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Evaluation of Gloss Variation with a Novel Method

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ABSTRACT

Gloss is very important optical property influencing the perceived quality of the paper surface as well as the surface after printing. Although the average gloss level of paper products or printed images is important to meet end use specifications, the occurrence of gloss mottle, or non-uniformity of gloss, is often of greater concern for meeting quality requirements, especially for the high gloss paper.

Gloss variation originates from the irregularities of paper surface, especially surface roughness of paper. Roughness of paper can be divided into micro-roughness (under 1㎛ scale in variation) and macro-roughness (over 1㎛ scale in variation) depending on the scale of the irregularities. A clearer understanding of the gloss variation of paper can be achieved by separating the contributions of these two scales of roughness, and characterizing them independently. In order to do this, a novel gloss measuring method was introduced. This can detect local gloss with very high resolution. The effect of macro-roughness on gloss variation, which was identified by the measurable surface topography, was separated from the total gloss variation by using this method. The effect of micro-roughness was then estimated indirectly. The local gloss variations of various paper samples were then evaluated to demonstrate the utility of this approach.

Keywords: *Gloss; micro-roughness; macro-roughness; gloss map; specular reflection; spot gloss; facet-angle; local gloss variation*

1. Introduction

Visual appearance of papers and its imaged surfaces is considered as one of the most important properties. Considerable attention has been given to gloss and origin of gloss defects by paper scientists since this greatly affects the appearance and the perceived quality of the product. The human eye has difficulty in resolving features smaller than 100㎛. Therefore, the actual surface roughness is barely detected by the eye under normal viewing condition. However, inhomogeneity of light intensity, as a three dimensional structure, can be easily detected by human perception because the eye has a logarithmic sensitivity to intensity and can differentiate very subtle differences, such as those resulting from gloss variation.[1,2,3] This is especially true for the gloss variation in papers with high gloss values where the contrast in gloss(defined as the contrast between the diffuse and the specular reflection) is more readily apparent. High

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gloss of printed surfaces is important for maximum color depth and a wide color range.[4]

Gloss variation is defined as the spatial change of gloss in a sample. The spatial resolution, therefore, is a very important factor for evaluating gloss variation. Since the conventional method for determining gloss test relatively large area(e.g. over 150 mm^2 measuring area for Hunter 75° gloss meter[5]), these methods are unsatisfactory for use in determining local gloss variation at scales that contribute to defects such as gloss mottle. Various methods have been introduced to measure fine scale variation in gloss. Many of these methods measure specular reflectance using apertures, which may be from 100μm to 900μm in spot diameter.[6,7,8,9,10] Although these methods showed a good applicability measuring local gloss variation to their limits of resolution, a much higher resolution is necessary to separate the contributions of surface roughness and micro structure to the perceived differences in gloss variation.

In other investigations[11,12,13,14], gloss variation was measured using spatial imaging instruments. With these methods, larger areas of samples were illuminated using a collimated light beam and the reflected image was examined using image analytical methods. A benefit of this approach is the high spatial resolution(20μm pixel size or smaller) and the ability to perform direct spatial comparisons between different surfaces. However, since the intensity of reflectance detected by the imaging unit is very sensitive to the experimental variations, such as various conditions of the illumination source and can be easily affected by the other optical properties of the samples such as color, the method requires careful calibration to obtain reliable results for the evaluation for printed samples.

In this work, a novel gloss measuring method was introduced for evaluating the gloss variations with very high resolution of about 10μm in spot diameter. The local gloss variations in various samples were measured. The surface topographies of the samples were measured in order to determine the origin of gloss variation. A point by point comparison between the specular reflected light, related to total gloss, and the surface contour allowed a calculation of the micro scale gloss variation of paper and printed samples.

2. Theoretical consideration

Gloss of paper and prints surfaces is greatly affected by the specular reflection intensity. Gloss has therefore been modeled and predicted based on the surface reflection theory, although gloss is a relative rather than absolute property of the surface. The mechanism of surface reflection has been studied extensively and the parameters of specular and diffuse reflection are well-established.[15,16,17] When a beam of light illuminates a surface such as paper, in addition to absorption and transmission, scattering may occur such that it may be reflected in various directions, especially in an angle opposite to the incident angle(specular). The amount of scattered light is determined by the differences in refractive index of air and the composing materials, i.e. fiber, and fillers, and by the irregularity of the surface contour or roughness Since there is no large difference between the refractive index of papermaking materials, for example, cellulose: 1.55, Kaolin clay : 1.56, talc : 1.57, chalk and marble : 1.58-1.66, the roughness is a major factor of the scattering. The presence of titanium dioxide, with a R.I. of 2.55, is a notable exception where variability of local reflectivity may be attributed to heterogeneous distribution of this filler/pigment.

Many investigators have studied the relationship between surface roughness and the light reflection properties.[18,19,20] From an optical standpoint, the material roughness can be considered as stochastic and may be divided into a spectrum of scales depending on the size or wavelength of surface asperities.[21] In case of paper, the surface roughness can be divided two scales, micro - and macro-, depending on the source of roughness.[22] Although the boundary between these two scales is arbitrary, it is generally accepted within paper science that the micro-roughness irregularity are < 1㎛ in scale for asperities within or below the wavelength of visible light, and macro-roughness are features within a range from 1㎛ to 100 ㎛, on the order of fiber width and thickness dimensions.[23,24,25]

The specular reflection in optically rough surface has been explained by using Eq. 1. Since the step height distribution of sample roughness can be described by a normal distribution, the bell shape of intensity distribution of specularly reflected light can be approximated by using the Guassian model. If a sample has the root mean square(RMS or $\mathfrak{R}$) of surface roughness, the intensity of specularly reflected light I is

$$I = I_0 \exp\left[-(4\pi \cdot \mathfrak{R}\frac{\cos\theta}{\lambda})^2\right] \quad (1)$$

Where I_0 is the reflectivity of fibers or coating color, λ is the wavelength of incident light and θ is the incident angle of light to the normal surface.[26,27]

This model assumes that the length scale of surface roughness was the same or smaller than that of light wavelength.[28] This model can explain the gloss variation in paper caused by the micro roughness, for example differences in coating pigment size or shape. However, the change of specular reflection by macro-roughness does not follow this model, as demonstrated by Oittinen.[29] She proposed a modified model for specular reflection, which included the surface slope as an added parameter to account for the macro-roughness. The surface slope was approximated the ratio of the RMS of macro-roughness and the characteristic depression width. However, since this surface slope was estimated from two-dimensional data set(x,z), it is necessary to find a more robust surface slope parameter which can account for the three-dimensional nature of the surface.

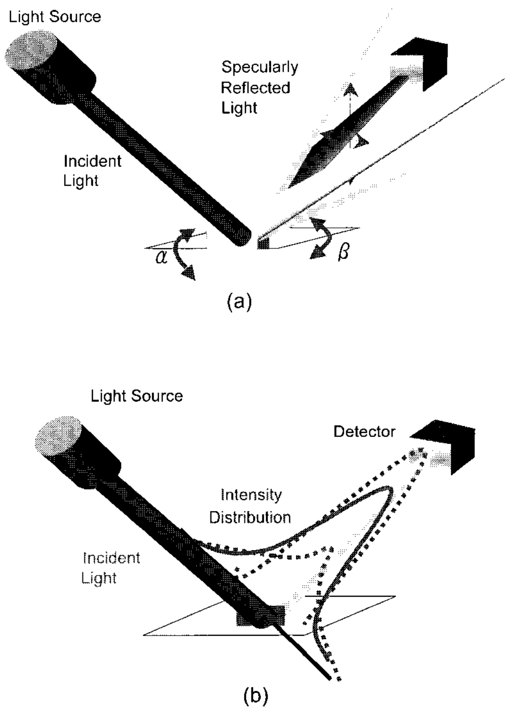

Figure 1. The Macro Facet Model for Specular Reflection.

(a) Effect of Facet Angle on the Direction of Specular Reflection

(b) Effect of the Micro Irregularities in a Macro Facet on the Intensity Distribution

In this study, a macro surface facet model is proposed to apply such an enhancement to experimental data. When the incident light is focused on a macro surface facet for a region of uniform slope within a certain tolerance, the specular reflection depends on the random optical roughness in the area and the tilt angle of the facet from the ideal flat plane as shown in figure1.

The local gloss value of a macro facet is a function of the random micro roughness of the area and the angle of the facet like,

$$g_n = f(R_n, S_n) \quad (2)$$

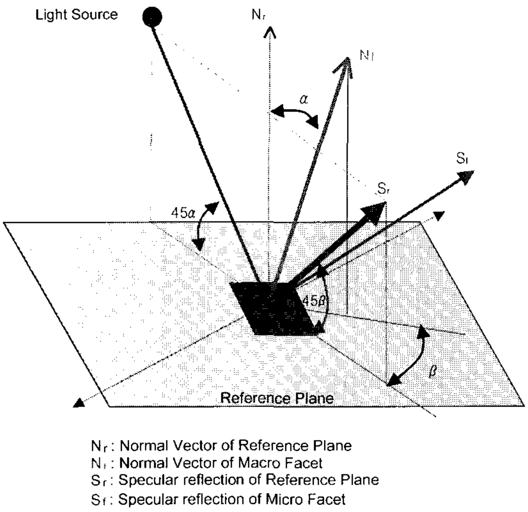

Figure 2. The Angle of Macro-Facet

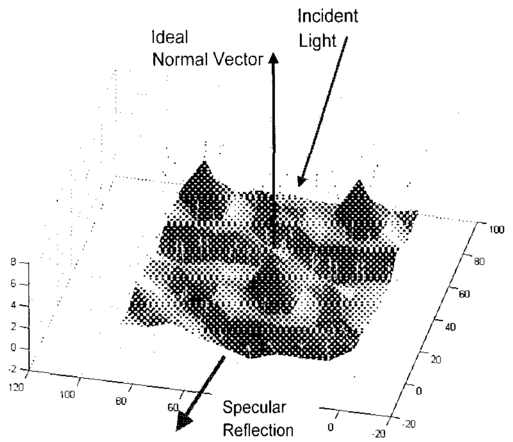

Figure 3. The Calculated Vertex Normal Vector on rough surface.

where g_n is local gloss, R_n is the intensity of specular reflected light of the small area, and S_n is the change of the intensity by the angle of the macro facet from reference plane. If the RMS of the macro facet is $\Re_n$, the R_n of the facet is given by equation(1).

S_n is the function of two typical facet angles as shown in figure 2.; α and β, and can be expressed by

$$S_n = F(\Phi,\ \alpha,\ \beta) \tag{3}$$

where Φ is the constant which is determined by the distribution of specular reflection light, the acceptance angle of detector and the properties of light source.

Since the gloss of a total area is the average of each local gloss, the total gloss will be

$$\bar{G} = \frac{1}{N}\sum_{n=1}^{N} g_n \tag{4}$$

Therefore the normalized gloss variation, G∏ is the variation of local gloss which is dependent on the variation of R_n, and S_n, and it can be calculated by

$$G' = \frac{\sqrt{\frac{1}{N-1}\sum_{n=1}^{N}(g_n - \bar{G})^2}}{\bar{G}} \tag{5}$$

If the variables R_n and S_n are identified, the gloss variation can be fully characterized. In this work, the local gloss, g_n was measured by using the reflected light of a focused laser as detected by a CCD detector. The normal vectors of each facet were calculated by using the step height data around the spot area as shown in figure 3. The arrows in figure represent the vertex normal vectors which were used for calculating α and β of the facet and specular reflection reduction. The local gloss variation map was rendered by using these normal vectors with assumption that every facet area had same reflection properties and there is a linear relationship between facet angles and the intensity of the specular reflection. This gloss map showed the effect of only macro-roughness, S_n, on the gloss variation. Any deviation of the measured local gloss values from the rendered gloss map determined from macro roughness, may be attributed to the micro-roughness or variation in local gloss between different facets.

3. Experimental

The instrument used in this study was developed for evaluating local surface roughness.[30)]

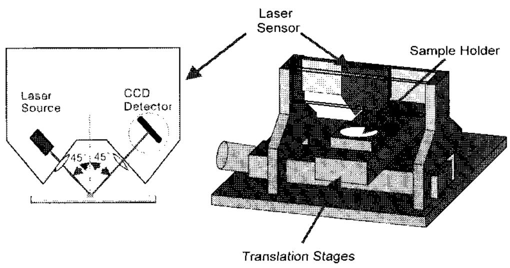

Figure 4. The schematic diagram of laser roughness-gloss profilometer.

Modification of the data acquisition enabled extraction of data useful in the determination of specular reflectance of the regions of about 20 by 20μm. An illustration of the instrument is provided in figure 4.

This instrument consists of X-Y positioning system and a laser sensor system. The positioning stage has a micro-stepping drive motor, which provides spatial positioning resolution 1 μm. A computer is used to control the position, and for collection of the data.

The laser sensor contains a laser light source (laser diode), a detector(CCD array), and the focusing optics. The sensor head was positioned above the sample surface using a micro-positioner so that a standoff distance of about 6.6mm was maintained. The light source is a visible red(780 nm wavelength) laser diode with a maximum power of the laser is 1.2mW and the power at aperture is 0.024mW. The light from the laser diode was collimated and directed toward the sample surface at an incident angle of 45° degrees. The spot diameter at the sample surface is typically about 10μm in diameter so that the measuring area is about 80μm^2 depending on the laser intensity level. The light reflected from the illuminated surface is imaged at 45° degrees through focusing optics onto a CCD array with 512 x 64 pixels. This provides a working range of 150μm and a minimum Z-directional resolution of 0.38μm.

As the sample is passed beneath the sensor, the position of detected spot on the CCD array is changed as a function of the surface contour, i.e. the distance from the sensor to the surface. The center of the spot is used as an indication of the spot position and is calculated by averaging one or more rows of pixels in the spot to determine the location of the center. By using this characteristic, surface roughness of various paper samples was measured.[30)] The results of that earlier study indicated that this instrument provided a useful vertical resolution of 0.8μm and horizontal resolution of 1.0μm within the detectors imaging range of 150μm.

The sizes of the spot detected on CCD array depends on the intensity of specular reflectance, which in turn is a result of the intensity of the incident laser beam, the sensitivity of the CCD array, and the reflectivity of the surface. It is possible to control the intensity of the laser source and the sensitivity of the CCD by changing instrument settings such as exposure time. At the same laser settings, the size of the detected spot is dependant only on the specular reflectivity within the small region on the surface. The size of the imaged spot is directly related to the intensity of specular reflectance. The larger detected spot size indicates that more light is specularly reflected from samples. For the measurement of surface roughness, the detector needs only to detect a certain amount of reflected light, a higher laser level with automatic exposure time is used. However, in case of gloss measurement, a lower laser level is set with a fixed exposure time.

4. Results and Discussion

4.1. Comparison of the present gloss measuring method with conventional method

Various commercial paper samples were selected for this experiment and the properties of the samples were shown in Table 1. Since TAPPI standard method, T 480 om -92, for the

Table 1. Gloss of Various Commercial Samples

Sample	TAPPI 75°	TAPPI 20°	Spot Gloss (average)	Gloss Variation (Spot Gloss)	Roughness (㎛)
A_1	13.00	4.30	24.10	12.24	4.33
A_2	26.03	4.30	30.51	6.29	1.29
A_3	43.25	7.37	44.22	12.47	1.38
A_4	45.18	6.60	46.43	11.08	3.20
A_5	52.86	7.58	48.97	8.74	1.56
A_6	70.05	13.73	52.69	3.66	0.58
A_7	71.30	12.07	54.99	3.48	0.54
A_8_P	82.06	26.53	61.90	6.38	3.26
A_9_P	82.37	29.65	61.56	5.77	1.13
A_10	87.63	69.06	66.43	1.34	0.64

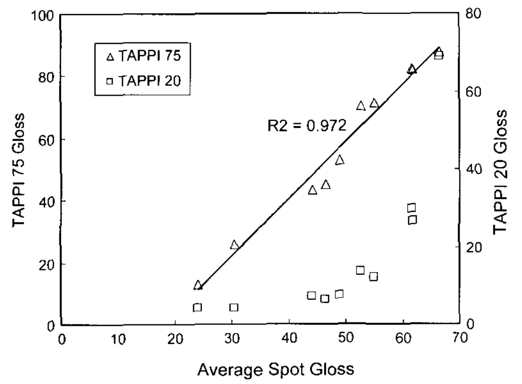

Figure 5. TAPPI Gloss versus Average Spot Gloss.

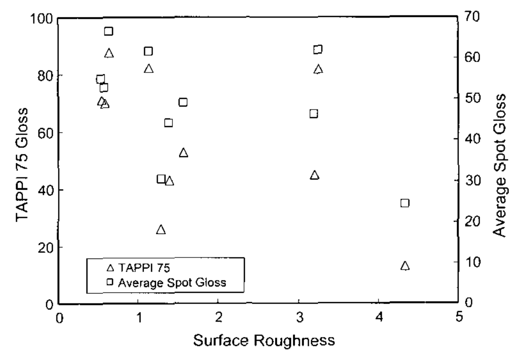

Figure 6. The Effect of Roughness on the TAPPI 75 Gloss and Average Spot Gloss. (*Unit of surface roughness: micrometer*)

75° gloss of paper has been widely used for measuring gloss of various paper samples, the gloss values by laser gloss-profilometer, referred to as 'Spot Gloss', were compared with the values of TAPPI method. The spot gloss value in table 1 are the average value of over 2000 local spot gloss values within a 100mm^2 test area.

TAPPI 20° gloss cannot detect the gloss difference between low gloss samples precisely[31)], thus there was a weak relationship between TAPPI 20° gloss and average spot gloss. However TAPPI 75° gloss showed a very strong relationship with the average spot gloss as shown in figure 5.

The figure 6 showed the effect of surface roughness on the gloss. The surface roughness was measured by the laser profilometer and expressed as the standard deviation of surface heights. Therefore these roughness values represented the variation of macro roughness. Although the samples showed a general trend so that higher gloss samples had smaller roughness values, the roughness values did not appear to be a significant factor that contributed to gloss.

4.2. The Gloss Variation of Printed MWC Paper

In case of mid - weight-coated(MWC) paper printed in a halftone pattern, the overall gloss

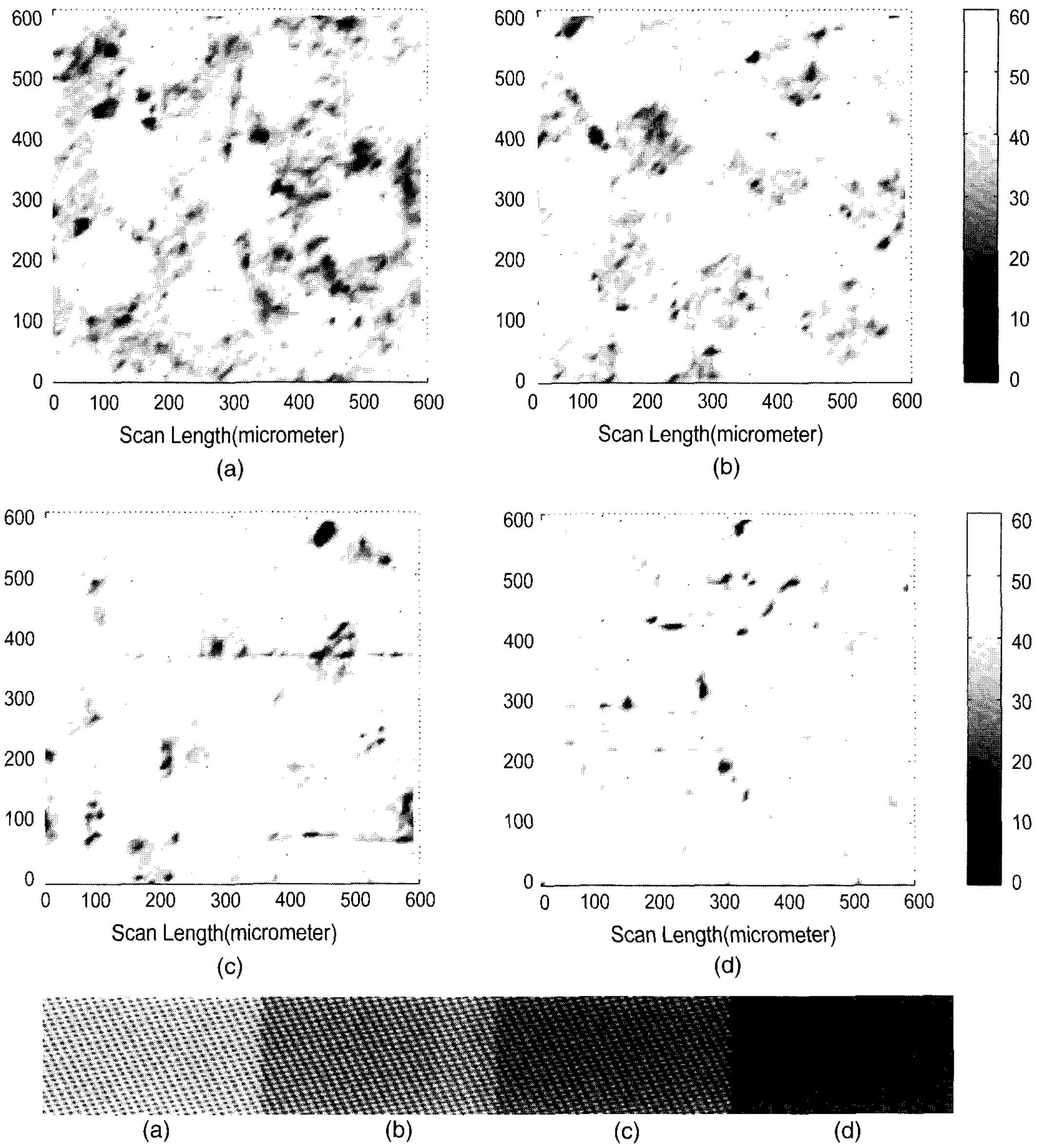

Figure 7. The Local Gloss Map of Offset Printed Paper.

and gloss variation of the paper and printed surface can not be measured by using conventional method since the spatial difference between regions of interest are much smaller than the aperture of the glossmeter.

Some typical offset printed MWC papers were selected for examination. All samples were printed by an offset lithographic printing method. The measuring area was 600㎛ by 600㎛ with 10㎛ interval and the gloss map was shown in figure 7.

The bottom image in figure 7 is the visual image of printed paper sample measured by using a CCD camera. There are four different printing densities in the sample, which were

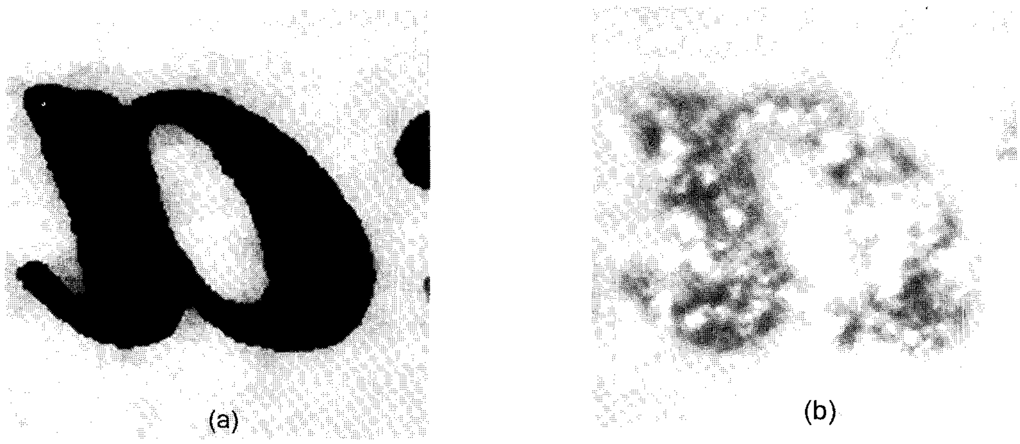

Figure 8. The Image of the printed Sample detected by CCD Camera.
(a) Detected with Normal Angle (b) Detected with 45° angle from normal angle

attained by systematically increasing the dot area. In the gloss map, the printed dot area, appeared as white, indicated that the gloss of printed area was higher than the unprinted area. The gloss difference between the two areas could therefore be quantified. In addition to the detection of print gloss contrast, the gloss variation pattern in printed area and in the unprinted area could be determined from the gloss map. The utility of this method for determinations of print gloss contrast and variation at scales less than the size of halftone dots was demonstrated.

4.3 Local Gloss Variation of Electrographic Images

In order to examine the selectivity of the method for detecting gloss, a character was imaged onto a smooth copy paper using electrographic imaging. The gloss of the character was further increased by pressing on the surface at elevated temperature with a Mylar film to melt and smooth the surface. The image of the character is shown in Figure 8(a), as image taken at 45° degrees using a CCD camera and illuminated by

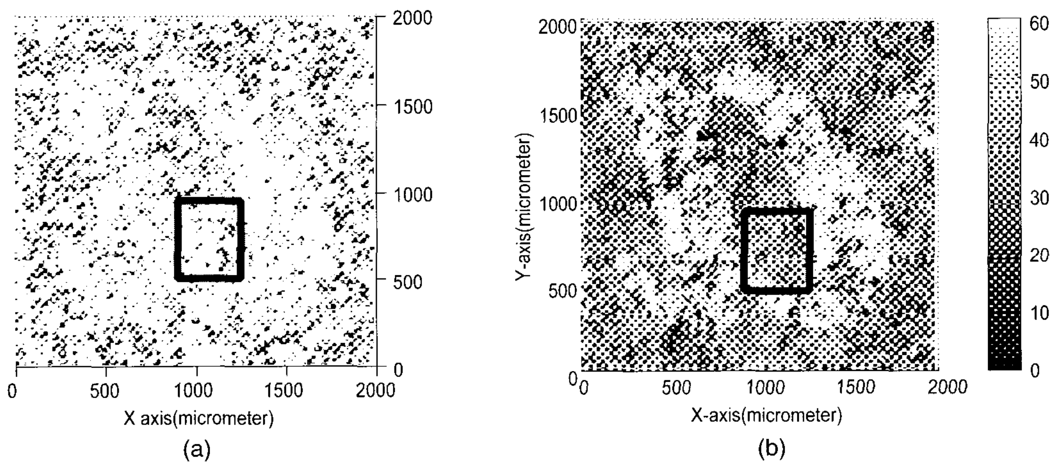

Figure 9. Gloss Map of printed Sample by the Spot Gloss Value and by the Macro-Roughness.
(a) Gloss Map by using Macro Roughness (b) Gloss Map by using Spot Gloss Values

a halogen lamp at an opposite incident angle of 45° degrees. As illustrated in Figure 8(b), the gloss variation can be detected in the image by this technique. In fact several investigators[11,12,14,32] determined gloss images using this method and evaluated the gloss variation using image analysis methods. Although the local gloss variation is evident using the experimental approach, differences in color between regions can also influence the measured gloss differential.

A gloss map was obtained using the laser sensor system shown in Figure 9, where it is clear that this method is not affected by variation of color or toner. Figure 10. showed the gloss map by using the normal vector angle of each macro facet, which was calculated by using the macro-roughness value. The smoother region appears whiter in the image. Generally, since the printed area was covered by toner, this area became more planar and smoother and gave a high spot gloss value. An inconsistency may exist in the original observation since it was shown earlier that by comparing the spot gloss map and facet gloss map for the square area in figure 9 and figure 10. Although the macro-roughness in the region appears more planar, the measured local spot gloss showed lower values. This decrease of spot gloss value in planar regions can be described by the micro-roughness in those facets.

Since the rough surface was covered by toner, the intensity of specular reflection light, R_{ii} value in printed area must be higher than unprinted area. Therefore, the R_{ii} value, which was determined by micro-roughness, was a major factor of gloss variation in this case.

4.4. Local Gloss Variation in LWC

Figure 10 shows the surface topography of an LWC that was commercially printed black by an offset lithographic process. This surface map illustrated well the existence of fibrous structure of the basestock below the coating layer. The

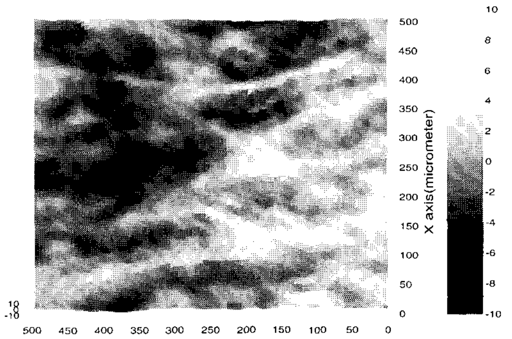

Figure 10. The Topography of an LWC paper (unit: micrometer).

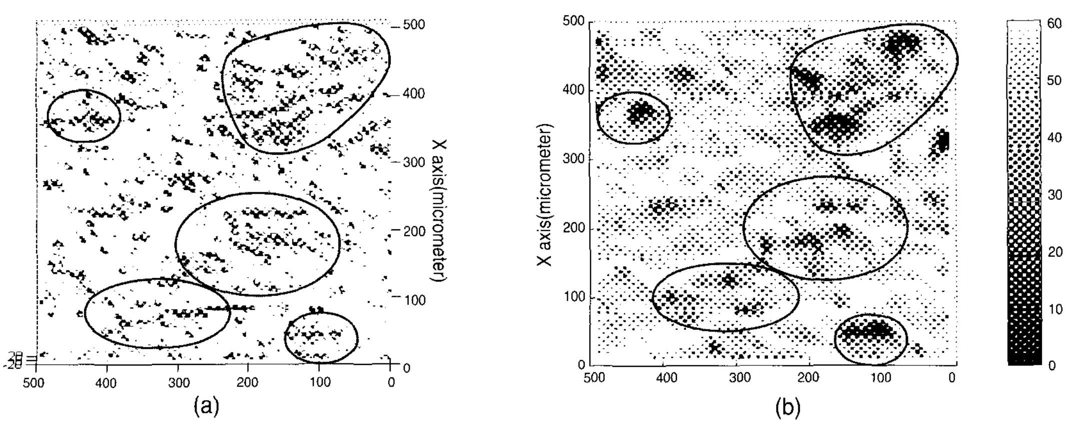

Figure 11. Gloss Map of LWC by the Spot Gloss Value and by the Macro-Roughness.
(a) Gloss Map by using Macro Roughness (b) Gloss Map by using Spot Gloss Values

macro scale roughness caused by the fibers affected the rendered macro facet angle map, which is shown in figure 11(a). By comparing the spot gloss map in Figure 11(b), the relationship between local gloss variation and macro-facet angle can be easily determined. The most significant contribution to the low gloss values observed in figure 11(b) are from tilting of the surface at the macro-roughness scale, rather than by local variation of submicron scale gloss.

5. Conclusion

Gloss variation is a function of micro-roughness and macro-roughness. In this study, a novel gloss measuring method, based on laser triangulation, was introduced to provide a mean to separate the contributions from each scale component to the total observed gloss, and its fine scale variation. For the various commercial paper samples, the average of local gloss values measured using this method were in good agreement with TAPPI 75° gloss(Hunter). The gloss map determined by using the sensor simplified the detection of local gloss variation and also provided the spatial and quantitative information of local gloss variation.

Typical MWC paper printed in a halftone pattern was evaluated. The results demonstrated that the utility of this method for determination of the print gloss contrast and variation at scales less than the size of halftone dots. Therefore, this method can be applied to the evaluation of the appearance properties of paper or printed images with very fine scale, on the order of 10㎛ micrometer.

The effect of macro-roughness on gloss variation for several samples was evaluated by using macro facet gloss map. In case of LWC, the local gloss variations in spot gloss map can be easily correlated with macro-facet angle variation in macro-facet gloss map point by point. Since the macro-facet gloss map was a function of only macro-roughness, this method can give a useful insight regarding the origin of local gloss variation.

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