Surface Characterization of Paper Products by Profilometry with a Fractal Dimension Analysis

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A surface profilometry technique was used to characterize the surfaces of paper products. A stylus-contact type profilometer capable of simultaneously generating both surface roughness- and friction-profiles was used. As a stylus for the profilometer, a conical shape whose tip was rounded to have a 0.5 mm curvature radius was designed and successfully employed in both printing & writing (P&W) papers and hygiene papers such as bathroom tissues and kitchen towel. From the profiles, the mean absolute deviation (MAD) from the averages, *i.e.*, *R*-MAD from the roughness average and *F*-MAD from the average coefficient of friction, were suggested as the new surface characterization parameters. To elucidate the surface roughness profiles by fractal dimension analysis, the variogram method was applied to get the fractal dimensions of the paper products. Generally, the value of the fractal dimension increased as the surface roughness increased. The surface profilometry technique with the fractal dimension analysis with the variogram method looks promising to gain additional insight on the surface characteristics of paper products.

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Keywords: Surface profilometry; Surface roughness profile; Friction profile; Mean absolute deviation; MAD; Fractal dimension analysis; Variogram method

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INTRODUCTION

Surface characterization plays an important role and finds many applications in the paper industry. Surface roughness and friction are the two main components of surface properties. The former is static and topographical and describes the geometry of the surface (ISO 13565-1 1996; ISO 3274 1996; ISO 4287 1997). The latter is dynamical and mechanical and describes the frictional forces between the two surfaces.

At present, a relationship between the roughness and the friction has not been well established. The reason is that the two properties belong to the extrinsic properties which depend on a test method with its testing conditions (Militky and Bajzik 2001).

Fellers *et al.* (1998) have reported that the coefficient of friction between the two paper surfaces should be higher for the smoother surfaces because the contact area between the two should be higher. In other words, the friction should be proportional to the contact area, which is inversely proportional to the surface roughness. Meanwhile, other investigators have reported that no relationship between the two should exist, being independent of each other (Garoff *et al.* 2002; Enomae *et al.* 2006).

Leach (2010) has demonstrated that even though two surfaces have the same average roughness, the friction can be totally different, supporting the argument that the two should be independent of each other. Thus, it should be prudent to determine both properties for the surface characterization (Ko *et al.* 2020), in order to avoid the wrong conclusions.

Surface profilometry is a technique to quantify the surface profiles of products. An interest in a stylus-type contact surface profilometric technique is growing in the paper industry because the technique resembles papermaking processes such as creping, coating, printing, lamination, calendaring, and embossing (Park *et al.* 2021; Moon *et al.* 2022). It is also similar to the method used for evaluating the quality attributes such as softness, wettability, printability, and absorption (Hollmark 1983a,b; Ampulski *et al.* 1991; Yokura *et al.* 2004; Ko *et al.* 2018, 2020)

As a surface profilometer, the KES-SE surface tester (Kato Tech Company (Kyoto, Japan) has been used to measure either roughness or friction of nonwovens, textiles, and tissue and paper products (Kato Tech 2018a,b). To this end, either a single U-tube stylus or a multiple-wire stylus has been used, although the former has been found to be more discriminating (Yokura *et al.* 2004). Since their findings, the single U-tube stylus has been preferred by other workers (Ko *et al.* 2017, 2019). Recently, the method of determining the surface friction of tissue products using the single U-tube stylus has been established as an ISO Standard (ISO 12625-18 2022).

However, it has been realized that this stylus does not work well on high-density paper such as writing & printing papers, kraft paper, and newsprint (Jeong *et al.* 2019; Moon *et al.* 2022). For these products, a design of a new stylus has been necessary.

Meanwhile, it was determined that the KES-SE surface tester should have the ability to be used to determine both the roughness and friction-properties simultaneously using the same stylus and under identical operating conditions. This allows one to examine the relationship between the two properties without ambiguity because the two profiles are generated at the exact same positions (Ko *et al.* 2019, 2020). In this stylus-type contact method, a stylus' shape and size, its contact force on the sample surface, and its scan speed have been identified as the key variables responsible for generating surface profiles (Kawabata 1980; Jeong *et al.* 2019; Ko *et al.* 2020; Moon *et al.* 2022).

It has been generally accepted that a finer tip size of a stylus should be necessary to determine the surface roughness on a microscale. The finer the tip is, the more accurate it is for roughness measurement. A tip radius of 1.5~2.5 μm (Taylor-Hobson 2002) to 32 μm (TAPPI T575 om-07 2012) has been used for commercial profilometers. Diamond or sapphire has mainly been used to produce a stylus of such a fine tip radius.

Once the surface profiles are obtained, typical parameters such as the roughness average (R_a) and the average coefficient of friction (μ) can be determined. The absolute mean deviation from the average, that is, *R*-MAD for the roughness, and *F*-MAD for the friction, have been suggested as new surface parameters (Ko *et al.* 2020; Park *et al.* 2021; Moon *et al.* 2022). *F*-MAD has been accepted as an ISO Standard for determining the friction properties of tissue products (ISO 12625-18 2022).

Fractal dimension analysis is a technique to quantify the surface profiles (Mandelbrot 1982). Since Mandelbrot introduced the term "fractal geometry," it has been found that fractal geometry exists everywhere in nature, as well as in the human body (Gleick 1987; Kaye 1989; Briggs 1992; Russ 2013; Barnsley 2014). It seems that fractal geometry should be the rule rather than the exception (Ko *et al.* 2015). Yet very few studies have been available for applying fractal dimension analysis techniques to quantify the surface profiles of paper products (Ko *et al.* 2015; Jeong *et al.* 2019; Moon *et al.* 2022).

The goal of this work was to characterize paper products by using a stylus-type contact method using a surface profilometer and to examine the relationship between the surface roughness and friction. Another objective was to explore the feasibility of using a fractal dimensional analysis technique to explore the nature of surface profiles.

Surface Roughness Characterization

For the surface roughness characterization using a stylus-contract type profilometer, a surface roughness profile is necessary. Figure 1 shows the surface roughness profiles of a printing and writing (P&W) paper and a bathroom tissue (BT) obtained using the Kato surface tester (Model: KES-SESRU, Kato Tech, Kyoto, Japan) (Kato Tech 2018a).

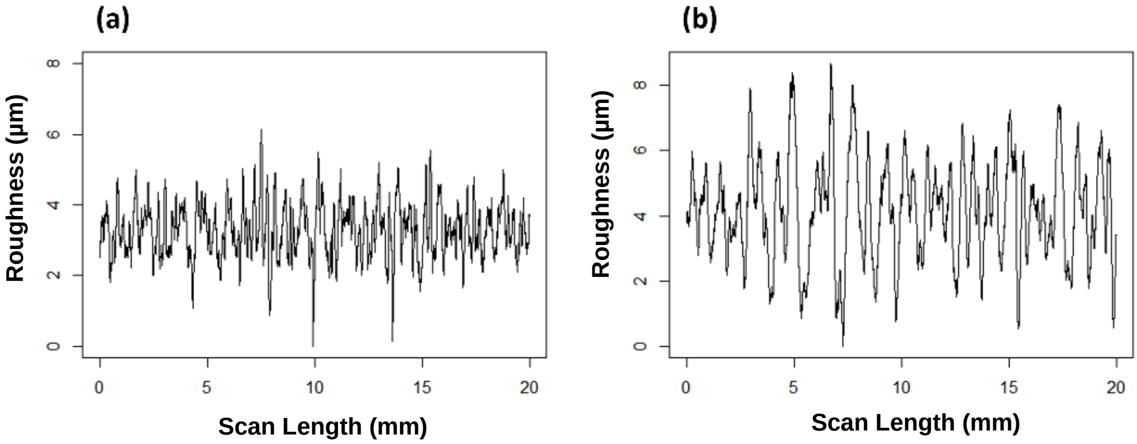

Fig. 1. Surface roughness profiles (A: P&W; B: bathroom tissue)

Determination of Surface Roughness Parameters

For a surface roughness profile as shown in Fig. 1, many surface parameters can be determined according to ISO 4287 (1997). The roughness average, R_a, was calculated according to Eq. 1 (Park *et al.* 2021),

$$R_a = \frac{1}{N}\sum_1^N |R_i| \tag{1}$$

where R_a is the roughness average (µm), R_i is the roughness (µm) at a scanning point *i* and *N* is the number of data points in the scan length. *N* is calculated from Eq. 2,

$$N = DAR \times L/V \tag{2}$$

where *DAR* is the data acquisition rate (Hz or points/s), *L* is the scan length (mm), and *V* is the scan speed (mm/s). (Park *et al.* 2021; Moon *et al.* 2022).

The spacing distance (SD) between two adjacent points can be calculated from Eq. 3 (Park *et al.* 2021; Moon *et al.* 2022).

$$SD = (L \times V)/(V/dar) = V/dar \tag{3}$$

SD may be interpreted as the measuring unit in a roughness profile, indicating a shorter *SD* with a shorter measuring unit. In Eq. 3, *SD* should be independent of the size of the stylus, being dependent only on the scan speed (*V*) and the data acquisition rate (*DAR).*

As a numerical illustration, at *DAR* = 1000 Hz, *L*= 20 mm, and *V* = 1 mm/s, *SD* becomes 1 micrometer.

The mean absolute deviation (*R*-MAD) from R_a has been defined as follows (Park *et al*. 2021),

$$R\text{-}MAD = \frac{1}{N}\sum_1^N \big||R_i| - R_a\big| \tag{4}$$

Figure 2 is a graphical representation of R_i, R_a, and $R\text{-}MAD$. R-MAD is calculated from dividing the shaded area by the scan length and it is shown as the dotted lines. In calculating R-MAD, R_a is treated as a constant in the same manner that thickness average is treated as a constant in calculating R_a.

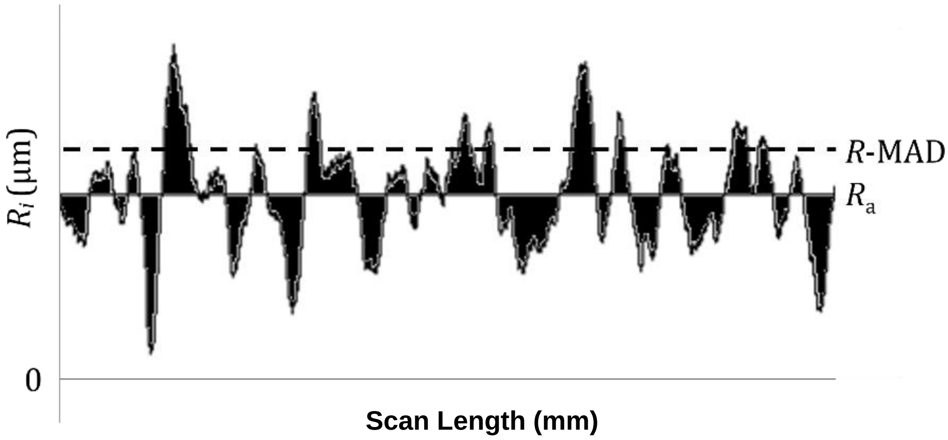

Fig. 2. A graphical representation of R_i, R_a, and R-MAD

Friction Characterization

The Kato Surface Tester can generate both surface roughness and friction-profiles at the same time using the same stylus under the same operating conditions. Figure 3 shows the friction profiles of the same samples shown in Fig. 1.

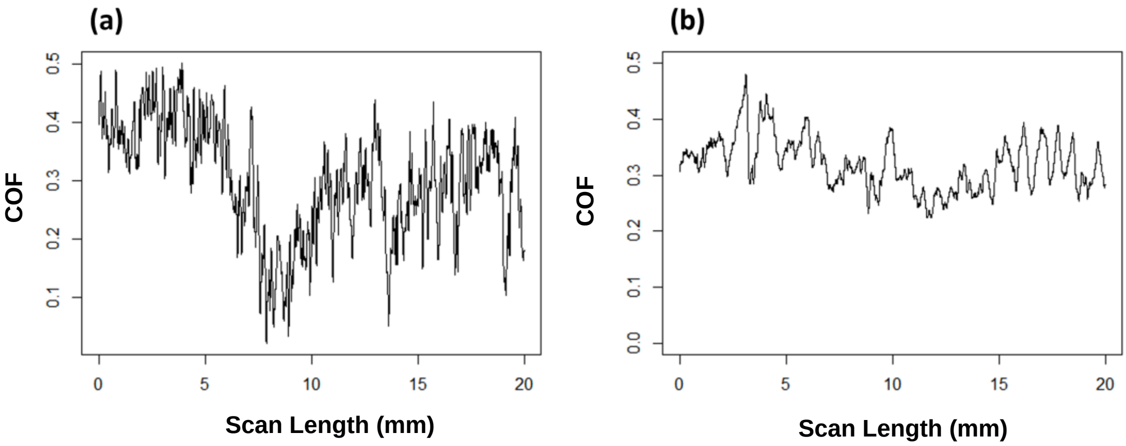

Fig. 3. Friction profiles (A: printing and writing; B: bathroom tissue)

The surface friction parameters, average of COF ($\bar{\mu}$) and the mean absolute deviation from the average coefficient of friction (F-MAD) are calculated from Eqs. 5 and 6, respectively.

$$\bar{\mu} = \frac{1}{N}\sum_{1}^{N}\mu_i \tag{5}$$

$$F\text{-}MAD = \frac{1}{N}\sum_{1}^{N}|\mu_i - \bar{\mu}| \tag{6}$$

where $\bar{\mu}$ is the average of COF, N is number of data points from the scan length, μ_i is the COF at point i, and F-MAD is the mean absolute deviation from the $\bar{\boldsymbol{\mu}}$ (Park *et al.* 2021; Moon *et al.* 2022). Here, N is calculated from Eq. 2.

Figure 4 shows a friction profile of the coefficient of friction *vs.* the scan length. The F-MAD is calculated by dividing the shaded area by the scan length and it is shown as the dotted lines.

In calculating F-MAD, average COF is treated as a constant in similar fashion to the case of R-MAD. F-MAD has been established as the ISO standard method in determining the friction of tissue products (ISO 12625-18 2022).

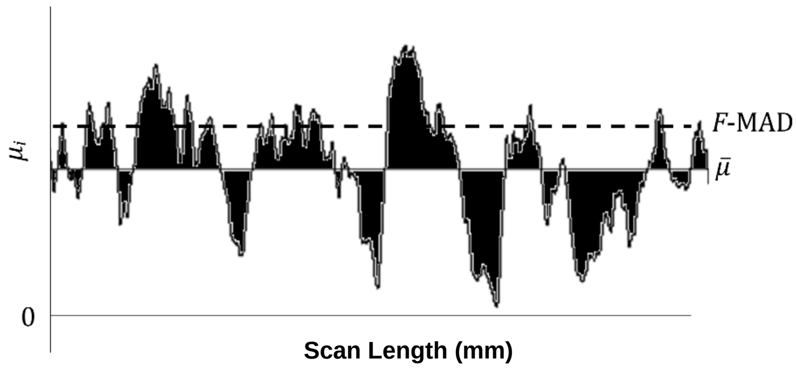

Fig. 4. A graphical representation of μ_i, $\bar{\mu}$(MIU) and *F*-MAD

Fractal Geometry Dimension Analysis of Surface Roughness Profiles

In determining the fractal geometry dimension from surface profiles, several methods are available. These include the Richardson Plot or the Box counting method (Richardson 1961; Kuparinen *et al.* 2005), computer simulation – *e.g.*, Mandelbrot set (Mandelbrot 1981), spectral density analysis with Fast Fourier Transform (PSD/FFT) (Falconer 2004), and the Variogram method (Mandelbrot 1982; Constantine and Hall 1984; Falconer 2004; Hall 1994).

Selecting a fractal dimension analysis method depends on the spacing distance between two adjacent points (Dalton and Herbert 1998; Militky *et al.* 2001; Ko *et al*. 2020). It also depends on the type of data acquisition; for example, the box counting method (or the Richardson Methods) has been commonly used to determine the fractal dimension analysis on the data acquired by Image Analyzer. (Kent 1991). In the present paper, the variogram method was used to determine fractal geometry dimensions from the surface profiles (Barnes 2002; Ko *et al.* 2020).

The Variogram Method

The Variogram method is a quantitative statistical procedure used to characterize the spatial continuity or roughness of a data set using autocorrelation between distances in the surface profile (Barns 2002; *Ko et al.* 2020). In statistics, autocorrelation means that the observations are dependent on each other. A higher autocorrelation means a higher dependency on each other. A distance between two pints is called lag, so lag *K* means any two points whose distance is equal to *K*. Therefore, a larger *K* means a larger spacing distance between two points (Constantine 1994).

In the variogram method, a variogram is computed from the autocorrelation function as Eq. 7 (Barnes 2002; Ko *et al.* 2020),

$$V_k = (1 - r_{(k+1)})/(1 - r_1) \tag{7}$$

where V_k is the Variogram at lag *k*, r_k is the autocorrelation at lag *k*.

Very few papers have been available on the fractal dimension values of paper products whose surface profiles are obtained using a stylus-contact type profilometer (Militky and Bajzik 2001). In the cited work the goal was to determine the fractal dimensions of nonwoven fabric surfaces from the surface roughness profiles obtained from the KES-SE surface tester. To this end, the variogram method by fractal dimension analysis was used. They realized, however, that at least about a couple of thousand surface profile data points would be required. In the present study, 20,000 data points were collected per 20 mm of the sample length, corresponding to a spacing distance of 1 μm.

Calculation of sample autocorrelation from the surface profile data of the surface roughness was performed using the time series analysis in JMP (2021), where a default of lag of *K*=15. Changing the lag *K* values used to calculate the autocorrelation may have an effect on the fractal dimension values. Figure 5 shows a plot of the variogram of V_k *vs. k* of a paper sample (P&W1 in MD) on a log-log scale. It shows that the slope starts to deviate at about log(Lag)= 1.0, corresponding to K=10 in this case. Thus, depending on the samples, the value of K which deviates from the initial slope may be different.

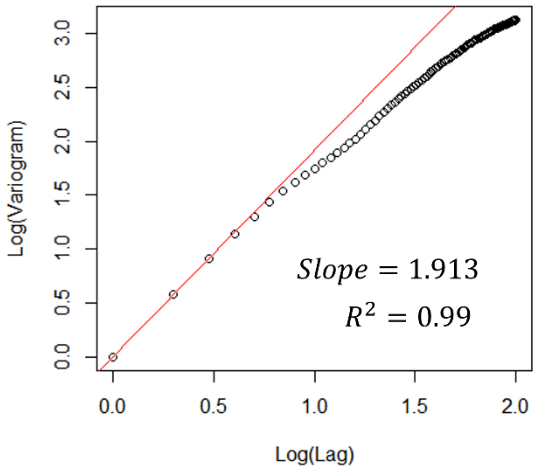

Fig. 5. The variogram plot on a log-scale (sample P&W1) in MD

In the variogram method, Fractal Dimension (FD) is determined from Eq. 8,

$$FD=2-|Slope|/2 \quad (8)$$

where the slope is determined by linear regression with zero-intercept from the variogram plot in Fig. 5. In Fig. 5, the following regression equation is obtained,

$Y = 1.913X$, R^2=0.99

where Y is log(Variogram), X is log(lag), and M is the slope. In Fig. 5, the following regression equation is obtained,

$Y = 1.913X$, R^2=0.99

Accordingly, the fractal dimension is

$$FD = 2 - |Slope|/2 = 2 - 1.913/2 = 1.044$$

According to Eq. 8, when abs(slope) = 2, FD becomes one, indicating that a surface profile should be a straight line. Meanwhile, when abs$|slope| \geq 2$, FD becomes zero, or negative, which has no physical meaning. Thus, FD of a roughness profile in one-dimension (e.g, the MD) should lie between 1 and 2 in order to have physical meaning. In this example, the sample surface seems rather smooth because its FD value is close to 1.0.

EXPERIMENTAL

Materials

Three Printing & Writing (P&W) paper specimens, two bathroom tissues (BT), and one paper towel were conditioned for longer than 48 h at a temperature of 23 °C ± 1 °C and a relative humidity (R.H.) of 50% ± 2%, according to ISO standard 187 (ISO 187, 1990). Table 2 shows a list of the samples, as well as their basis weight, thickness, and density.

Table 2. Physical Properties of Samples

Sample	Grade		Basis Weight (g/m^2)	Thickness (mm)	Density (g/cm^3)
P&W1	Printing and writing		80.3	0.11	0.74
P&W2	Printing and writing	Uncoated	70.5	0.09	0.76
P&W3		Coated	117.7	0.11	1.11
BT1	Bathroom tissue		48.3	0.20	0.24
BT2	Bathroom tissue		48.2	0.24	0.20
PT	Paper towel		56.1	0.28	0.21

The Morphologies of the Samples

SEM (Scanning electron microscopic, JEOL, JSM-7401F, Japan) photographs were taken of these samples. Figure 6 shows the SEM photographs P&W1 and P&W2 at magnifications of 1000x and P&W3 at magnifications of 1000x, and 10000x, respectively.

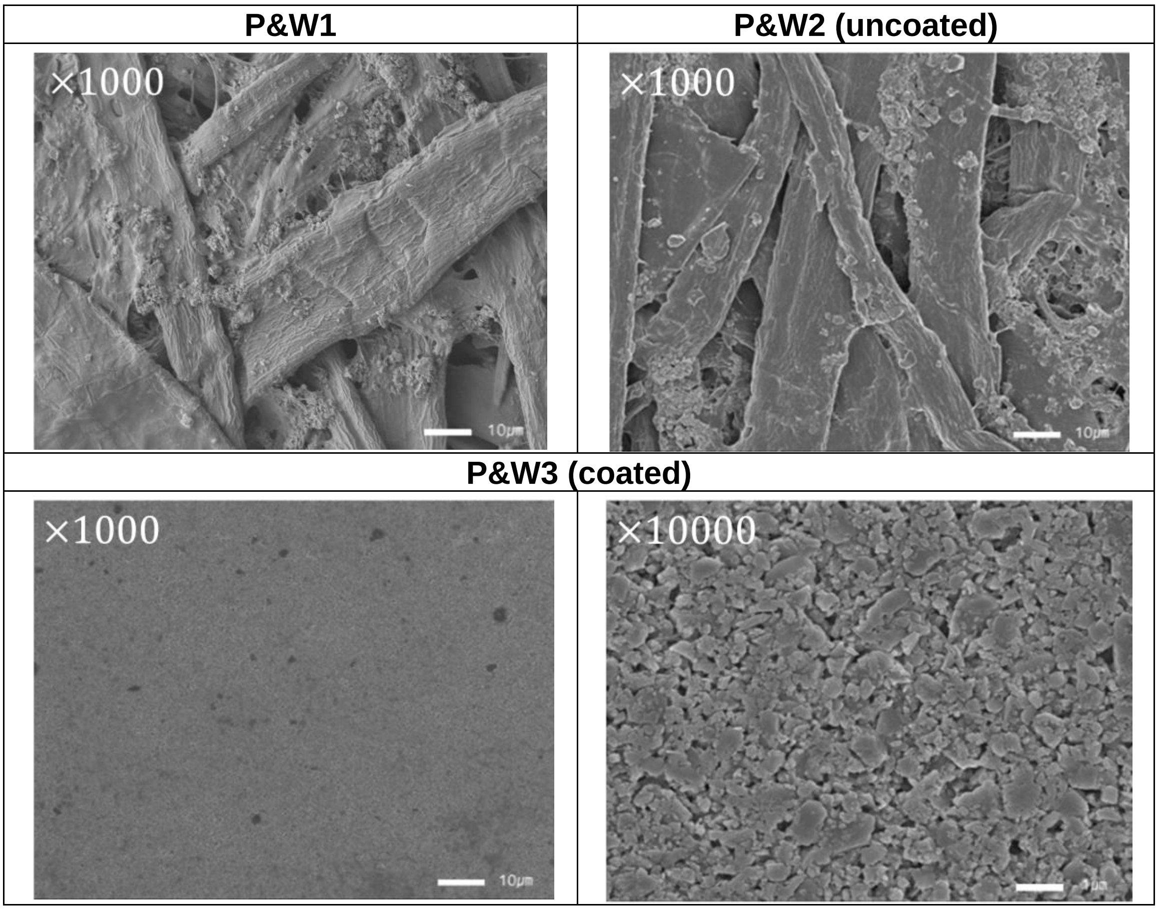

Fig. 6. SEM photographs of P&W1, P&W2 (uncoated) and P&W3 (coated) samples

Optical photographs of BT1, BT2, and PT were taken using OSD (OptiTopo surface deviation) equipment (L&W, Sweden). For each sample, three regions having different embossing patterns were taken, as shown in Fig. 7. In the figure, the arrow indicates the machine direction (MD) where scanning was done to get roughness profiles.

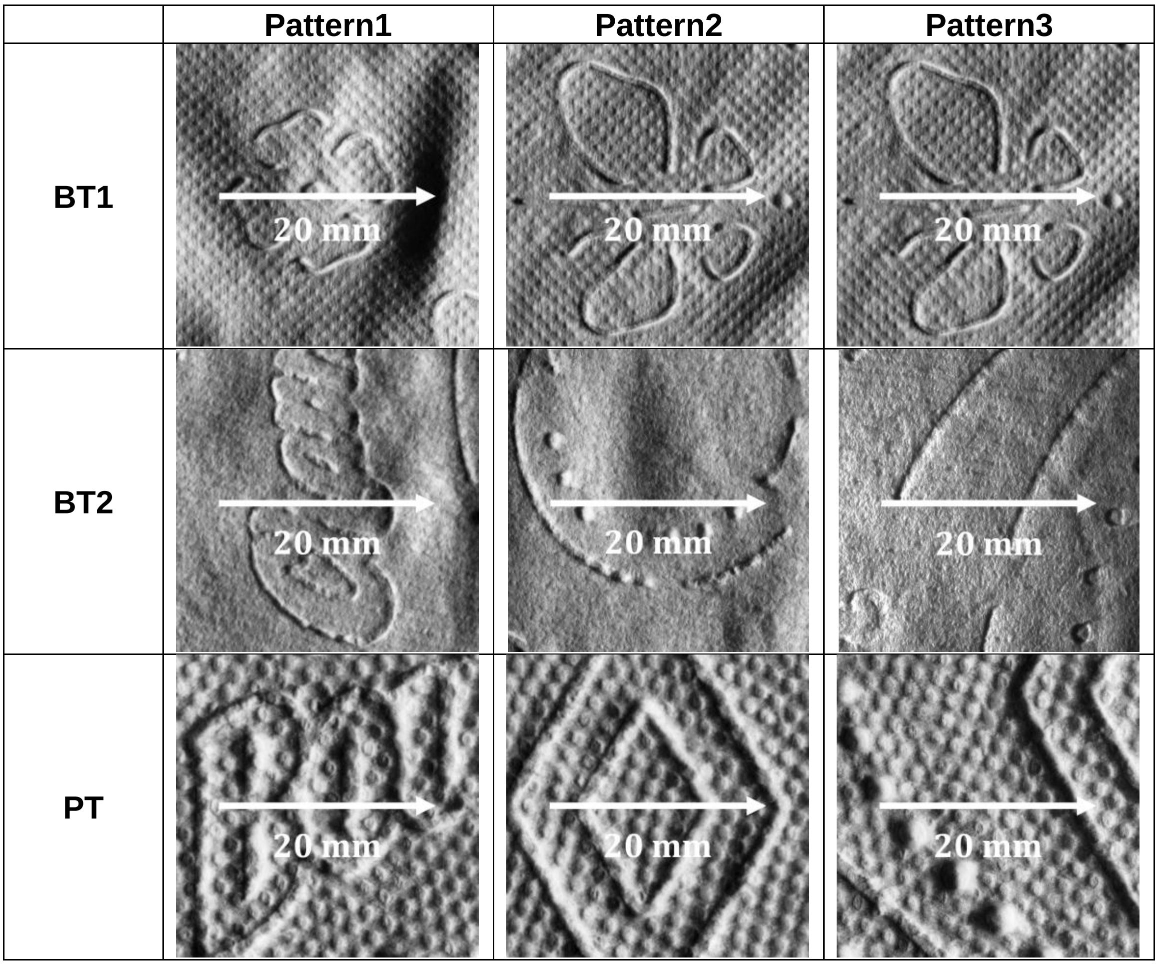

Fig. 7. Optical Photographs of Bathroom tissue (BT1 and BT2) and Paper Towel (PT)

The Surface Characterization: Surface Roughness and Friction

The surface tester (KES-SESRU, Kato Tech Co., Ltd., Kyoto, Japan) was used. (Kato Tech 2018a,b; Park *et al.* 2021).

It is to be noted that in this instrument it is the sample plate, not the stylus, which moves. This is in contrast to a conventional instrument as described in ISO 3274. Thus, the system used in the present work seems very likely to cause less damage to the sample surfaces than the conventional equipment.

Originally, this tester has been set up to employ a single-U type stylus suitable for testing tissue and paper towel products (Kato Tech 2018a; 2018b; Park *et al.* 2021; Yokura *et al*. 2004). Recently, this method has been established as ISO standard to determine the friction of tissue products (ISO 12625-18). It has been, however, realized that this stylus was not suitable for testing P&W samples.

A stylus was designed by rounding the tip of the conical stylus. It was made from a stainless steel (ASTM A681, P21/P20+S). Figure 8 shows the configuration of the profilometer with the tip of the rounded stylus. The contact area between such a stylus design and a sample surface may be assumed to be negligible unless the surface is compressed under the contact force. Thus, the contact area with the sample surface may be safely assumed to be independent of the radius of the curvature of the stylus tip.

The rounded-tip diameter of 1.0 mm was designed and used for both P&W samples and tissue samples.

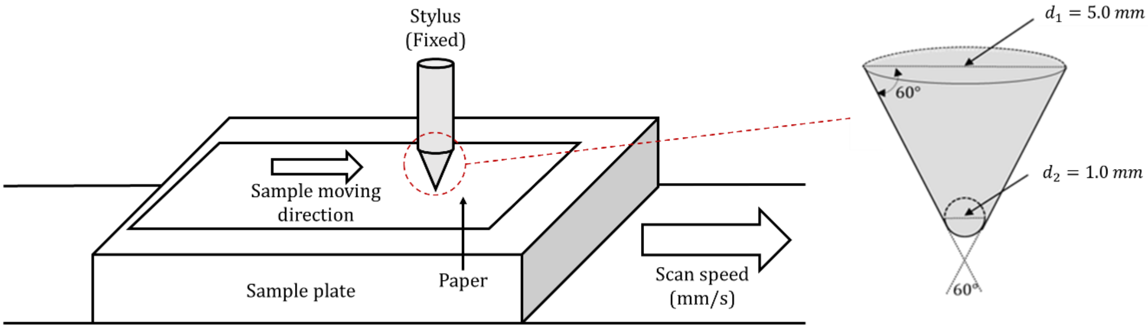

Fig. 8. Configuration of the profilometer with the stylus

The testing conditions were as follows: scan length 20 mm; scan speed 1 mm/s; and data acquisition rate 1000 Hz (or 1000 point/s). For each sample, 10 measurements were taken in the machine direction (MD) The testing was performed at 23 °C ± 1 °C and at R.H. of 50% ± 2%.

RESULTS AND DISCUSSION

Determination of Surface Roughness Parameters

Printing & Writing(P&W) Samples

Figure 9 shows the roughness profiles of P&W samples in the machine direction(MD). It shows that the profiles were widely different from each other.

The roughness average (R_a) and the mean absolute deviation (R-MAD) were calculated using Eqs. 1 and 4, respectively. The coefficient of variation (COV) in percentage was determined from 10 measurements for each sample.

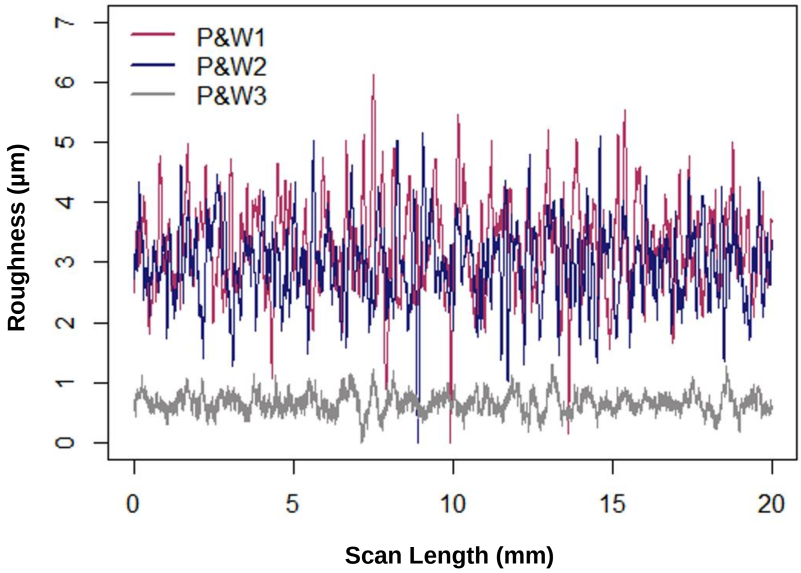

Fig. 9. Roughness profiles of P&W Samples

Table 3 shows the results. A couple of items are noted in the table. First, R-MAD and its COV were significantly lower than its corresponding R_a and COV. This can support the argument what R-MAD should be a measure of the true surface profile, unlike R_a which depends on the testing conditions, as described in Fig. 2. It shows that R_a is treated as a constant in calculating R-MAD.

Second, comparing P&W2 (uncoated) with its coated P&W3 indicates that both R_a and R-MAD had been reduced remarkably by about 70%. Similar results have been obtained by other investigators (Jeong *et al*. 2019; Park *et al.* 2021). This confirms that the effect of coating on a paper surface can be determined by determining the R_a and R-MAD from the roughness profiles using a surface profilometer.

Table 3. Results for R_a and R-MAD of P&W

Sample	R_a		R-MAD	
	Avg (μm)	COV (%)	Avg (μm)	COV (%)
P&W1	2.66	16.8	0.62	0.8
P&W2	2.23	13.5	0.54	6.6
P&W3	0.51	15.3	0.12	11.0

* Machine direction

Bathroom Tissue (BT1, BT2) and Paper Towel (PT) Samples

Table 4 shows the results of R_a and R-MAD of Tissue (BT1, BT2) and Towel (PT) samples. Figure 10 shows the roughness profiles of Bathroom tissues (BT1 and BT2) and paper towel (PT) according to their embossing patterns, respectively.

The figure shows that R_a and R-MAD had been affected by the embossing patterns of the samples. As shown in Fig. 7 for the BT1 sample, Pattern 2 was much more remarkable than its Pattern 3, resulting in a high value of R_a and R-MAD. Nevertheless, the difference in R-MAD between the two was much smaller than that of R_a, *i.e*., 4% *vs*. 56%. This indicates that an embossing pattern should influence R-MAD much less than R_a.

Table 4. Results for R_a and R-MAD of BT1, BT2, and PT

Sample	Parameter	Pattern 1		Pattern 2		Pattern 3	
		Avg (μm)	COV (%)	Avg (μm)	COV (%)	Avg (μm)	COV (%)
BT1	R_a	12.45	25.3	13.17	11.6	5.78	21.3
	R-MAD	1.58	11.5	1.51	7.8	1.23	8.7
BT2	R_a	12.29	28.4	13.45	13.7	9.10	47.2
	R-MAD	1.53	10.6	1.69	12.3	1.44	12.1
PT	R_a	14.06	0.3	14.08	0.4	12.54	18.0
	R-MAD	2.04	16.4	2.02	10.1	1.95	11.9

* Machine direction

Most commercial tissues and paper towels are embossed. Therefore, it is extremely challenging to determine the R_a of such products. To avoid this problem, Hollmark (1983a,b) tried to avoid the embossing regions for determining the surface roughness. A determination of R-MAD should eliminate the problem, as shown in the present study.

The reason why R-MAD is less sensitive to embossing may be explained from Eq. 2 and Fig. 2, which show that in calculating R-MAD, R_a is treated as a constant. Accordingly, while R_a depends on testing conditions as well as the embossing pattern of a sample, R-MAD should be much less dependent on them.

Determination of Friction Parameters

Printing & Writing(P&W) Samples

Figure 10 shows the friction profiles of P&W samples. Table 5 shows the values of average coefficient of friction ($\bar{\mu}$) and *F*-MAD of the P&W samples. It shows that *F*-MAD was much lower than $\bar{\mu}$, as is the case with R_a and *R*-MAD shown in Table 3. As shown in eq. 6, in calculating *F*-MAD, $\bar{\mu}$ is treated as a constant. Thus, while $\bar{\mu}$ depends on the testing conditions, *F*-MAD should be much less dependent on them.

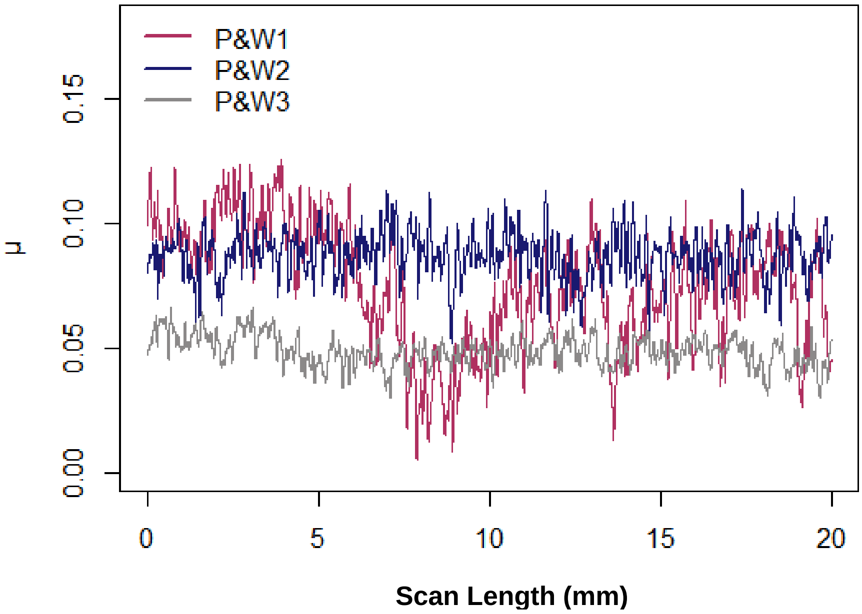

Fig. 10. Friction profiles of P&W samples

The effect of coating on $\bar{\mu}$ and *F*-MAD can be seen by comparing the values of $\bar{\mu}$ and *F*-MAD of P2 (uncoated) with those of P3 (coated). Table 6 shows both $\bar{\mu}$ and *F*-MAD of P2 decreased after the coating (P3), which is consistent with the roughness as discussed earlier. However, the degree of the decrease in *F*-MAD was much more significant than in $\bar{\mu}$ (60% for *F*-MAD *vs.* 28 % for $\bar{\mu}$). This suggests that the effect of coating can be better determined from *F*-MAD than $\bar{\mu}$.

Table 5. Results for $\bar{\mu}$ and *F*-MAD of P&W

Sample	$\bar{\mu}$		*F*-MAD	
	Avg	COV (%)	Avg	COV (%)
P&W1	0.34	15.1	0.053	36.4
P&W2	0.29	13.4	0.050	34.9
P&W3	0.21	15.9	0.020	34.6

* Machine direction

Table 6. Effects of Coating on Friction

Sample	$\bar{\mu}$	*F*-MAD
	Avg	Avg
P2	0.29	0.050
P3	0.21	0.020
Change (%)	27.5	60.0

Bathroom Tissue (BT1, BT2) and Paper Towel(PT) Samples

Table 7 shows the results of $\bar{\mu}$ and *F*-MAD of the tissue and towel samples.

Table 7. Results for $\bar{\mu}$ and *F*-MAD of BT1, BT2, and PT

Sample	Parameter	Pattern 1		Pattern 2		Pattern 3	
		Avg (μm)	COV (%)	Avg (μm)	COV (%)	Avg (μm)	COV (%)
BT1	$\bar{\mu}$	0.35	16.6	0.30	10.7	0.32	8.4
	F-MAD	0.083	21.5	0.076	12.1	0.058	8.9
BT2	$\bar{\mu}$	0.29	32.6	0.42	21.9	0.40	29.5
	F-MAD	0.089	40.5	0.113	20.5	0.086	38.5
PT	$\bar{\mu}$	0.41	48.4	0.31	24.4	0.32	28.0
	F-MAD	0.247	41.6	0.193	14.4	0.159	29.6

* Machine direction

Surface Roughness (R_a and *R*-MAD) vs. Friction ($\bar{\mu}$, *F*-MAD) $\bar{\mu}$ *vs.* R_a

Figure 11 shows a plot of $\bar{\mu}$ *vs.* R_a of the six samples (with 12 data points). The correlation between the two was very poor, which indicates that the two are independent of each other. Thus, it should be prudent to measure both properties for surface characterization, although it is the friction properties that contribute to the softness of tissue and towel (Ko *et al*. 2020).

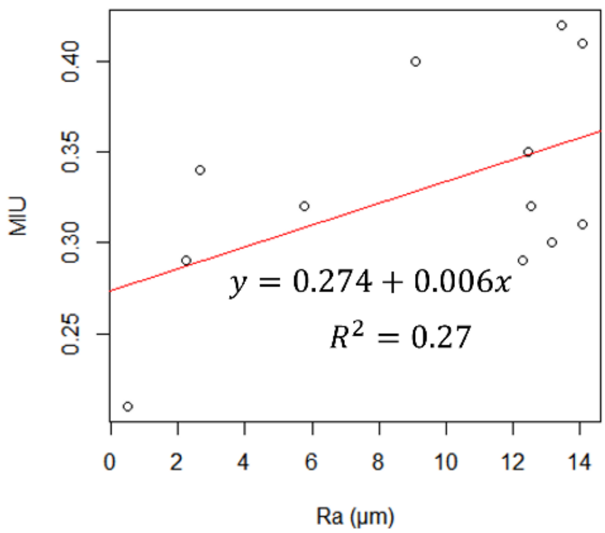

Fig. 11. $\bar{\mu}$ *vs.* R_a

R-MAD vs. F-MAD

Figure 12 shows a plot of *F*-MAD vs. *R*-MAD of the six samples (with 12 data points). It seems to show a better correlation than the correlation between R_a and $\bar{\mu}$.

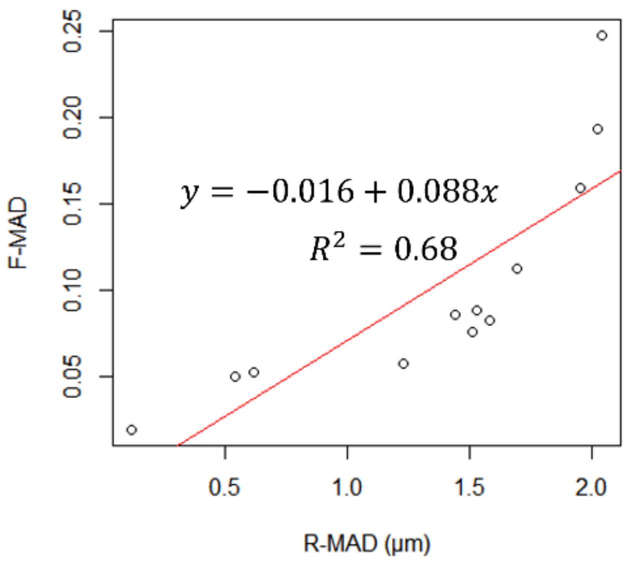

Fig. 12. *F*-MAD *vs.* *R*-MAD

Fractal Dimension Analysis on the Surface Roughness

Printing & Writing (P&W) samples

Fractal dimension (FD) value of each P&W sample was determined using the Variogram method. Table 8 shows the FD values with of the R_a and *R*-MAD. According to Table 8, FD values were close to each other. This may indicate that the roughness profile may not be distinguishable for the three P&W samples.

Table 8. Results for Fractal Dimension (FD) of P&W

Sample	R_a		*R*-MAD		*R*-FD	
	Avg (µm)	COV (%)	Avg (µm)	COV (%)	Avg	COV (%)
P&W1	2.66	16.8	0.62	0.8	1.073	0.8
P&W2	2.23	13.5	0.54	6.6	1.082	1.3
P&W3	0.51	15.3	0.12	11.0	1.053	0.5

* Machine direction

Bathroom Tissue (BT1, BT2) and Paper Towel (PT) Samples

Table 9 shows the results of R_a, *R*-MAD and FD of BT1, BT2, and PT samples. It shows the FD values of all the samples lie between 1.11 ~ 1.14, which is considered within a narrow range. This may indicate that their roughness profiles may have similar characteristics. However, compared with Table 8 for the P&W samples, the tissue products seem to generate a higher FD value, indicating a higher degree of the roughness. The roughness of a paper consists of several scales of the surface roughness from a micro-scale (*i.e.*, individual fibers), roughness (the sheet prior to converting), and macro-scale (after converting such as creping and embossing). Decoupling of these scales into each scale by a fractal dimension analysis, to a much smaller scale (*i.e.*, submicron) of a roughness profile may be necessary. In this case, the power spectrum density (PSD) might be employed.

Table 9. Results for Fractal Dimension (FD) of Bathroom Tissue (BT1 and BT2) and Paper Towel (PT) Samples

Sample	Parameter	Pattern 1		Pattern 2		Pattern 3	
		Avg (μm)	COV (%)	Avg (μm)	COV (%)	Avg (μm)	COV (%)
BT1	R_a	12.45	25.3	13.17	11.6	5.78	21.3
	R-MAD	1.58	11.5	1.51	7.8	1.23	8.7
	FD	1.143	2.1	1.132	3.0	1.133	4.5
BT2	R_a	12.29	28.4	13.45	13.7	9.10	47.2
	R-MAD	1.53	10.6	1.69	12.3	1.44	12.1
	FD	1.126	5.3	1.137	4.2	1.119	5.7
PT	R_a	14.06	0.3	14.08	0.4	12.54	18.0
	R-MAD	2.04	16.4	2.02	10.1	1.95	11.9
	FD	1.127	4.3	1.118	5.7	1.129	4.0

* Machine direction

CONCLUSIONS

1. In the surface profilometry technique, the stylus is one of the most critical components that affects generating surface profiles. A stylus with a rounded-tip diameter of 1.0 mm was successfully designed for use on tissue, towel, and P&W samples. The remarkable feature of this design is that it provides a minimal contact with the sample surface because its contact area with the surface is spherical. There is minimal damage to the sample surface because its contact area is rounded, *i.e.*, not sharp.
2. In a profilometry method, a spacing distance in the scanning direction was determined by a data acquisition rate at a given scan speed. Surprisingly, the size of the stylus did not play any role in determining the spacing distance.
3. A data acquisition rate of 1000 Hz (*i.e.*, 1000 points/s) provided stable and reliable profiles of surface roughness and friction for paper samples, resulting in the spacing distance of 1 μm at the scan speed of 1 mm/s. It is remarkable to obtain such SD with the designed stylus whose tip diameter is 1000 μm made from a stainless steel (ASTM A681). In contrast, the conventional commercial profilometers have the stylus whose tip diameter is 25 μm, made of diamond or sapphire, which are very expensive. A use of this newly designed stylus is likely to speed up applying this profilometry technique for the surface characterization of paper products in the future.
4. As a new surface characterization parameter, the mean absolute deviation (MAD) was suggested. This aspect can be expressed as two quantities: the *R*-MAD for the surface roughness and the *F*-MAD for the surface friction. MAD represents the deviation from R_a or $\bar{\mu}$. It is critically important to realize that while R_a or $\bar{\mu}$ depends on the instrument and its operating conditions, *R*-MAD or *F*-MAD should not depend on them

because these represent the variations within the sample. It was also realized that they are not likely to be significantly affected by converting processes such as embossing and creping.

5. The variogram method was successfully applied to determine fractal dimension (FD) of the tissue, paper towel, P&W samples from the roughness profiles. In this method, spacing distance was found to be the most critical factor and a spacing distance of 1 um was found to be adequate for the variogram method. Yet, the interpretation of the fractal dimension values of these products requires further investigation.

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REFERENCES CITED

Ampulski, R. S., Sawdai, A. H., Spendel, W., and Weinstein, B. (1991). “Methods for the measurement of the mechanical properties of tissue paper,” in: *Proceedings of the International Paper Physics Conference*, Kailua Kona, HI, USA, 19-30.

Barns, R. (2002). “Variogram tutorial,” Golden software.

Barnsley, M. F. (2014). *Fractals Everywhere*, Elsevier, Academic Press.

Constantine, A. G., and Hall, P. (1994). “Characterizing surface smoothness via estimation of effective fractal dimension,” *Journal of the Royal Statistical Society. Series B (Methodological)* 56(1), 97-113.

Enomae, T., Yamaguchi, N., and Onabe, F. (2006). “Influence of coating properties on paper-to-paper friction of coated paper,” *Journal of Wood Science* 52, 509-513.

Falconer, K. (2004). *Fractal Geometry: Mathematical Foundations and Applications*, John Wiley & Sons, Hoboken, NJ, USA.

Fellers, C., Backstrom, M., Htun, M., and Lindholm, G. (1998). “Paper-to-paper friction – Paper structure and moisture,” *Nordic Pulp & Paper Research Journal* 13(3), 225-232. DOI: 10.3183/npprj-1998-13-03-p225-232

Garoff, N., Nilvebrant, N. O., and Fellers, C. (2002). “Friction of linerboard based on recycled fiber,” *Journal of Applied Polymer Science* 85(7), 1511-1520.

Hobson, T. (2002). *Form Taylsurf Intra Operator’s Handbook*.

Hollmark, H. (1983a). “Mechanical properties of tissue,” in: *Handbook of Physical and Mechanical Testing of Paper and Paperboard*, Vol. 1, R. E. Mark (ed.), Marcel Dekker Inc., New York, NY, USA, pp. 497-521.

Hollmark, H. (1983b). “Evaluation of tissue paper softness,” *TAPPI Journal* 66(2), 97-99.

ISO 187 (1990). “Paper, board and pulps — Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples,” International Organization for Standardization, Geneva, Switzerland.

ISO 3274 (1996). “Geometrical product specifications (GPS) – Surface texture: Profile method – Nominal characteristics of contact (stylus) instruments,” International Organization for Standardization, Geneva, Switzerland.

ISO 4287 (1997). “Geometrical product specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameter," International Organization for Standardization, Geneva, Switzerland.

ISO 13565-1 (1996). "Geometrical product specifications (GPS) — Surface texture: Profile method; Surfaces having stratified functional properties — Part 1: Filtering and general measurement conditions," International Organization for Standardization, Geneva, Switzerland.

ISO 12625-18 (2022). "Tissue and tissue products. determination of surface friction," International Organization for Standardization, Geneva, Switzerland.

Jeong, H. S., Ko, Y. C., and Kim, H. J. (2019). "Effects of a stylus on the surface roughness determination in a contact method for paper and paperboard," *Nordic Pulp & Paper Research Journal* 34(4), 442-452. DOI: 10.1515/npprj-2019-0011

JMP Statistical Discovery LLC (2021). JMP Statistical Discovery Version 17, London, Ont, Canada.

Kato Tech Co. (2018a). *Roughness Tester, KS-SRU-KR, Operation Manual*, ver. 1.03, Kato Tech Co., Ltd., Kyoto, Japan.

Kato Tech Co. (2018b). *Friction Tester, KW-SRU-KF, Operation Manual*, ver. 1.03, Kato Tech Co., Ltd., Kyoto, Japan.

Kawabata, S. (1980). *The Standardization and Analysis of Hand Evaluation*, 2nd Edition, Textile Machinery Society of Japan, Osaka, Japan.

Kaye, B. H. (1989). *A Random Walk through Fractal Dimensions*, VCH, Verlagsgesellschaft.

Kent, H. J. (1991). "The fractal dimension of paper surface topography," *Nordic Pulp & Paper Research Journal* 6(4), 191-196.

Ko, Y. C., Park, J. Y., and Kim, H. J. (2017). "Characterization of surface properties of paper towels," *Journal of Korea Technical Association of the Pulp and Paper Industry* 49(6), 81-89.

Ko, Y. C., Melani, L., Park, N. Y., and Kim, H. J. (2020). "Surface characterization of paper and paperboard using a stylus contact method," *Nordic Pulp & Paper Research Journal* 35(1), 78-88. DOI: 10.1515/npprj-2019-0005

Ko, Y. C., Park, J. M., and Shin, S. J. (2019). "The principles of fractal geometry and its applications for pulp and paper industry," *Journal of Korea Technical Association of the Pulp and Paper Industry* 47(4), 177-186.

Ko, Y. C., Park, J. Y., Melani, L., Park, N. Y., and Kim, H. J. (2019). "Principles of developing physical test methods for disposable consumer products," *Nordic Pulp & Paper Research Journal* 34(1), 75-87. DOI: 10.1515/npprj-2018-0029

Kuparinen, T., Rodionov, O., Toivanen, P., Mielikainen, J., Bochko, V., Korkalainen, A., and Vartiainen, E. (2005). "Fractal dimension analysis and statistical processing of paper surface images towards surface roughness measurement," in: Image Analysis: 14th Scandinavian Conference, SCIA 2005, Joensuu, Finland, June 19-22, 2005. Proceedings 14 (pp. 1218-1227). Springer, Berlin, Heidelberg.

Leach, R. K. (2010). "Surface topography characterization," in: *Fundamental Principles of Engineering Nanometrology*, Elsevier, Amsterdam, Netherlands, 211-262. DOI: 10.1016/B978-0-08-096454-6.10008-9

Mandelbrot, B. B. (1982). *The Fractal Geometry of Nature*, W. H. Freeman, New York.

Militky, J., and Bajzik, V. (2001) Surface roughness and fractal dimension, *Journal of the Textile Institute* 92(3), 91-113. DOI: 10.1080/00405000108659617

Moon, B. G., Park, N. Y., Ko, Y. C., and Kim, H. J. (2022). "Characterization of paper surfaces by friction profilometry," *BioResources* 17(4), 6067-6078. DOI: 10.15376/biores.17.4.6067-6078

Park, N. Y., Ko, Y. C, Kim, H. J., and Moon, B. G. (2021). "Surface characterization of paper products via a stylus-type contact method," *BioResources* 16(3), 5667-5678. DOI: 10.15376/biores.16.3.5667-5678

Russ, J. C. (2013). *Fractal Surfaces*, Springer Science & Business Media.
TAPPI T575 om-07 (2012). "Roughness of paper and paperboard, stylus (Emveco-type) method," TAPPI Press, Atlanta, GA, USA.
Yokura, H., Kohono, S., and Iwasaki, M. (2004). "Objective hand measurement of toilet paper," *Journal of Textile Engineering* 50(1), 1-5. DOI: 10.4188/jte.50.1

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