The Effect of Ink Jet Paper Roughness on Print Gloss

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Roughness of a variety of commercial Epson and Kodak 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 paper roughness and paper and print gloss were studied. From all three roughness testing methods used, the best correlation was found for AFM. Pigment based and dye based inks were found to have different effects on print gloss of Epson and Kodak papers. Topography of ink film was also studied by atomic force microscopy.

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Introduction

The worldwide importance of electronic print processes is constantly increasing. Multi-color ink jet technology is growing, especially for the home and office markets.[1] A large and growing consumer market for ink jet has developed 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, wetability, 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.[2–6] The gloss providing layer consists of a pigment and a synthetic polymer formed from a latex or water soluble polymer as a binder.[2–7]

Roughness, or smoothness, of paper is a very important property for print quality. Surface roughness is usually divided into microscale and macroscale components.[8,9] Although there is not total agreement on the boundary between those two, we define the macroscale component as consisting of features larger than 10 μm which are usually due to poor fiber dispersion, ionic destabilization or flocculation, roughness of base paper, or insufficient coating or calendering. The microscale component consists of features considerably smaller than 10 μm, due to pigment particle size distribution, particle shape, binder type, film shrinkage, drying conditions, coating holdout, and coating weight.[6] Research groups studying the roughness and its effect on gloss have agreed upon the fact that common roughness numbers are insufficient to predict gloss.[9] It sometimes occurs that the rougher surfaces have higher gloss. Among the classical roughness measuring methods, the Parker Print-Surf (PPS) method has been widely used in the paper and printing industries because of the possibility of measuring roughness at different pressures, 500–1000–2000 kPa, to mimic the conditions at a printing nip. The PPS tester uses a contact air leak principle, measuring airflow between substrate in a 51 μm wide ring. It recalculates the airflow into a mean gap between the surface and the flat circular land pressed against it.[10] The measurement obtained from all air leak instruments is called macroroughness. 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 halftone dot can range from 20 to 60 μm in diameter, whereas various air leak measurements can span widths ranging from 51 to 13,500 μm.[11] Therefore, the need for measuring microroughness is growing.

Surface characterization using atomic force microscopy (AFM) is now possible.[12–14] AFM was invented by Binnig, and introduced in 1985 by Binnig, Quate, and Gerber,[15] as an offshoot from the scanning tunneling microscope (STM).[16] 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

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photodiode detector as a function of probe position is converted into a 3D image by an image processing system.[15,17] 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 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 oscillation.[18] Therefore, tapping mode AFM is suitable for studying paper samples.

Other new methods for measuring microroughness are the stylus profilometer and laser profilometer. 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, stylus traces could be observed depending on the conditions of stylus radius and load, and the surface hardness of paper.[19] It was found that careful selection of stylus radius and load conditions can ensure no permanent damage to the 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.[20]

Other reported non-contact methods include confocal laser scanning microscopy (CLSM),[21] 3D sheet analyzer,[22] and interferometric microscopy.[23] The roughness is calculated from a 3D topographic image of paper surface obtained through these optical methods.

The goal of the present project was to compare three different test methods for surface roughness of ink jet printing papers and find the most relevant one, which provides in the best correlation with paper gloss as well as print gloss. A preliminary report was given elsewhere.[24]

Experimental

Samples

Three commercial Epson ink jet photo papers, Premium Glossy Photo Paper (simplified as Epson Glossy), Premium Luster Photo Paper (Epson Luster), and Archival Matte Paper (Epson Matte), along with two Kodak ink jet premium picture papers, High Gloss Picture Paper (Kodak Gloss) and Satin Picture Paper (Kodak Satin) were used in all experiments. The Epson papers used are known to be of the microporous type, while the Kodak papers used are the resinous type characterized by a swellable coating.[25]

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. Archival ink and UltraChrome ink are both pigment based inks.[26,27]

Parker Print-Surf (PPS)

A Messmer Instrument PPS Model 90 was employed at pressure of 2000 kPa 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 1 μm was used. The test conditions were 500 readings per group, 3 groups, 0.1 mm reading space, and 0.5 mm/s scanning speed. The roughness R was calculated using equation (1):

$$R = \quad |Z_{i+1} - Z_i\,|/499; \;\; i = 1, 2, \cdots, 499 \qquad (1)$$

where Z is the vertical position of the stylus.

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 tapping mode was used with a silicon tip (radius of the tip end curvature ~ 10 nm). Topographic data were obtained over a 70 μm × 70 μm area with a typical scanning rate of 0.5 Hz. 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, expressed by Eq. (2):

$$RMS\ roughness = \sqrt{\frac{1}{n}\sum_{i}^{n}(Zi - \overline{Z})^2} \qquad (2)$$

where Z is the vertical position of the tip.

The surface was observed after all measurements to monitor changes produced by scanning. There were no visible scratches on the paper surface and therefore it can be concluded that the pressure on the 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-GlossTM Glossmeter. The gloss of printed samples was tested on CMYK solid colors using the same geometries. Other print properties of these samples were discussed elsewhere.[26,27]

Results and Discussion

Atomic Force Microscopic (AFM) images of Epson Glossy, Epson Luster, Kodak gloss, and Kodak Satin papers are shown in Fig. 1. The surface of Epson Glossy paper is the smoothest among all substrates, averaging 9.71 nm. The surface of Epson Luster (22.39 nm) and Kodak Gloss paper (18.11 nm) were considerably rougher than Epson Glossy paper. Kodak Satin paper has very rough surface, reaching 312.1 nm. The surface of Epson Matte paper was too rough for current settings of the AFM. The maximum vertical depth the tip can reach is 6 μm, so the AFM could not be used when the distance between the highest peak and the lowest valley of the surface exceeded 6 μm; this method can only be applied on relatively smooth surfaces.

The comparison of the results of the three roughness testing methods as well as the results of paper gloss at 60° and 75° are presented in Table I. 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 the two profilometric techniques would correlate better, while PPS, measuring under pressure, would include compressibility and thus, give a lower correlation. It is important to note that the PPS roughness is often two orders of magnitude larger than the other two methods. Epson Glossy paper was the

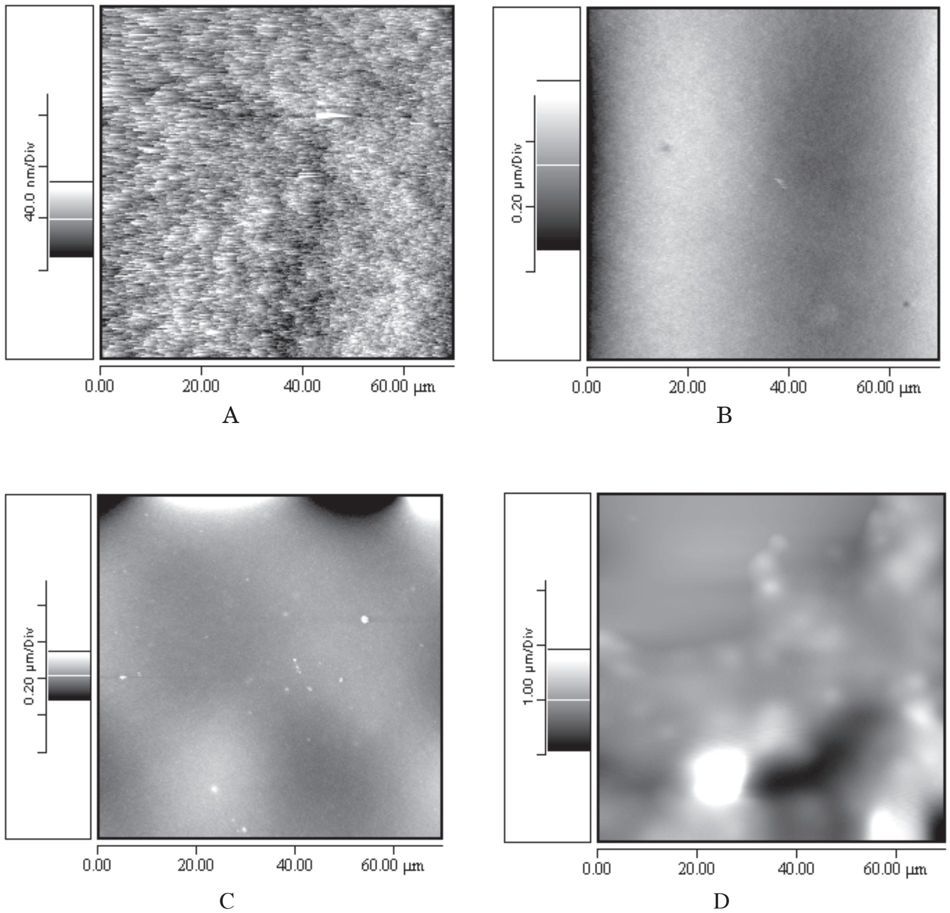

Figure 1. AFM images of paper topography: Epson Glossy (**A**-upper left), Epson Luster (**B**-upper right), Kodak Gloss (**C**-lower left), and Kodak Satin (**D**-lower right).

smoothest, while Epson Matte paper was the roughest according to all three methods. Epson Luster, Kodak Gloss and Kodak Satin papers have close PPS roughness values, but Epson Luster paper has much higher profilometer roughness, and Kodak Satin paper has much higher AFM roughness. This probably means that the surface of the Epson Luster paper is rough on the microscale, but smooth on the nanoscale. On the contrary, the surface of the Kodak Satin paper is smooth at the microscale, but rough on the nanoscale.

Some gloss values were out of the measurement range at one angle or the other, but are presented here for comparison purposes. The 75° 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 only 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 Kodak Gloss paper. According to Fresnel theory,[4–6,28] 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 papers have coating layers with higher refractive index than the Epson papers.

TABLE I. Correlation Coefficients between the Roughness of Papers by Different Methods and Paper Gloss

Sample	PPS (µm)	Profilometer (µm)	AFM (nm)	Paper gloss (60°, %)	(75°, %)
Epson Glossy	1.04	.355	9.71	34.64	62.92
Epson Luster	3.23	2.30	22.39	17.06	50.84
Epson Matte	6.78	1.404	–	2.60	6.80
Kodak Gloss	3.22	.942	18.11	77.80	95.00
Kodak Satin	3.11	1.072	312.1	27.04	67.54
	PPS	Profilometer	AFM	60° Gloss	75° Gloss
PPS	1				
Profilometer	0.937	1			
AFM	0.903	0.893	1		
60° Gloss	–0.468	–0.676	–0.598	1	
75° Gloss	–0.722	–0.880	–0.864	0.896	1

The correlation coefficients between paper roughness and print gloss at 60° and 75° for all three printers are listed in Tables II through IV. The correlations of

TABLE II. Correlation Coefficients between Paper Roughness and Print Gloss for Photo 2200 Ink Jet Printer

	PPS	Profilometer	AFM	60° Paper gloss	60° Print gloss			
					C	M	Y	K
C	–0.914	–0.953	–0.897	0.782	1			
M	–0.910	–0.946	–0.892	0.785	1.000	1		
Y	–0.934	–0.908	–0.828	0.665	0.970	0.973	1	
K	–0.943	–0.905	–0.854	0.653	0.971	0.974	0.998	1
	PPS	Profilometer	AFM	75° Paper gloss	75° Print gloss			
					C	M	Y	K
C	–0.908	–0.935	–0.990	0.916	1			
M	–0.939	–0.941	–0.992	0.880	0.996	1		
Y	–0.947	–0.927	–0.992	0.855	0.990	0.998	1	
K	–0.928	–0.941	–0.977	0.905	0.992	0.991	0.989	1

TABLE III. Correlation Coefficients between Paper Roughness and Print Gloss for Pro 5000 Ink Jet Printer

	PPS	Profilometer	AFM	60° Paper gloss	60° Print gloss			
					C	M	Y	K
C	–0.666	–0.863	–0.745	0.943	1			
M	–0.695	–0.879	–0.745	0.939	0.997	1		
Y	–0.696	–0.875	–0.747	0.943	0.996	1.000	1	
K	–0.656	–0.827	–0.740	0.973	0.985	0.987	0.990	1
	PPS	Profilometer	AFM	75° Paper gloss	75° Print gloss			
					C	M	Y	K
C	–0.798	–0.926	–0.920	0.975	1			
M	–0.823	–0.942	–0.928	0.972	0.999	1		
Y	–0.786	–0.926	–0.900	0.989	0.996	0.996	1	
K	–0.846	–0.955	–0.927	0.978	0.989	0.994	0.993	1

roughness to print gloss are higher than to paper gloss with all three methods. Ink jet printing is non-impact printing, not like the classical printing processes with contact pressure, so the ink film surface topography mainly 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 test method with the highest correlation of nearly 100% to print gloss with the Photo 2200 printer is AFM. AFM and the stylus profilometer both have high correlation with print gloss for all three printers, and only PPS with the Pro 5000 printer has a low correlation.

The ink also has an effect on the print gloss, which can be seen by comparing the three different printers. Paper gloss and print gloss correlate much better 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 in diameter.[26,27]

The 60° and 75° print gloss by three printers are compared in Fig. 2 for all five papers, with the dotted line indicating paper gloss value. It is found that for microporous Epson papers, higher print gloss was obtained with the Pro 5500 and Photo 2200 printers using pigment based inks than Pro 5000 printer using dye based inks. 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.[3,4,6] Dye based inks cannot improve upon the paper because the dye molecules are too small to efficiently fill the low spots in the coating. For resinous Kodak papers, a different effect was observed. The Pro 5000 printer with dye based inks achieved as high print gloss as obtained by Pro 5500 and Photo 2200 printers, and even higher print gloss for the yellow color. Colorant type is thus not a dominant factor in print gloss in the case of resinous ink jet papers. It was also found that negative delta gloss values were obtained for Kodak Gloss paper, most likely because the water based inks can swell the coating, creating a rougher surface, resulting in lower print gloss and ultimately negative delta gloss (Fig. 2).

Figure 3 shows AFM images of a black ink film surface on Epson 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 31.77 nm, 36.09 nm and 27.7 nm respectively (from left to right). The Pro 5000 printer uses dye based inks; therefore the ink film surface is smoother than obtained using pigment based inks because the dyes have smaller particle sizes than pigments. This ink film roughness is, however, about three times larger than the corresponding paper roughness.

TABLE IV. Correlation Coefficients between Paper Roughness and Print Gloss for Pro 5500 Ink Jet Printer

	PPS	Profilometer	AFM	60° Paper gloss	60° Print gloss			
				(60°)	C	M	Y	K
C	–0.938	–0.927	–0.850	0.693	1			
M	–0.918	–0.769	–0.731	0.357	0.912	1		
Y	–0.939	–0.821	–0.794	0.460	0.951	0.992	1	
K	–0.927	–0.930	–0.837	0.713	0.999	0.898	0.939	1
	PPS	Profilometer	AFM	75° Paper gloss	75° Print gloss			
					C	M	Y	K
C	–0.961	–0.947	–0.984	0.857	1			
M	–0.970	–0.894	–0.964	0.761	0.983	1		
Y	–0.963	–0.901	–0.970	0.793	0.988	0.998	1	
K	–0.942	–0.971	–0.974	0.897	0.991	0.952	0.959	1

Ink film thickness measurements were performed using AFM. The scale of AFM is very small, so only the film thickness at the border can be measured. The profile of cyan ink printed on Kodak Gloss paper by Pro 5500 printer is shown in Fig. 4. The dark area is the paper substrate, and the bright area is the ink film. 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 150 nm. Based on the ink pigment size,[26,27] this corresponds to approximately a monolayer of ink pigment particles. This point needs further investigation, with more careful sampling.

Conclusions

AFM roughness correlates better with the paper and print gloss at 75° than at 60°. Good correlation with paper and print gloss at both angles was found with results from the stylus profilometer. Pigment based and dye based inks have different effects on print gloss of Epson and Kodak papers. Higher print gloss was found with the Pro 5500 and Photo 2200 printers using pig-

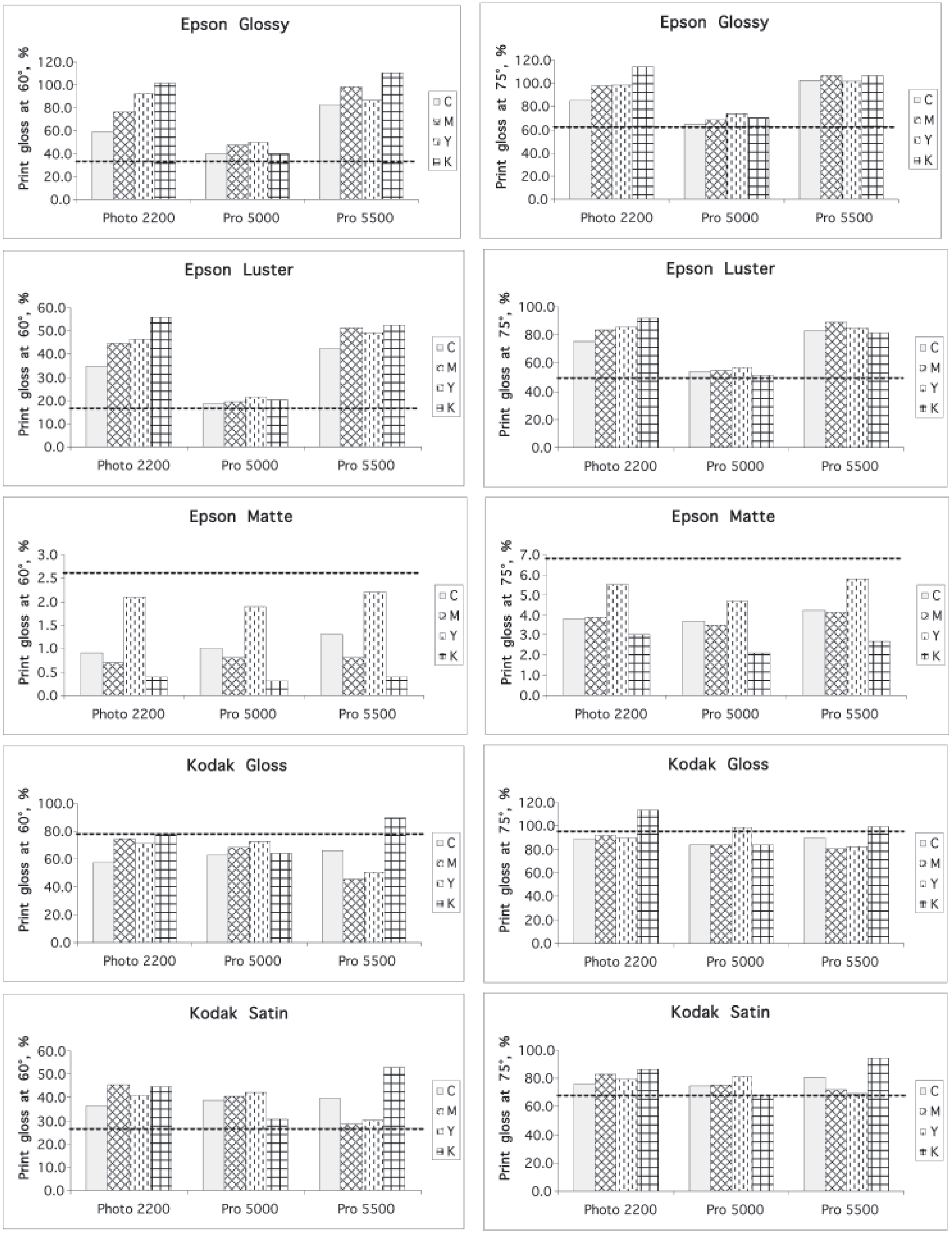

Figure 2. Comparisons of print gloss at 60° (left) and 75° (right) between three printers for all five papers, with dotted line indicating paper gloss value. (Print gloss lower than the paper gloss results in negative delta gloss).

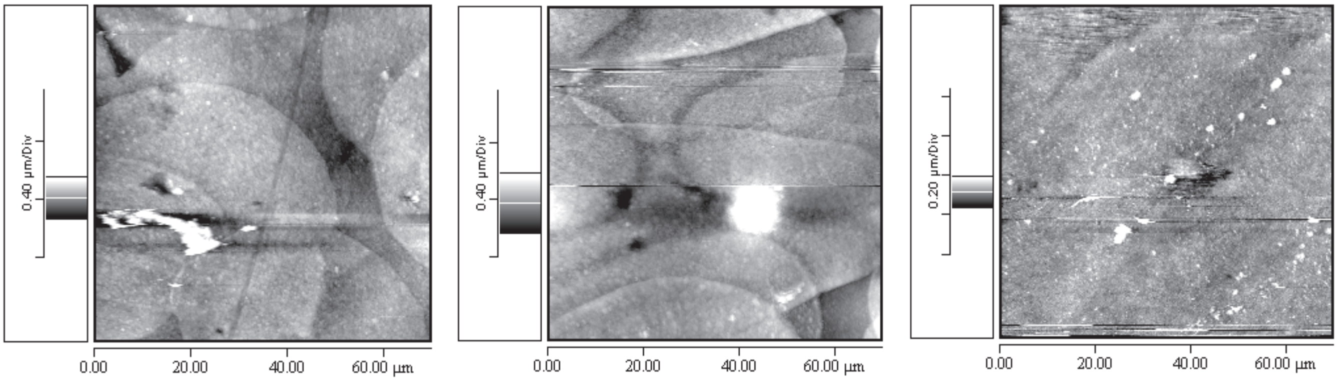

Figure 3. AFM images of black ink film topography on Epson Glossy paper printed by: Pro 5500 printer (left), Photo 2200 printer (center), and Pro 5000 printer (right).

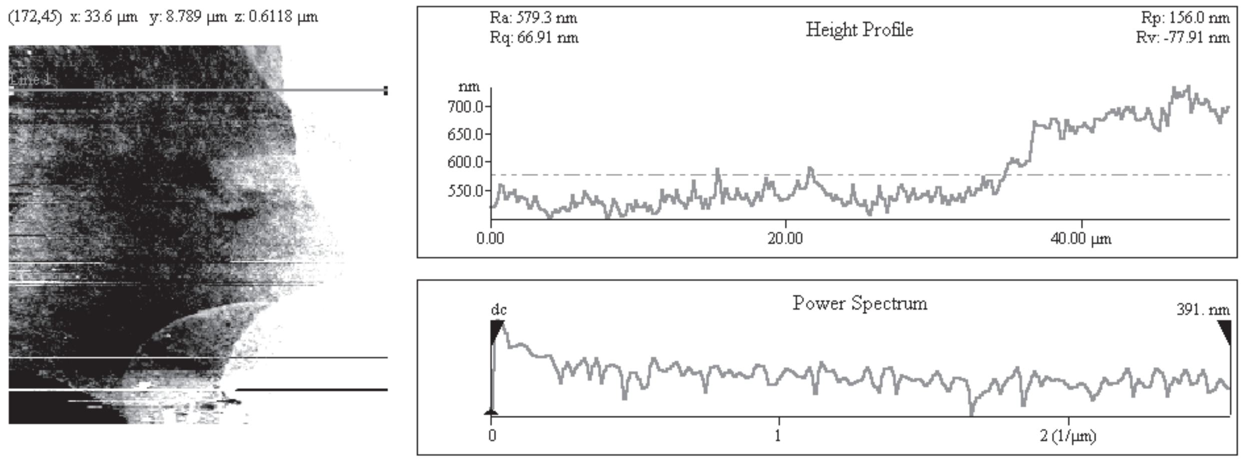

Figure 4. Ink film thickness measurement using AFM.

ment based inks than Pro 5000 printer using dye based inks for the Epson papers. On the contrary, the printers had less effect on print gloss for Kodak papers. However, the Pro 5000 printer shows a higher correlation between paper gloss and print gloss. 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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