MEASURING WATER-INDUCED ROUGHENING OF LWC PAPER AND ITS EFFECT ON PRINTED GLOSS

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ABSTRACT

We developed a millsite procedure to precisely apply water to lightweight coated paper in the small amounts occurring in commercial web offset printing. The reduction in Hunter 75° gloss is an indirect measure of the roughening effect that this thin water film has on the white paper. Commercial offset printing trials suggest that less than half of the white paper gloss reduction appears as a printed gloss reduction. This is because the Hunter gloss measurement does not distinguish between the gloss reduction from macro-roughening and that from micro-roughening which the ink film later covers. Despite this limitation, the simple water treatment procedure can still help to identify more quickly paper making process and material changes that give reduced roughening and have a chance to improve the final printed gloss. Not all of the water-induced roughening occurs at the fiber dimension level; the coating also exhibited a significant micro-scale roughening from the water.

Key words: Hunter 75° gloss, fiber rising, print roughening, facet angle, IGT Print Tester.

INTRODUCTION

The commercial lightweight coated (LWC) paper reported here, though manufactured to satisfactory white paper gloss level, has lower gloss after printing than many other papers (Figure 1). Some of this lower printed gloss might arise from a greater propensity to roughen in the presence of water from the web offset printing process (1, 2). The gloss reduction of unprinted SC and LWC papers was related by Béland *et al* to the "raised fibers" caused by water roughening (3). Others have experimentally shown a relationship between gloss and various dimensions of roughness (e.g., 4, 5, 6). This work documents the development of a convenient test, easily implemented in a mill setting, that indirectly indicates the water-induced roughening propensity of a coated and supercalendered paper.

The test is based on measuring the Hunter 75° gloss reduction of as-manufactured paper after applying a water amount similar to that occurring in offset printing. This method is much more rapid and convenient in a mill setting than making non-contacting roughness measurements using, for example, laser profilometry or confocal microscopy. Common paper mill roughness instruments like the Parker PrintSurf are unsuitable for measuring the roughness that affects gloss because the airleak principle upon which they are based requires the surface to be compressed into a condition totally unlike that of the gloss measurement. If the conditions used in the wetting/roughening procedure approximate those occurring during printing, the associated printed gloss reduction can perhaps be predicted from the water-treated white paper gloss reduction without resorting to expensive commercial printing trials with their attendant long turn-around times and expense.

Water contacts the paper surface during offset printing, both in the unimaged and the imaged areas. The sorption of even a small amount of water into paper made from a mechanical furnish causes immediate and sometimes dramatic structural changes affecting a wide range of dimensions (7, 8). This roughening phenomenon ("fiber rising", "fiber puffing", "print roughening", "heatset roughening") causes large-angle light scattering, reducing the gloss level and giving the print less "snap" (less difference between the white paper and the printed gloss). For machine-made paper, the water-induced roughening often has a strong machine-direction (MD) component related somewhat to fiber alignment but mainly (we think) to uniaxial drying restraint of the base sheet. Thus, the gloss (especially the 75° gloss) measured in the paper machine cross-direction (CD) is both lower (9) and is reduced more by water-induced roughening than it is in the MD.

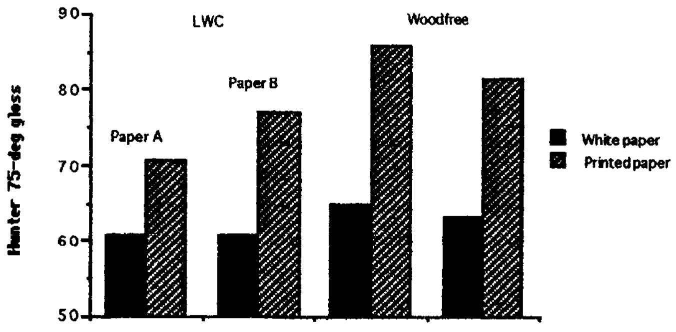


Figure 1. Gloss comparison. Paper A is the LWC paper reported in this work. Paper B is a typical LWC. The two papers shown on the right for comparison are Woodfree (trace groundwood) grades and thus are not direct competitors to the LWC papers on the left.

Precisely applying a known amount of water to a coated paper surface is difficult. The amount taken by the paper depends on the interaction between the application variables (speed, nip pressure, applicator, doctor, and blanket conditions) and the paper's ability to accept the water (porosity, coat weight uniformity, surface chemistry). Several different application methods have been used (10) but in our work we used the IGT Print Tester equipped with a special aluminum anilox roller and a doctor assembly. The roller surface contains cells arranged in a randomized array (different sizes, shapes, depths, and spacings) which store water applied by a cotton swab, the excess of which is doctored off by a rubber wipe. The water stored in the cells is transferred to the paper under pressure in a rolling nip. The amount transferred should simulate that applied during the offset printing process.

To be practical in a paper mill, the white paper gloss reduction caused by the standard water treatment should allow a reasonably accurate prediction of the final printed gloss (a paper with more gloss reduction than another should have lower printed gloss after adjusting for their difference in white paper gloss). To help establish this prediction, white paper samples were commercially web offset printed. Samples from these same white papers were also water treated and measured for gloss reduction. To compare with these gloss reduction measurements, some of the samples were measured and imaged with a confocal laser scanning microscope (CLSM) to quantify the topographical changes caused by water application and also by printing.

TABLE 1. GLOSS MEASURING PRECISION FOR THE WATER TREAMENT PROCEDURE

UNTREATED PAPER	TREATED PAPER	TRTD PAPER, MOVE SAMPLE
N = 12	N = 5	N = 18
mean = 55.2	mean = 38.7	mean = 38.2
SD = 0.23	SD = 0.11	SD = 0.62
COV = 0.4%	COV = 0.3%	COV = 1.6%

Notes: Calibrate gloss meter, remove, replace, and measure same paper sample for Felt Side Hunter 75° gloss (CD orientation). Repeat 24 hours later (no change, within ± 0.2 units). Using a fixture to precisely locate the paper sample, the measuring area is about 24 cm from the head end of the 4.5 cm-wide x 33 cm-long paper sample, about halfway down the 25 mm-wide x 20 cm-long applied water pattern. Column 3 shows the effect of not precisely locating the sample in the gloss meter; the variability increases 6-fold but still remains small. Eighteen measurements made moving across the 25 mm applied water area.

TABLE 2. EFFECT OF WATER APPLICATION SPEED AND GLOSS MEASURING ORIENTATION ON FELT SIDE GLOSS REDUCTION.

	0.26 M/SEC		0.35 M/SEC
	CD ORIENTED	MD ORIENTED	MD ORIENTED
Δgloss	16.2	9.9	10.6
SD	0.45	1.1	1.5
COV	2.8%	11.2%	14.2%
N	10	20	20

Notes: 1. Δgloss = white - treated and is based on paired (before/after) measurements.
2. Highest application pressure used.

EXPERIMENTAL

The paper used for this work, Paper A, was a ≈60 g/m^2 (40 lb/3300ft^2) No. 5 LWC containing 55-60% pressurized groundwood. Each gloss data point reported here is the mean of at least ten separate paper samples. Each gloss reduction data point is based on the mean of paired gloss measurements (before/after water treatment at the same area) on these same samples. All variation data in this report are reported in terms of 1 standard deviation (SD) or on the coefficient of variation, COV (SD/mean). Macro-roughening in this report refers to the fiber dimensions and above; micro-roughness is from about several microns and below.

The manufacturer of the custom-modified anilox roller (Research North America, Cherry Hill, NJ) determined the amount of water transferred to our LWC paper, ≈1.25 g-H_2O/m^2, using a nickel-based dye, a color densitometer, and gravimetric measurement. (Other LWC papers could have slightly different water transfer amounts using the same application conditions and this should be considered when making comparisons between different papers.) We used a dyed water solution to indicate the water application uniformity. This showed the necessity to use the slowest printing speed (0.26 m/sec), otherwise some of the water could not be forced into the coated paper, collecting instead in the ingoing nip. This gave a blotchy "rivulet-like" appearance to the dye pattern.

The dye solution also revealed increasingly worse application uniformity after about seven successive paper samples were run through the tester. We think that the cotton swab became too dry, causing depletion of the roller surface and also chattering of the doctor blade. For the highest precision, we also found that no backlash should be used in the IGT tester and that the cotton swab should be wetted with an eye dropper so that the doctor blade need not be lifted off the roller. The observed dye patterns, plus the gloss reduction data in Table 1, indicate a reasonable precision for this water application procedure.

For our LWC paper the anilox roller seems to be near its water application limit (minimum printing speed,

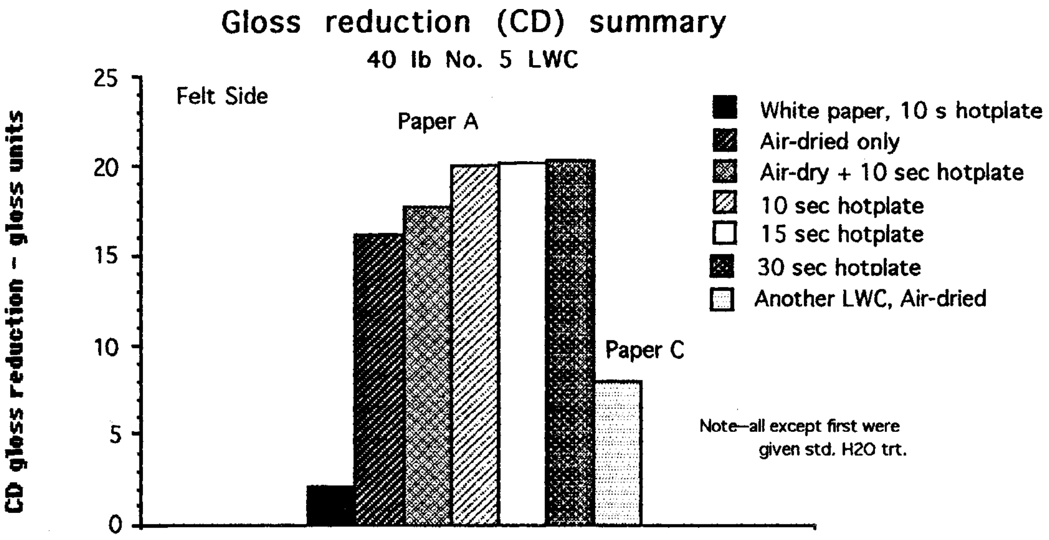


Figure 2. Summary of drying intensity experiments.

maximum doctoring pressure, and fairly high printing nip pressure setting of 50 kgf). Other papers which accept water less readily than the our sample paper might therefore result in a non uniform application unless another custom-built roller were used.

The felt side of Paper A was used for all our initial investigations on the water application procedure. As earlier mentioned, the orientation of the gloss measurement has a large effect on the gloss reduction (Table 2). The Felt Side CD gloss reduction was more than six units higher due to the strong MD-orientation of the roughening mentioned earlier and to the high 75° incidence angle (low grazing angle) for the Hunter gloss meter. The CD variability also was much lower. These gloss reduction data also support observations from the dye experiments that higher water application speeds give somewhat more variation for this paper. Note the very high gloss reduction after applying only ≈ 1.25 g-H_2O/m^2 to the white paper.

Drying intensity has only a slight affect on both the gloss reduction and its variation (Figure 2). Drying the water treated papers on a 220°C (425°F) curved hot plate (water-treated side outwards), whether for 10 or 30 seconds, increased the gloss reduction by only about 2 units over simple air drying. There was a small (2 units) gloss reduction associated with merely heating the untreated paper without applying any water.

Water-induced roughening occurs immediately upon water application but, unreported in the literature, during subsequent air drying the gloss rises significantly (Figure 3). Though we did not investigate the reason, this could happen if the surface was relaxing back toward a smoother state (losing roughness) as it air dried (11). All other gloss data in this report were obtained after the samples had air-dried for at least 10 minutes and therefore include this gloss-recovery effect.

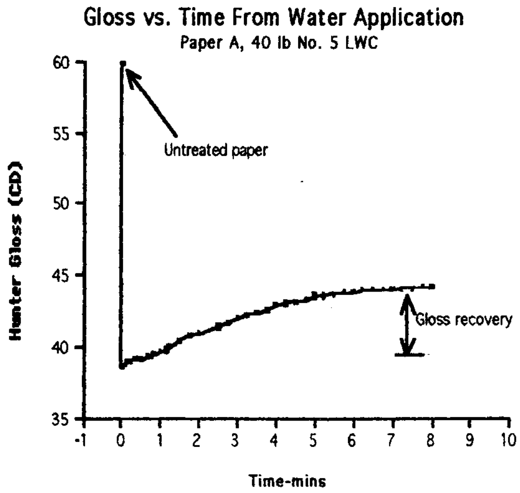
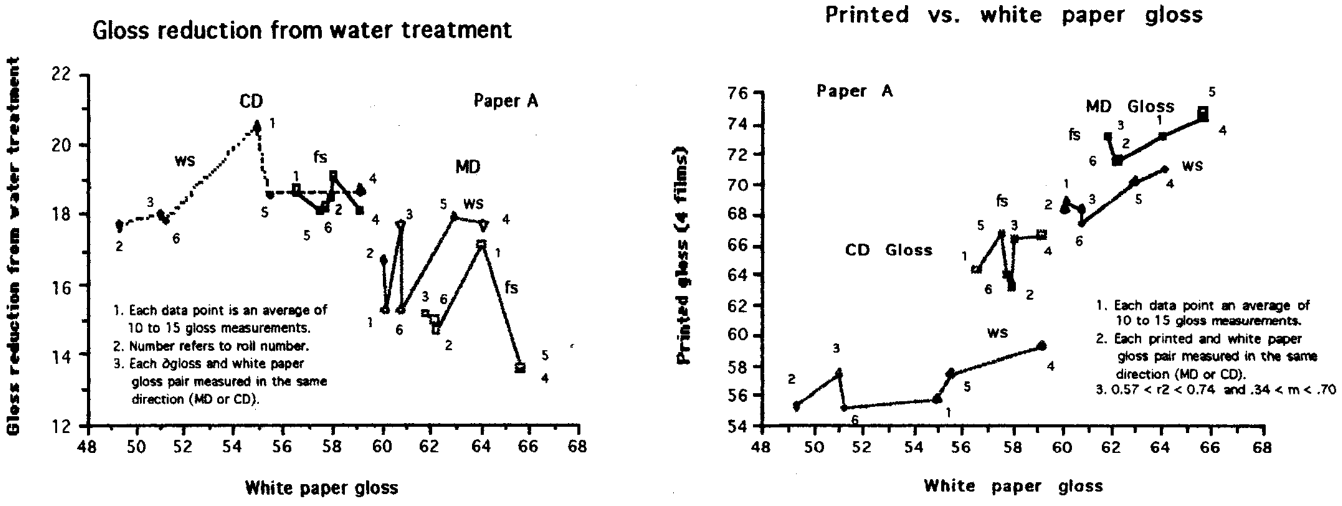


Figure 3. Gloss increase with time after water application. The time between water application and the first gloss measurement is less than 10 seconds.



(a) (b)

Figure 4. Results of one print trial (Paper A end rolls).

PRINTING TRIALS

In order to relate printed gloss to water-treated paper gloss, samples were commercially heatset offset printed using a standard form. Print density, color match, and ink film thickness were manually set by the pressman and monitored during the trial. The printed gloss was measured in the heavily-printed black area (100% K, 60% C, 50% M, 50% Y = 260%) of the test print where we expected to find the greatest roughening. Paper samples from the trial rolls were also measured for white paper gloss and gloss after standard water treatment. In all cases, Hunter 75° gloss of the Felt and Wire sides, as well as MD and CD orientation, was measured.

For one print trial, six end rolls were randomly selected from the paper production line (No.s 1-6 in Figure 4). Paper is normally manufactured to meet a gloss target but the data here show a somewhat wide range of gloss, especially the Wire Side. This side exhibits a much lower gloss level despite it normally having a higher coat weight (10-20%) and being run against more hard rolls through the supercalender.

The six rolls were printed and gloss was measured for the white, water-treated, and printed paper. The gloss reduction from water treatment does not seem influenced by the initial gloss level (Figure 4a). This was typical for all the papers we tested but may not be true over a wider range of white paper gloss. Note again the surprisingly large gloss reduction for this paper with a water application of only 1.25 g-H_2O/m^2. There was a good correlation between the printed gloss and the white paper gloss and the Wire Side printed gloss was exceptionally lower by 4-8 units at the same white paper gloss level (Figure 4b).

These print trials provide limited data to judge how well the water treatment procedure can predict the final printed gloss. The difference between two papers in gloss after they have been water treated simultaneously accounts for their original white paper gloss difference and their gloss reduction difference. For example, their difference in gloss after water treatment would predict Sample 3 Felt Side MD

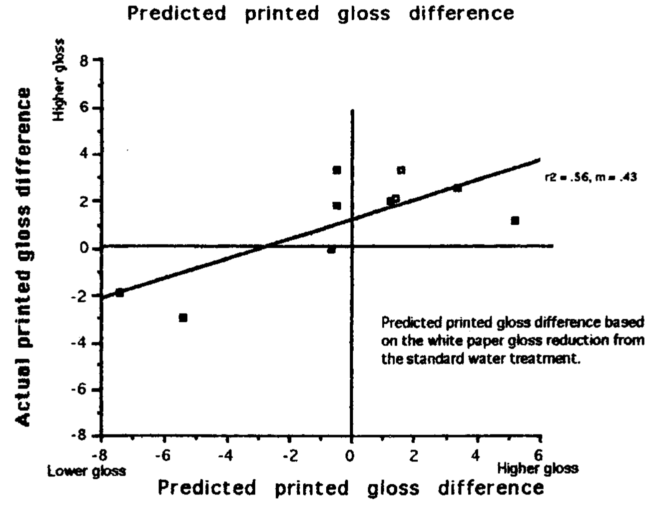


Figure 5. Actual vs. Predicted printed gloss difference between some of the print trial papers.

TABLE 3. G3 Macro-Roughness--μm
Initial water treatment experiments (Paper A)
313 μm x 313 μm measuring area

	Low-Gloss sample (44.1 Hunter gloss)				High-Gloss sample (63.1 Hunter gloss)			
Occasion	1	2	3	mean	1	2	3	mean
White	3.54	3.62	3.77	3.64	3.45	3.33	3.35	3.38
H2O Trtd	4.26	4.36	4.40	4.34	4.13	4.10	3.99	4.07
%inc	20%	20%	17%	20%	20%	23%	19%	20%
N	8	8	10		8	9	10	

10% < s/mean < 20% (based on 110 measurements).
No G3 measurements were made on WS.
Paper measured on three separate occasions.
Measurements courtesy of C. Antoine of UQTR (Paprican host laboratory).

TABLE 4. Roughness for Roll No. 4 paper (highest gloss paper)

	G3 Macro-roughness -μm			PPS (S10) Roughness--μm		
	FS	WS	% diff	FS	WS	% diff
White	3.54	4.02	14%	1.20	1.29	8%
H2O-trtd	4.16	4.06	2%	–	–	
% inc	18%	1%				
Prtd 4 colors	5.08	4.90	4%	2.28	2.53	11%
% inc	44%	22%		90%	96%	
N	5	5		15	15	

4 color print = 100% K, 60% C, 50% M, 50% Y = 260% ink coverage.
Measurements courtesy of C. Antoine of UQTR (Paprican host laboratory).

to have lower printed MD gloss than Sample 4 by 5 units. Actually, Sample 3 had 3 units lower gloss, a 2 unit prediction error. The predictions using the water treatment procedure show that only about half or less of the gloss reduction due to water-induced roughening is seen in the print (Figure 5).

CLSM IMAGING

To show how the water treatment affected the paper surface, several samples of white, water treated, and printed paper were studied using the confocal laser scanning microscope (CLSM). The CLSM allows high-resolution measurement and imaging of paper surface elevation (12). The spatial and height resolutions used for this work were 0.61 μm x 0.61 μm and < 1.0 μm respectively and the acquired image area over which the roughness was calculated was 313 μm x 313 μm. The surfaces of all samples were measured in an uncompressed condition, the same as that used in making the gloss measurement. Our spatial resolution allowed the micro-roughness to be observed but this was not actually measured.

The G3 roughness relates to the average thickness of the "roughness volume," the volume contained between a reference plane passing through the highest elevation point in the image and the actual paper surface underneath. Thus, it is a 3D-based statistic of the paper surface. Because the G3 is measured over a large field of view (relative to the wavelength of light), we refer to it in this work as the "G3 macro-roughness." The PPS(S10) roughness is the cube root of the mean cube of the airleak gap created between the compressed paper surface and an annular measuring head (13). Though both are roughness measurements, the PPS and G3 as used here are not equivalent--the latter provides a better quantification of the paper surface for our purposes, especially since it measures a truly uncompressed sample, the condition under which the prints are viewed and the gloss measurements are made.

The roughness measurements are presented in Table 3 for Paper A used in the initial water treatment investigations and in Table 4 for the paper used in the print trial. The white paper G3 macro-roughness increased 20% after standard water application and 45% after heavy printing. Based on five measured areas, the white paper Wire Side G3 macro-roughness is significantly greater than the Felt Side, but after water treatment or after heavy printing the two sides are much more alike (Table 4). This implies that the white paper Wire Side, though starting out rougher,

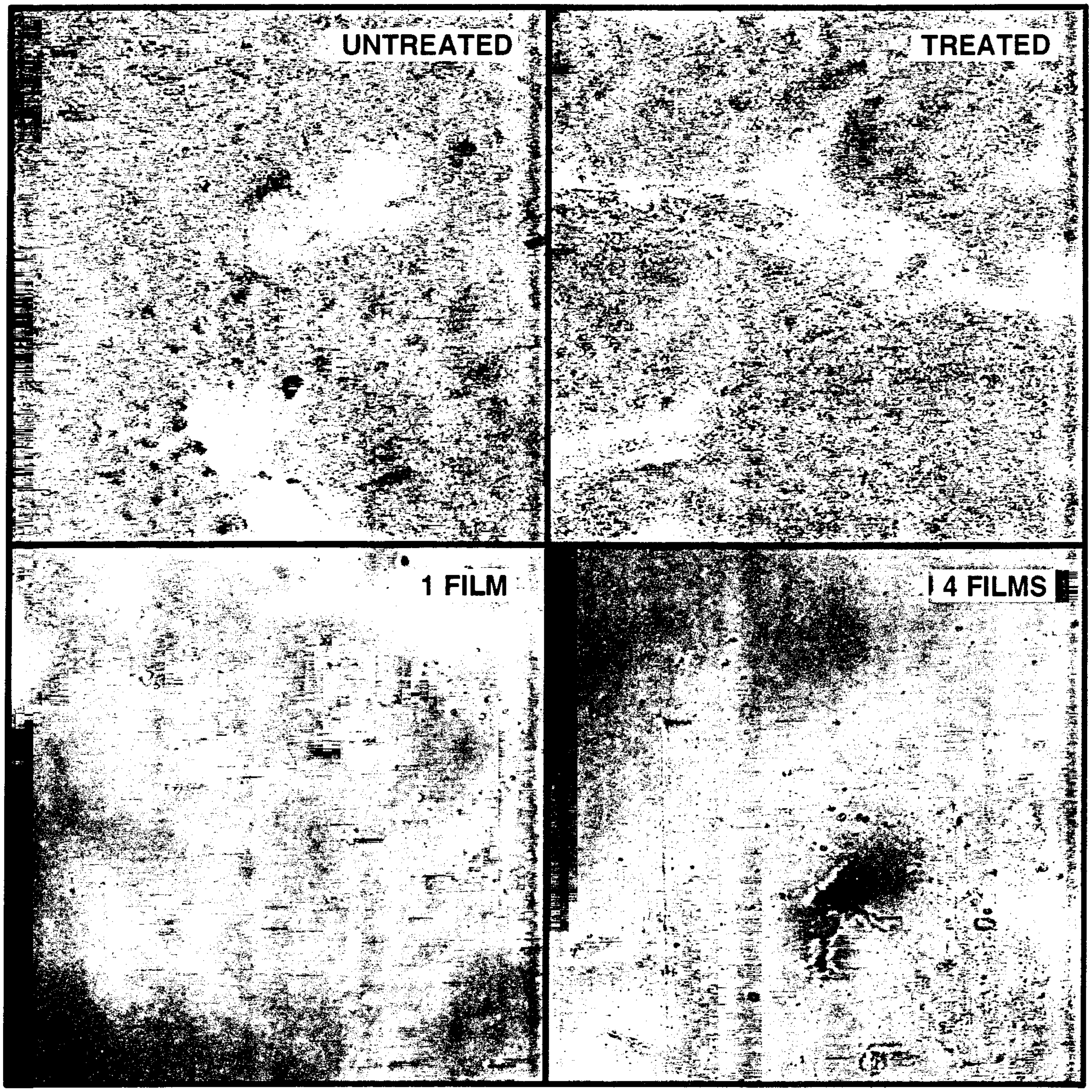
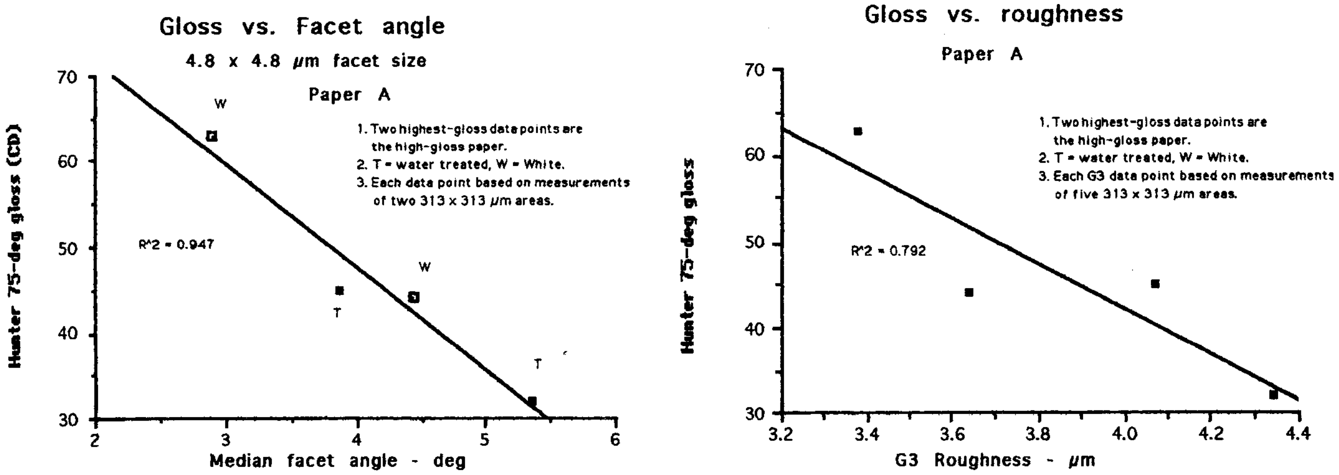


Figure 6. CLSM images of paper from Roll No. 4. (a) white paper, (b) water-treated paper, (c) printed black 1 film (100%), and (d) printed black 4 films (CMYK 260%). Note the fine, highly aligned marks after printing 4 films. Image field size is 313 μm x 313 μm. Images courtesy of C. Antoine of UQTR (Paprican host laboratory).

doesn't roughen as much with water (More data is necessary to confirm this conclusion). The wire side has more coating and this side of the basesheet, though rougher, is also much denser and stronger.

Topographical images (color coded for height) and roughness measurements were made of paper from Roll No. 4, the highest-gloss paper used in the print trial. Though some of the important details cannot be observed in the reproduction here (Figure 6), the original images demonstrate that the water treatment and the printing processes each cause a drastic topographical change on both the micro- and the macro-scales. After water contacts the paper, many raised fiber forms can be seen under the coating, often with the coating actually cracked along the fiber. Also dramatically shown is that the ink, whether one or many films, appears to cover the micro-scale coating "graininess" seen already in the original white paper but amplified after the water treatment. This is in agreement with Wågberg's findings where the ink gave a "smoothe-



(a) (b)

Figure 7. Relationship between gloss and the (a) median facet angle or the (b) G3 roughness for Paper A. Facet angle based on a 4.8 x 4.8 μm facet size and was measured over two 313 x 313 μm areas. G3 an average of five such areas. r^2 between median facet angle and G3 is 0.63.

ning" effect for the higher-frequency disturbances (10). With heavier ink coverage, the surface exhibits another kind of micro-roughening, highly aligned in the printing direction (Figure 6d). In addition, there are numerous (500-2000/mm^2) "pits" in the paper coating, 5-10 μm deep and wide and other much larger (>50 μm) but less frequent pits. The sizes and shapes (but not the frequency) of the latter seem very similar to the explosion-like craters seen after printing. Curiously, many of these craters have pinnacles or blisters rising from their centers (Figure 6d). Finally, there are infrequent but very large (several 100 μm) and irregularly-shaped craters with debris nearby on the printed surface.

These images give dramatic visual evidence that some of the Hunter gloss reduction that we measured in the white paper probably is due to coating micro-roughening but that this micro-roughening might not have much effect on the final printed gloss.

FACET ANGLE

The angle that small, essentially flat, places (facets) makes in the paper surface theoretically has a strong influence on the measured gloss. Using the topographical data set measured by the CLSM, the surface of the roughened paper can be modeled as an assembly of facets whose angle with a reference plane can then be calculated. The facets can be presented in the form of a facet angle image (the first derivative of the topographical image) which nicely shows the flat and steep places in the paper surface (6). Other statistics such as facet angle distribution and the median facet angle (the angle above which half the surface is tilted more) can be calculated.

The median facet angle was determined for a high and a low gloss paper. As predicted from theory, there is a strong correlation between the median facet angle and the Hunter gloss measurement for both the treated and the untreated papers (Figure 7a). This data shows that half the surface of each of these papers is tilted a surprising 3° or more from the mean plane of the paper, an amount which has been shown to greatly reduce the specular reflection and thus the Hunter gloss (6). Though not as good as the facet angle, G3 roughness also correlates quite well with the gloss (Figure 7b). The correlation between median facet angle and G3 roughness is $r^2 = 0.63$, meaning that the two surface parameters are not a simple restatement of the other.

DISCUSSION

Applying only 1.25 g/m^2 of water to the paper surface causes a significant topographical change and is accompanied by a dramatic loss in the Hunter 75° gloss level. CLSM microscopy showed that this loss is associated with roughening that occurs over a wide range of dimensions. The G3 roughness, as used here, is considered a "macro" measurement because it is measured over a large field size relative to the wavelength of light. Octave band passing the G3 data (16) could separate the roughness into different size classes and might be a useful way to measure the micro-roughening that our CLSM imaging revealed in the coating. This micro-roughening contributed an unknown portion of the gloss reduction from the water treatment but apparently does not greatly affect the printed gloss because our microscopy showed that the ink film covers it.

Micro-roughening reduces our ability to accurately predict the water-induced print gloss reduction. This is because the Hunter gloss meter cannot distinguish the effect on gloss from different roughening dimensions; it integrates the specular reflection resulting from all dimensions. The micro-roughening also partly explains why a large white paper gloss reduction appears as a much smaller printed gloss reduction. Also noteworthy is that we measured the printed gloss of a heavily printed black area (260%). If the gloss had been measured in lighter tones the micro-roughening might have been a greater proportion of the printed gloss reduction.

The median facet angle is not merely another way to state G3 roughness; we feel that it gives much better information about the way the surface is tilted and thus relates more directly to its light reflection behaviour--two surfaces with the same G3 roughness can have markedly different facet angle distributions. We use the median rather than the average facet angle because the former is not weighted so much by highly-tilted facets which, beyond several degrees, contribute little further gloss reduction (6).

Since the facet size chosen was large (relative to the wavelength of light), we feel that the good correlation with both the white paper gloss and the water-treated paper gloss demonstrates that an important part of the gloss reduction from water treatment has a physical explanation in the macro-roughening that we measured and imaged. This likely would not have occurred if the entire difference was due only to micro-roughening, something we did not measure. Still, micro-roughening may be a much larger factor than we realized before undertaking this work. Since it reduces our ability to predict printed gloss changes, it is an area where further analysis, such as octave band passing the CLSM data, might be helpful.

There was a rather large proportion (50%) of the four paper surfaces which were tilted by 3° or more. That tilt angles this small greatly reduce the specular reflection intensity is nicely demonstrated in Figure 7a where a change in median facet angle of only 1° results in a surprising 10 unit change in Hunter 75° gloss. One purpose of coating followed by supercalendering is to bring as much of the surface to near-zero tilt as possible while (hopefully) maintaining other paper properties. If the coating coverage is poor and if the surface roughens after water is applied, the number of highly tilted facets can be significant as our measurements show.

The tiny pit trails (Figure 7d), aligned in the printing direction, present an intriguing question. These pits are not an artifact from the CLSM image acquisition. They appeared in every CLSM image of printed paper and on both sides of the paper. Faintly visible in the 100% black print, they were especially prominent in the 260% 4-color black print. The pit trails are too small to be associated with ink filament splitting in the exit of the printing nip. One suggestion is that they might be associated with escaping water vapor and ink solvent but this explanation does not clarify why the trails should be so highly aligned in the printing direction.

The randomly located larger pits and craters are probably present in many heatset offset prints (e.g., photo by Peterson and Griffith on Feb. 96 JPPS cover). The pits in our paper surface seem to have their origin in the white paper because their sizes are so similar between the white and printed paper. Like Truncellito (18) we feel these pits, up to several microns or more deep, become filled with excess ink which can form a skin during rapid drying, causing “pinnacles” and “blisters” to form as solvent and/or water vapor attempt to escape. Some of these probably even explode. Instead of being ink-related, another possibility suggested by ESEM observations, is that a polymeric component of the coating bubbles up and then may burst due to the intense heat during heatset drying (19).

The gloss recovery we observed was a previously unreported phenomenon (2). Further experiments led us to conclude that the gloss recovery was real and not merely an opacity effect. It is suggested that, after the initial water-induced roughening, the paper surface might relax (or recover) to a flatter condition, causing the gloss to rise (11).

CONCLUSION

The water treatment/gloss measurement procedure provides an indirect, but precise, quantitative indication of water-induced roughening propensity caused by the combined effects of micro and macro roughening. Easily implemented in a paper mill setting, this method allows the preliminary evaluation of process and material changes which affect roughening propensity, before resorting to full-scale print trials. Because of its inherent inability to distinguish between micro- and macro-roughening, the procedure must not be used indiscriminately to predict absolute values of printed gloss changes. Our print trials indicated that, depending probably on the proportion of macro roughening, generally about half the white paper gloss reduction appears as a loss in printed gloss. This is because the ink film covers the micro-roughening.

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