The Effect of Ink Jet Papers Roughness on Print Gloss and Ink Film Thickness

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Abstract

Roughness of a variety of commercial ink jet papers was tested by Parker Print Surf (PPS), EMVECO stylus profilometer and Atomic Force Microscopy (AFM). The papers were printed on three Epson ink jet printers. Correlations between roughness and paper or print gloss were studied. From all three roughness-testing methods used, the best correlation was found for AFM. Topography of ink film was also studied by AFM.

Introduction

The worldwide importance of electronic print processes is constantly increasing. The growth of multi color ink-jet technology is especially growing for the home and office markets [1]. A large and growing consumer market for ink jet has become noticed in packaging, publication, and specialty areas. The quality of ink jet printing is influenced by the printers in use as well, as by the physico-chemical properties of printing ink and print substrate. To mention a few, these interactions are influenced by interfacial charges, wettability, and adsorption phenomena. An ink-jet recording sheet comprises a support such as paper, at least one ink-receiving layer on the support, and a gloss-providing layer formed on the ink-receiving layer. The ink-receiving layer consists essentially of a pigment and a binder [2-5]. The gloss-providing layer consists of a pigment and a synthetic polymer formed from a latex or water soluble polymer as a binder[2-6].

Roughness, or smoothness, of paper is a very important property for print quality. Surface roughness is usually divided into microscale and macroscale components[7,8]. Although there is not total agreement on the boundary between those two, the macroscale component consists of features larger than 10 μm and is usually due to poor fiber dispersion, ionic destabilization or flocculation, roughness of base paper, or insufficient coating or calendaring. The microscale component consists of features considerably smaller than 10μm, due to pigment particle size distribution, particle shape, binder type, film shrinkage, drying condition, coating holdout, and coating weight[5]. Research groups studying the roughness and its effect on gloss agreed upon the fact that common roughness numbers are insufficient to predict gloss[8]. It sometimes occurs that the rougher surfaces have higher gloss. From the classical roughness measuring methods, the Parker Print-Surf (PPS)[9] method has been widely used in paper and printing industries because of the possibility of measuring roughness at different pressures, from 500 to 2000 kPa, to mimic the conditions at a printing nip. The PPS tester uses a contact air-leak principle, measuring air flow between substrate in a 51μm wide ring. It recalculates the airflow into a mean gap between the surface and the flat circular land pressed against it[9]. The measurement obtained from all air-leak instruments is called macro-roughness. One key disadvantage is that these instruments lack the sensitivity to measure on a scale small enough to be relevant to printing. For example, a half-tone dot can range from 20 to 60μm in diameter. Various air-leak measurements can span widths ranging from 51 to 13,500 μm[10]. Therefore, the need for measuring micro-roughness is growing.

Surface characterization using atomic force microscopy (AFM) has been reported recently[11-13]. AFM was invented by Binnig [14], and introduced in 1985 by Binnig, Quate, and Gerber, as an offshoot from the scanning tunneling microscope [15] (STM).Since then, AFM has rapidly developed into a powerful and invaluable surface analysis technique on both micro- and nanoscale. The sample surface is scanned with a sharp tip mounted on a cantilever. The small deflections of the cantilever are measured using a focused laser beam, which is reflected off the cantilever to a photodiode detector. The x, y, z piezoelectric scanner located under the sample provides the precise movement of the sample. The variation in voltage signals from the photodiode detector as a function of probe position is converted into a 3D image by image processing system[16].

The tapping mode in AFM was developed especially for studying soft and fragile samples. Instead of dragging the tip across the surface in the conventional contact mode, the tapping mode is done by oscillating the cantilever with a frequency of few hundred kilohertz near its resonance. The oscillation and the force on the sample are maintained constant by a feedback loop. The tip is brought close to the surface until it begins to touch the surface by tapping it gently. While scanning the surface, the amplitude alternates depending on the topography. No lateral, shear, or friction force is applied to the sample and no sticking occurs, since the tip contacts the surface briefly during each oscillations[17]. Therefore, tapping mode AFM is suitable for studying paper samples.

Newer methods for measuring micro-roughness are the stylus profilometer [18] and laser profilometer [19]. A stylus profilometer uses a preloaded fine cone-shaped stylus dragged across the surface. The vertical movement of the stylus compresses a piezoelectric element, which generates a fairly linear voltage response. The stylus profilometer is widely used to characterize the surface roughness of metals. When it is applied to paper, the stylus traces could be observed depending on the conditions of stylus radius and load, and the surface hardness of paper[18]. It was found that careful selection of stylus radius and load conditions can ensure no permanent damage of paper surface. The newer laser profilometer uses a monochromatic laser light source. It is a non-contact method so there is no damage to the paper surface [19].

Other reported non-contact methods include confocal laser scanning microscopy (CLSM)[20], 3D sheet analyser[21], interferometric microscopy[22]. The roughness is calculated from a 3D topographic image of paper surface obtained through optical methods. The goal of this project was to compare three different test methods for surface roughness of ink jet printing papers and find the most relevant one, which should be in the best correlation with paper gloss as well as print gloss.

Experimental

Samples

Three commercial Epson ink jet photo papers, Premium Glossy Photo Paper, Premium Luster Photo Paper, and Archival Matte Paper, along with Kodak ink jet premium picture papers, High Gloss Picture Paper and Satin Picture Paper were used in all experiments. Other print properties of these samples were discussed in a companion paper [23].

Printing

Three different ink jet printers were used: the Epson Stylus® Pro 5000 ink jet with a dye-based ink set, the Epson Stylus® Pro 5500 ink jet employing Archival ink technology, and the Epson Stylus® Photo 2200 ink jet printer with UltraChrome ink [23].

Parker Print-Surf (PPS)

A Messmer Instrument PPS Model 90 was employed at pressure of 2000kPa and hard backing. The roughness was calculated as the mean of 10 readings at different locations.

Stylus Profilometer

An EMVECO® Electronic Microgage Model 210 with the spherical steel stylus having a radius of 1μm was used. The test conditions were 500 readings per group, 3 groups, 0.1mm reading space, and 0.5mm/s scanning speed. A roughness profile was obtained, as shown in **Figure 1**. The roughness R was calculated using equation (1):

$$R = \Sigma (X_{i+1} - X_i) / 499 \qquad i = 1, 2, \cdots, 499 \quad \textbf{(1)}$$

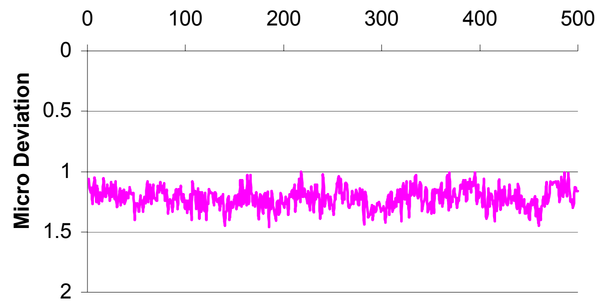

Figure 1. *Emveco Roughness profile measured as Micro Deviation [μm].*

Atomic Force Microscopy (AFM)

The AFM measurements were carried out using a Park Scientific Instruments Model Autoprobe CP, Scanning Probe Microscopy with Proscan version 1.3 software. The non-contact tapping mode was used with a silicon tip of 20nm in diameter. The samples were attached to the sample holder with double-sided tape. Topographic data were obtained over a 70μm × 70μm area. The scanning rate was 0.5Hz. All images were flattened, i.e., the mean plane of the height distribution was subtracted from each image. The roughness values were reported as the root-mean-square (rms) deviation of the surface heights from the mean surface plane. The surface was observed after all measurements. There were no visible scratches on the paper surface after measurements and therefore it can be concluded that the pressure on profilometer and AFM was not too high to damage the paper surface.

Paper and Print Gloss

Paper gloss (at 60 and 75˚) was measured using a Gardco® Novo-Gloss™ Glossmeter. The gloss of printed samples was tested on CMYK solid colors using the same geometries.

Results and Discussion

Atomic Force Microscopic (AFM) images of Glossy, Luster, High gloss, and Satin papers are shown at **Figure 2**. The surface of Glossy paper is smoothest from all substrates, averaging 9.71 nm. The surface of Luster (22.39 nm) and High Gloss paper (18.11nm) were considerably rougher than Glossy paper. Satin paper has very rough surface, reaching 312.1 nm. The surface of Matte paper was too rough for current settings of AFM. The maximum vertical depth the tip can reach was 6μm, so the AFM could not be used when the distance between the highest peak and the lowest valley of the surface exceeded 6μm. Apparently, this method can only be applied ton relatively smooth surfaces.

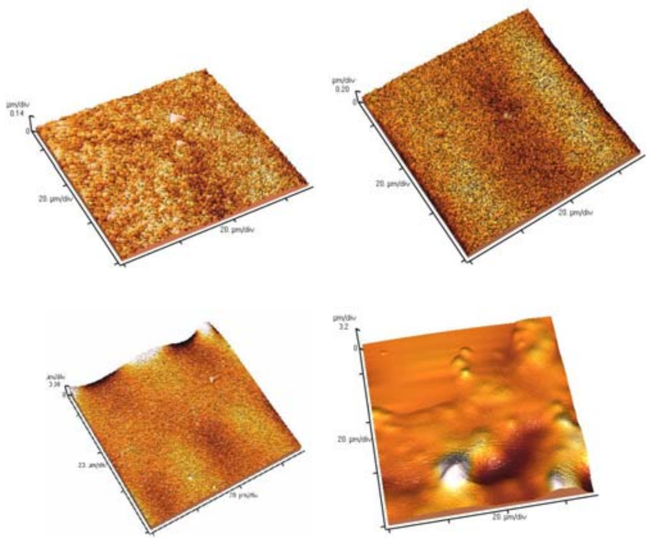

***Figure 2**. AFM images of paper topography: Glossy (upper left), Luster (upper right), High gloss (lower left), and Satin (lower right)*

The comparison of the results of the three roughness testing methods as well as the results of paper and print gloss are presented in **Tables 1-4**. Correlation coefficients for roughness method and paper/print gloss are given in **Table 5**. A good correlation exists between the PPS and stylus profilometer test methods (93.7%). A little lower correlation was obtained between PPS and AFM (90.3%) and between stylus profilometer and AFM (89.3%), which is surprising, because it was expected that both profilometric techniques will correlate better, while PPS, measuring at pressure, will include compressibility and thus, give a lower correlation. It is important to note that the PPS roughness is often two orders of magnitude lager than the other two methods. Glossy paper was the smoothest, while Matte paper was the roughest according to all three methods. Luster, High Gloss and Satin paper have close PPS roughness, but Luster paper has much higher profilometer roughness, and Satin paper has much higher AFM roughness. It probably means that the surface of Luster paper is rough on a microscale, but smooth on nanoscale. On the contrary, the surface of the Satin paper is smooth at the microscale, but rough on nanoscale.

Table 1: Roughness of papers by different methods

Sample No.	PPS (µm)	Profilometer (nm)	AFM (nm)
Glossy	1.04	14.0	9.71
Luster	3.23	90.4	22.39
Matte	6.78	173.4	-
High Gloss	3.22	37.1	18.11
Satin	3.11	42.2	312.1

Table 2: Paper and Print Gloss (75° upper and 60° lower) from Pro 5500 Ink Jet Printer.

Sample Name	Paper gloss (%)	Print gloss (%) C	M	Y	K
Glossy	62.92	102.3	106.4	101.4	107.1
Luster	50.84	82.6	89.0	85.1	81.8
Matte	6.8	4.2	4.1	5.8	2.7
High Gloss	95.00	89.6	80.9	82.6	99.7
Satin	67.54	81.1	72.2	69.1	94.7

Sample Name	Paper gloss (%)	Print gloss (%) C	M	Y	K
Glossy	34.64	82.5	98.4	86.8	110.5
Luster	17.06	42.1	51.4	49.2	52.5
Matte	2.60	1.0	0.8	1.9	0.3
High Gloss	77.80	66.0	45.5	50.1	90.0
Satin	27.04	39.7	28.4	30.4	52.8

Table 3: Print gloss (75° upper and 60° lower) for Photo 2200 Ink Jet Printer

Sample Name	Print gloss (75°, %) C	M	Y	K
Glossy	85.3	97.6	98.8	113.8
Luster	75.5	83.4	85.9	91.7
Matte	3.8	3.9	5.5	3.0
High Gloss	89.0	91.7	89.5	113.2
Satin	75.8	82.7	79.6	86.3

Sample Name	Print gloss (60°, %) C	M	Y	K
Glossy	59.5	76.9	92.9	101.5
Luster	34.8	44.8	46.3	55.7
Matte	0.9	0.7	2.1	0.4
High Gloss	57.5	74.5	70.8	77.8
Satin	36.6	45.6	40.8	44.8

Table 4: Print gloss (75° upper and 60° lower) for Pro 5000 Ink Jet Printer.

Sample	Print gloss (75°, %)			
No.	**C**	**M**	**Y**	**K**
Glossy	64.5	68.3	73.6	70.2
Luster	53.8	54.5	57.1	51.3
Matte	3.7	3.5	4.7	2.1
High Gloss	83.5	84.2	98.3	84.2
Satin	75.0	75.3	81.4	68.0
Sample	Print gloss (60°, %)			
No.	**C**	**M**	**Y**	**K**
Glossy	40.1	47.4	50.2	40.0
Luster	18.6	19.3	21.6	20.1
Matte	1.0	0.8	1.9	0.3
High Gloss	62.8	68.4	72.2	64.4
Satin	38.8	40.6	42.1	30.5

Table 5: Correlation coefficients for paper gloss and ink gloss for different printers.

				G	l	o	ss	
	PPS	**Profilometer**	**AFM**	**Paper**	**C**	**M**	**Y**	
Profilometer	0.937	1						
AFM	0.903	0.893	1					
75° Gloss Paper	-0.737	-0.887	-0.877	1				
5500-C	-0.959	-0.946	-0.985	0.871	1			
5500-M	-0.969	-0.895	-0.967	0.782	0.985	1		
5500-Y	-0.962	-0.903	-0.973	0.812	0.989	0.998	1	
5500-K	-0.941	-0.970	-0.975	0.908	0.992	0.955	0.962	
60° Gloss Paper	-0.468	-0.676	-0.598	1				
5500-C	-0.938	-0.927	-0.850	0.693	1			
5500-M	-0.918	-0.769	-0.731	0.357	0.912	1		
5500-Y	-0.939	-0.821	-0.794	0.460	0.951	0.992	1	
5500-K	-0.927	-0.930	-0.837	0.713	0.999	0.898	0.939	
75° 2200-C	-0.908	-0.935	-0.990	0.916	1			
75° 2200-M	-0.939	-0.941	-0.992	0.880	0.996	1		
75° 2200-Y	-0.947	-0.927	-0.992	0.855	0.990	0.998	1	
75° 2200-K	-0.928	-0.941	-0.977	0.905	0.992	0.991	0.989	
60° 2200-C	-0.914	-0.953	-0.897	0.782	1			
60° 2200-M	-0.910	-0.946	-0.892	0.785	1.000	1		
60° 2200-Y	-0.934	-0.908	-0.828	0.665	0.970	0.973	1	
60° 2200-K	-0.943	-0.905	-0.854	0.653	0.971	0.974	0.998	

Table 5 continued

75° 5000-C	-0.804	-0.927	-0.925	0.978	1			
75° 5000-M	-0.828	-0.942	-0.932	0.976	0.999	1		
75° 5000-Y	-0.791	-0.928	-0.906	0.991	0.996	0.996	1	
75° 5000-K	-0.849	-0.955	-0.930	0.981	0.990	0.994	0.994	
60° 5000-C	-0.666	-0.863	-0.745	0.943	1			
60° 5000-M	-0.695	-0.879	-0.745	0.939	0.997	1		
60° 5000-Y	-0.696	-0.875	-0.747	0.943	0.996	1.000	1	
60° 5000-K	-0.656	-0.827	-0.740	0.973	0.985	0.987	0.990	

Some gloss values for Glossy paper and High Gloss were out of the measurement range at one or the other angles but are presented just for comparison reasons. he 75^0 angle appears the most suitable for comparison of all the substrates in this experiment. The correlation of PPS roughness and paper gloss is low, reaching 72.2%. EMVECO profilometer and AFM showed higher correlations (88.0% and 86.4%). Interestingly, both Kodak papers are rougher than Epson Glossy paper, but have much higher gloss values, especially High Gloss paper. According to Fresnel theory[5,24], The gloss of paper is determined by the incident angle of light, incident light wavelength, and refractive index and the surface roughness of the paper. For an instrument of defined incident angle of light and wavelength, the gloss is determined by the refractive index and surface roughness of the paper. In this experiment, the wavelength and angle of incident light was the same for all the samples. Therefore, the reason probably was that Kodak paper has coating layer with higher refractive index than Epson papers.

The correlation of roughness to print gloss is higher than to paper gloss with all three methods. The test method with highest correlation of nearly 100% to print gloss is AFM with the Photo 2200 printer. AFM and stylus profilometer both have high correlation to print gloss with all three printers, and PPS only has low correlation with the Pro 5000 printer. Ink jet printing is non-impact printing, not like the classical printing processes with contact pressure, so the ink film surface topography depends on paper surface. Since the ink is the same for the same printer, the refractive index of each ink film is the same for all the samples. Therefore, the print gloss value is more determined by the surface roughness.

The ink also has effect on the print gloss, which can be seen by comparing the three different printers. Paper gloss and print gloss correlate much more for the Pro 5000 printer (>97%) than the other two. The Pro 5000 printer uses dye-based ink, unlike other two printers using pigment-based ink. Dyes are made of single molecules, while pigments are composed of much larger particles around 100 nm [23]. Pigment-based inks can achieve very high positive delta gloss (Delta gloss is the difference between print and paper gloss), because of packing of ink particles with coating pigment particles. Paper coating gloss depends on packing of different size coating pigment particles [3,5]. Dye-based inks cannot improve upon the paper because the dye molecules are too small to efficiently fill the low spots in the coating. Sometimes even negative delta gloss was obtained, because the water based inks can swell the coating.

Figure 3 shows AFM images of black ink film surface on Glossy paper printed by all three printers. Ink droplets can be observed clearly in the images of the Pro 5500 and Photo 2200 printers. Dyes were distributed very evenly in the image of Pro 5000 printer. Their RMS roughness values are 31.77nm, 36.09nm and 27.7nm respectively (from left to right and down). The Pro 5000 printers use dye-based inks, therefore the ink film surface is smoother than using pigment-based inks because dyes have smaller particle sizes than pigments. This ink film roughness is, however, about three times larger than the corresponding paper gloss.

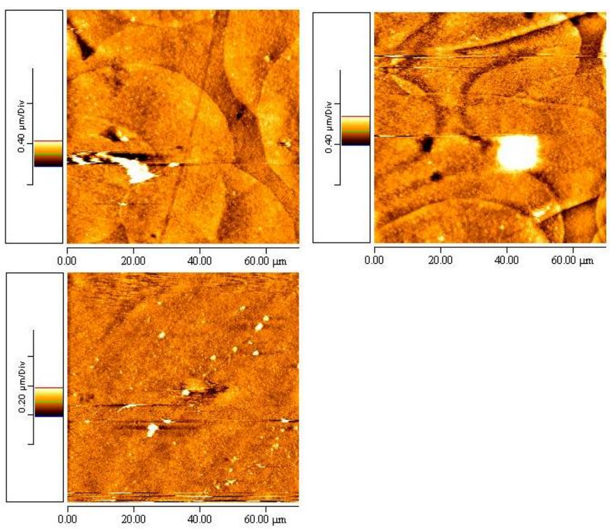

Figure 3. *AFM images of black ink film topography on Glossy paper printed by: Pro 5500 printer (left), Photo 2200 printer (right), and Pro 5000 printed (down).*

Ink film thickness measurements were performed using AFM. The scale of AFM is very small, and so only the film thickness at the border can be measured. The Epson 5500 cyan ink profile is shown in **Figure 4**. As seen there, the ink film is not uniform at the border. For example, the top line crosses two droplets, and the ink film thickness is about 150nm.

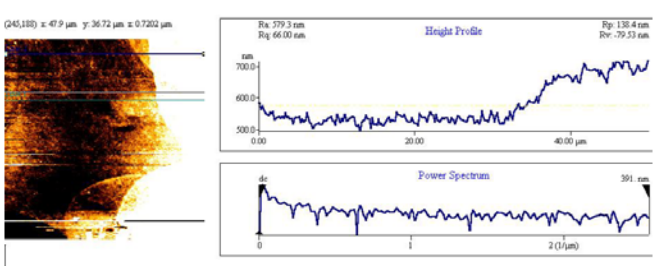

Figure 4. *Ink film thickness measurement using AFM.*

Therefore, the ink film thickness measurement was considered not reliable and measurements were abandoned.

Conclusion

AFM roughness measurement can only be applied on relative smooth surfaces, for microroughness determination, and it is quite time consuming. The paper- and print gloss at 75˚ correlates better with AFM than at 60. Good correlation with paper- and print gloss at both angles was found with results from the stylus profilometer. Higher print gloss was found with the Pro 5500 and Photo 2200 printers using pigment-based inks than Pro 5000 printer using dye-based inks, However, the Pro 5000 printer has higher correlation between paper gloss and print gloss.Epson papers are more compatible with the Epson printers than Kodak papers. The black ink film surface printed on Epson Glossy paper was studied using AFM. Dyed ink films resulted in smoother ink film surfaces than pigmented ones.

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