. Oil uptake measured (y_{measured}) vs oil uptake predicted by the MLR model ($\hat{y}_{\text{MLR predicted}}$), $R^2 = 0.8$.

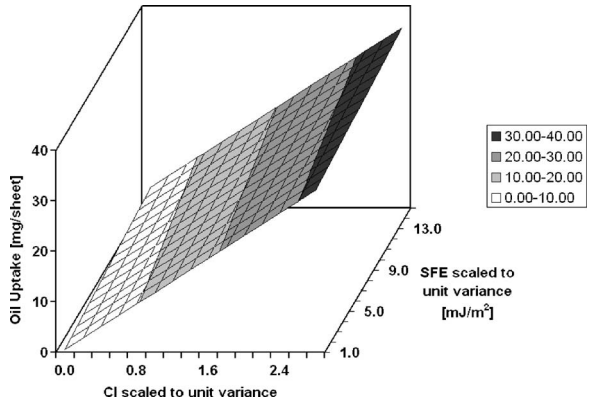


Figure 9. The 3D contour plot describes the relationship between oil uptake, surface free energy of paper, and contact area index (CI).

porosity and oil uptake. It is expected that porosity may play a minor role in the initial transfer of oil from the fuser roll to paper. The effects of pore size, volume, and distribution on oil uptake all require thorough investigation. In addition, work of adhesion between oil and paper at fusing conditions has a good potential for describing the oil uptake process within the fusing nip. At ambient conditions, $W_{PO,AMB}$ was found to have a positive correlation with oil uptake; however, with work of adhesion values calculated at conditions similar to fusing conditions ($W_{PO,fusing}$), the correlation between $W_{PO,fusing}$ and oil uptake may improve. Therefore, $W_{PO,fusing}$ may also help to account for the unexplained variance in the oil uptake data. Moreover, surface tension of oil and accurate contact angle measurements of oil on paper at fusing conditions require further investigation in order to accurately calculate $W_{PO,fusing}$.

CONCLUSIONS

A systematic study was carried out to investigate the relationship between fuser oil uptake and paper properties in high-speed xerographic printing. A partial least-squares (PLS) regression model was developed to identify the key paper properties that are significantly correlated with the uptake of a typical silicon-based oil; rms roughness and ambient contact angle measurements of the oil on paper were found to have strong negative correlations with oil uptake. Caliper, basis weight, bending stiffness, and surface free energy had positive correlations with oil uptake.

Contact angle measurements and SFE were both included in the PLS model. Although both parameters describe the surface chemistry of paper, the contact angle measurements were more convenient to obtain as it involved only one fluid, fuser oil. The PLS results showed that both parameters indicate the same trend with oil uptake, providing the experimenter with confidence to use the more convenient method to determine the correlation between oil uptake and surface chemistry of paper. Furthermore, the predictive ability of this PLS model will improve with validation using a new paper set.

Surface free energy (SFE) of paper was found to have the strongest positive correlation with oil uptake in the PLS regression model, and this positive correlation was also confirmed in a linear regression of the two parameters with an $R^2=0.65$. Therefore, SFE was determined to be a dominant property that describes the wetting behavior of oil on paper.

A contact area index (CI) was used to compare the degree of contact between paper and the fuser roll at the nip. CI was developed as a function of surface texture (rms roughness and surface curvature), nip pressure as estimated as a function of caliper, and elastic moduli of paper and the fuser roll. CI and oil uptake were found to have a positive correlation, suggesting that surface texture and stiffness of the paper have significant influences on oil uptake.

A multiple linear regression model was developed by regressing oil uptake against CI and SFE. Both CI and SFE were treated as independent factors affecting oil uptake. These two factors were found to be dominant parameters in predicting oil uptake, as the MLR model accounted for 80% of the variance in the oil uptake data. Therefore, oil uptake can be explained mechanistically in terms of the wetting behavior of oil on paper and by a contact area index to describe the degree of contact between paper and the fuser roll at the nip. Other factors that potentially may have significant affects on oil uptake are surface porosity of paper and the work of adhesion between oil and paper at fusing conditions. Both parameters require further investigation.

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