

Effect of Stylus Size on Surface Roughness Characterization of Paper Products

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Surface roughness plays a critical role in determining the performance and quality of paper products; however, its accurate determination depends strongly on the geometry of the stylus used in contact profilometry. Herein, the effect of stylus-tip size on surface roughness characterization was evaluated along with the suitability of fractal dimension (FD) analysis as a supplementary metric. Styluses with tip radii ranging from 0.25 to 1.75 mm were examined, and a 0.5-mm stylus tip (0.5R) yielded the most stable and reliable surface roughness measurements under a constant contact force of 5 gf. Coating considerably reduced surface roughness fluctuations, with the roughness mean absolute deviation (RMAD) decreasing by 78%. A comparison between a 0.5R conical stylus and a pyramidal stylus showed strong agreement in the R_a and RMAD values, confirming that the conical design maintained minimal contact area. High-resolution profilometry (0.1- μ m spacing distance and 200,000 data points per scan) enabled the computation of FD via power spectral density analysis. FD values approached 2 for coated paper, reflecting a transition from line-dominated to more areal surface structures. These findings indicate that stylus selection critically affects surface roughness characterizations and that FD serves as a useful complementary descriptor for surface roughness changes.

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INTRODUCTION

Surface properties consist of surface roughness and surface friction. Surface roughness can be assessed using non-contact methods, such as optical techniques (Thwaite 1982), or indirect approaches, including air-leak methods (ISO 8791-2 2013; ISO 8791-3 2017; ISO 8791-4 2021). In contrast, friction is inherently a dynamic and mechanical property that governs the interaction between two contacting surfaces. Therefore, a stylus-based contact method offers a promising approach, as it enables the simultaneous evaluation of both surface roughness and friction under direct mechanical interaction.

Stylus-based surface profilometry has garnered considerable interest within the paper industry because this technique mirrors key manufacturing operations such as creping, coating, printing, lamination, calendaring, and embossing; the method offers insights into essential surface properties such as softness, wettability, printability, and absorption (Jeong *et al.* 2019; Ko *et al.* 2019; Park *et al.* 2021; Moon *et al.* 2022; Lee, Y. J. *et al.* 2023). Although optical techniques provide non-contact evaluation, their spatial

resolution is constrained by diffraction limits and surface reflectivity characteristics (Poon and Bhushan 1995). This limitation may restrict the acquisition of fine structural details. Furthermore, measurements become less reliable for surfaces exhibiting large roughness amplitudes or for paper with low opacity, where light transmission can interfere with accurate surface detection.

In stylus-based surface profilometry, a stylus is traversed across the sample surface in a predetermined direction, and variations in height along the scan length are recorded to generate a surface roughness profile (Lee 2013). The stylus physically contacts the sample surface, and the stylus geometry, applied contact force, and scanning speed influence the reliability of surface roughness measurements (Jeong *et al.* 2019; Ko *et al.* 2019; Park *et al.* 2021).

The KES-SE surface tester (Kato Tech Co., Ltd., Kyoto, Japan) is used as a surface profilometer to measure the roughness and friction of printing paper, newspaper, paperboard, and hygiene paper products (Jeong *et al.* 2019; Ko *et al.* 2019; Park *et al.* 2020; Moon *et al.* 2022; Lee, Y. J. *et al.* 2023; Lee, J. M. *et al.* 2023; Kweon *et al.* 2024). Until recent decades, a standardized stylus-based surface profilometry has not been developed for determining the surface roughness of paper and paperboard. However, a recently published international standard, ISO 24118-1 (2023), provides guidelines for stylus-based surface profilometry of paper and paperboard. Although stylus-based methods such as TAPPI T 575-om-07 (Emveco method) are used for surface roughness measurements, they are limited in scope and do not offer a unified international standard for all materials.

The measurement resolution of stylus-based surface profilometry increases with decreasing spacing distance (SD) between sampling points and reduced stylus tip size (Leach and Hart 2001). However, manufacturing such fine tip geometry is expensive, thereby limiting the practical resolution attainable in commercial profilometers (Jeong *et al.* 2019). The authors proposed a conical stylus with a defined spherical tip radius to address this challenge. Although the overall stylus geometry is conical, contact with the sample surface occurs at the spherical apex. Therefore, the effective contact area is governed by the spherical tip radius (Park *et al.* 2021; Moon *et al.* 2022; Lee, Y. J. *et al.* 2023). This contact area can be considered negligible unless the applied contact force is sufficiently high to cause surface compression. Park *et al.* (2021) determined the optimal contact force; however, the effect of stylus-tip curvature on surface roughness characterizations remains underexplored.

Surface parameters such as the arithmetic mean height (R_a), root mean square deviation (R_q), and core roughness depth (R_k) computed from height variations along a measured profile (Webb *et al.* 2012) can be misinterpreted if measurement variability is not carefully managed. Notably, the fractal dimensions (FDs) of surface profiles with identical mean values and standard deviations may vary considerably (Ko *et al.* 2019, 2025). This indicates that surfaces with similar average roughness values can have considerably different topographical features (Lee, Y. J. *et al.* 2023; Lee *et al.* 2025b).

Surface profiles can be quantitatively described *via* FD analysis (Mandelbrot 1983; Ko *et al.* 2025). Fractal behaviors of natural and engineered systems can be effectively described using FDs (Ko *et al.* 2015, 2019). However, only a few studies have determined the FDs of paper surfaces based on their roughness profiles determined *via* stylus-based surface profilometry (Militký and Bajzik 2001; Lee, Y. J. *et al.* 2023; Lee *et al.* 2025b). Militký and Bajzik (2001) calculated the FDs of nonwoven fabrics from their roughness profiles obtained using the KES-SE surface tester, and used the variogram method for subsequent analysis. Results indicated that several thousand data points were required to

achieve reliable FD estimates.

Subsequently, Lee, Y. J. *et al.* (2023) determined the FDs of printing papers using a SD of 1 μm and collected ~20,000 data points over a 20-mm scan length. The FDs exhibited a narrow range of 1.11 to 1.14, indicating that the profiles exhibited similar surface characteristics. However, the surface roughness of paper arises from multiple structural scales from individual fibers to the intrinsic roughness of the sheet and macro features produced during converting operations such as creping or embossing (Kajanto *et al.* 1998). To understand each of these mechanisms, FD analysis must be performed at finer scales, possibly in the submicron range. To this end, power spectral density (PSD) analysis is a useful high-resolution alternative to FD analysis (Chan *et al.* 1995; Gneiting *et al.* 2012; Lee *et al.* 2025b).

In this study, the impact of the curvature of a conical stylus tip on the determination of surface roughness of paper products was systematically examined. Based on this evaluation, an optimal stylus condition was identified. FDs were subsequently derived from high-resolution (0.1 μm) roughness profiles using PSD analysis. This is the first report to evaluate the influence of stylus tip size on roughness determination of paper surfaces and to derive FDs from optimized submicron-resolution profilometry data using PSD analysis.

EXPERIMENTAL

Materials

Paper samples with different grades were conditioned for longer than 48 h at 23 ± 1 °C and $50 \pm 2\%$ relative humidity (RH) according to ISO 187 (2022). Table 1 shows the basis weight, thickness, and density of these samples. Both uncoated or base paper (BP) and coated paper (CP, BP coated with a colored coating) were analyzed to analyze the surface characteristics associated with the surface coating. Table 1 shows the physical properties of these samples.

Table 1. Physical Properties of Paper Samples

Sample	Type	Basis weight (g/m ²)	Thickness (mm)	Density (g/cm ³)
WP	P&W ^a	80.8	0.11	0.73
NP	Newsprint	46.1	0.05	0.94
LP	Liner	172.0	0.24	0.71
KP	Kraft	79.6	0.11	0.72
BP ^b	P&W	Uncoated	70.5	0.09
CP ^b		Coated	118.6	0.11

^aP&W: printing and writing

^bCP: coated paper using BP as the base substrate

Design of Stylus

Various stainless-steel styluses with tip radii (R_{tip}) of 0.25 to 1.75 mm were designed according to the specifications outlined in KS M 4057 (2025) and ASTM A681-08 (2015) standards, as shown in Fig. 2. The contact area theoretically remains at 0 (or minimal), regardless of the tip size (Moon *et al.* 2022; Lee, Y. J. *et al.* 2023).

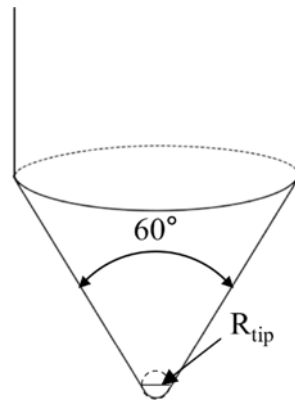


Fig. 1. Schematic of the conical stylus showing minimal theoretical contact area independent of tip radius

Surface Roughness Characterization

The KES-SESUR surface tester was used for surface roughness characterizations. The sample plate moves and the stylus remains stationary in this instrument (Park *et al.* 2021; Lee, J. M. *et al.* 2023; Lee, Y. J. *et al.* 2023), contrary to that in conventional stylus-based profilometers described in ISO 25178-601 (2025). Therefore, this configuration is expected to impose less mechanical damage on the sample surface. Stylus-based profilometry has recently been standardized in ISO 24118-1 (2023) for characterizing the surface roughness of paper and paperboard. The measurement conditions were a scan length of 20 mm, a scan speed of 1 mm/s, and a data acquisition rate of 1000 Hz (1000 points/s), as proposed by Lee, Y. J. *et al.* (2023). A contact force of 5 gf was applied during all measurements, and 10 measurements were taken along the machine direction (MD) for each sample. All tests were performed at 23 ± 1 °C and $50 \pm 2\%$ RH.

Various surface parameters were determined from the obtained surface roughness profiles according to ISO 21920-2 (2021). The roughness average, R_a , was calculated using Eq. 1,

$$R_a = \frac{1}{N} \sum_{i=1}^N |R_i| \quad (1)$$

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

$$N = \text{DAR} \times L/V \quad (2)$$

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

$$\text{SD} = (V/L)/(\text{dar}/L) = V/\text{dar} \quad (3)$$

where SD represents the sampling interval of the roughness profile, where a shorter interval yields higher resolution. In Eq. 3, SD is independent of the stylus size and depends only on the scan speed (V) and the data acquisition rate (DAR). At DAR = 1000 Hz, $L = 20$ mm, and $V = 1$ mm/s, the SD becomes 1 micron.

The roughness mean absolute deviation (RMAD) was determined from R_a , as shown in Eq. 4.

$$\text{RMAD} = \frac{1}{N} \sum_1^N |R_i - R_a|. \quad (4)$$

When calculating RMAD, R_a is treated as constant. Note that RMAD is not equivalent to R_a . In addition, RMAD has been accepted as an ISO standard parameter for determining the surface roughness properties of paper and paperboard (ISO 24118-1 2023).

FD Analysis

FDs were determined from the surface roughness profiles *via* PSD analysis (Chan *et al.* 1995). A one-dimensional surface profile $z(x)$ sampled at a spatial interval Δx was converted into the frequency domain using the periodogram method (Chan *et al.* 1995; Gneiting *et al.* 2012). For self-affine fractal surfaces, the PSD amplitude $P(f)$ at a spatial frequency f follows the power-law relationship, as shown in Eq. 5.

$$P(f) \propto f^{-\beta}. \quad (5)$$

Taking the base-10 logarithm yields the following linear form,

$$\log_{10} P(f) = -\beta \log_{10} f + C, \quad (6)$$

where β is the spectral exponent obtained from the slope of the regression line in the log-log plot.

For a one-dimensional surface profile, FD is calculated by Eq. 7.

$$\text{FD} = \frac{5-\beta}{2}. \quad (7)$$

This relationship is widely used for analyzing self-affine fractal surfaces, consistent with the formulations adopted in previous PSD-based FD analyses (Chan *et al.* 1995; Militký and Bajžik 2001; Gneiting *et al.* 2012; Lee *et al.* 2025a,b).

PPS Measurements

For comparison, roughness was additionally evaluated using the Parker Print Surface (PPS) method, representing an indirect air-leak approach (ISO 8791-4, 2021). In this method, the specimen is clamped between a flat sensing surface and a resilient backing, and air is drawn across the measuring land under a controlled pressure difference. The measured airflow or pressure drop is converted to an equivalent air gap expressed in micrometers.

RESULTS AND DISCUSSION

Effect of Stylus Size on Surface Roughness

Figure 2 shows the plots of R_a and RMAD as a function of the stylus tip radius (R_{tip}) for each sample. R_a considerably depends on R_{tip} , whereas RMAD remains stable across the same range. These findings are consistent with previously reported results that R_a is influenced by the instrument and its operating conditions, whereas RMAD, which reflects the intrinsic variations within the sample surface, does not depend on such external factors (Lee, Y. J. *et al.* 2023). Note that R_a is considered a constant in RMAD calculations (Eq. 4). Thus, although R_a may vary with the stylus size, RMAD remains unchanged and independent of the stylus geometry; this behavior was anticipated from the stylus design shown in Fig. 1.

To examine the influence of R_{tip} on R_a and RMAD, each paper sample was tested under identical conditions. A contact force of 5 gf was applied (Park *et al.* 2021), and a series of styluses with tip radii of 0.25 to 1.75 mm were employed. Although contact force is also a critical parameter in stylus-based measurements, where excessively low force may fail to fully capture surface features and excessively high force may induce surface deformation or damage, the present study adopted the 5 gf condition based on the validated protocol reported by Park *et al.* (2021).

When R_{tip} was smaller than 0.35 mm, R_a and RMAD became unstable. A similar instability was observed at an R_{tip} of ≥ 0.75 mm. At an R_{tip} within 0.35 to 0.5 mm, R_a and RMAD remained largely stable. This trend was consistent with previous findings (Moon *et al.* 2022) that an R_{tip} of 0.5 mm is suitable for the friction profilometry of paper products.

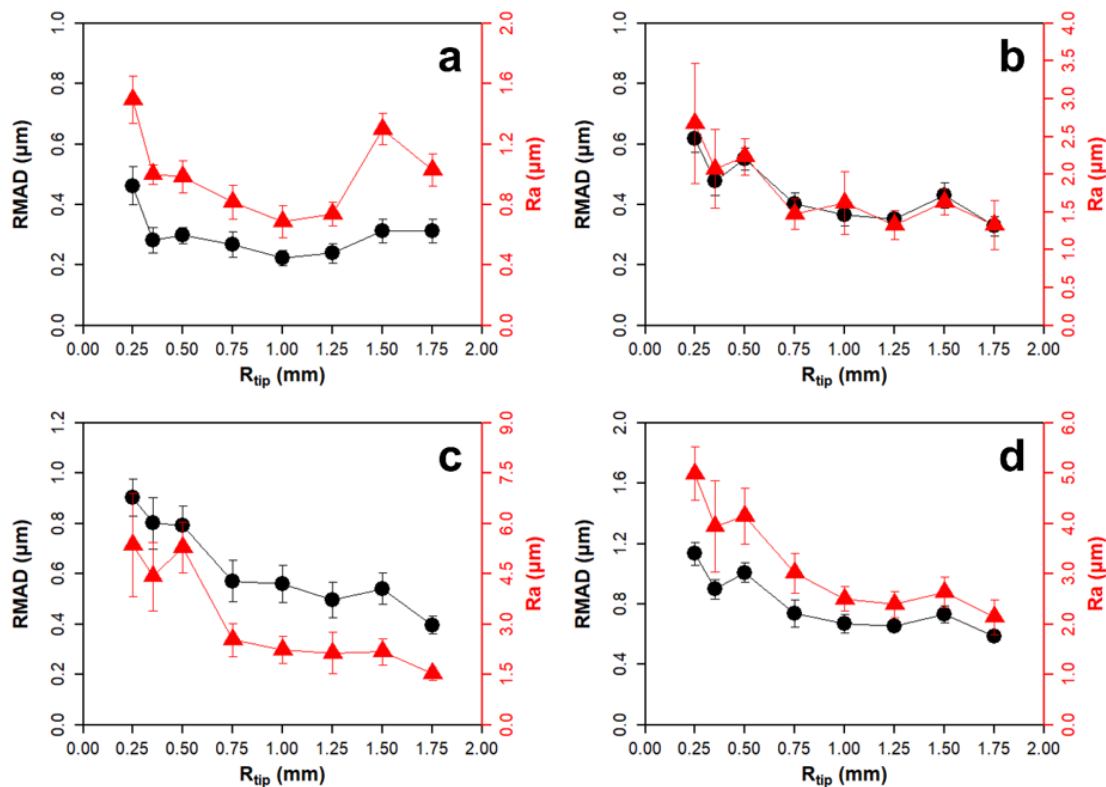


Fig. 2. Variations in RMAD (black circles) and R_a (red triangles) as a function of R_{tip} for four paper products: (a) WP, (b) NP, (c) LP, and (d) KP. Measurements were conducted at R_{tip} ranging from 0.25 to 1.75 mm under a constant contact force of 5 gf. Error bars represent the standard deviation across 10 measurements.

Although R_{tip} ranged from ~ 0.25 to 1.75 mm, contact occurred at the spherical apex of the stylus. While the contact can be approximated as point-like in a geometric sense, the real contact area is finite and depends on the applied load and surface compliance (Moon *et al.* 2022). When the R_{tip} was too small (*i.e.*, below 0.35 mm), the stylus became excessively sharp and caused damage or tearing of the sample (Park *et al.* 2021; Lee, Y. J. *et al.* 2023). In contrast, when the R_{tip} exceeded 0.5 mm, the resulting measurements differed considerably from those obtained with smaller tip sizes. These findings indicated that an R_{tip} of 0.35 to 0.50 mm was ideal for surface roughness measurements; therefore, an R_{tip} of 0.50 mm was chosen for subsequent experiments.

Effect of Coating on Surface Roughness

To analyze the effect of coating on the surface roughness of paper samples, the roughness profiles of BP and CP were compared under optimized testing conditions (Fig. 3). The RMAD values for BP and CP were 0.54 and 0.12, respectively. These profiles clearly show that coating considerably reduces the fluctuations in surface roughness, consistent with previously reported results (Jeong *et al.* 2019; Ko *et al.* 2019), and effectively suppresses surface irregularities. Thus, stylus-based surface profilometry is a promising approach for evaluating the surface roughness of coatings.

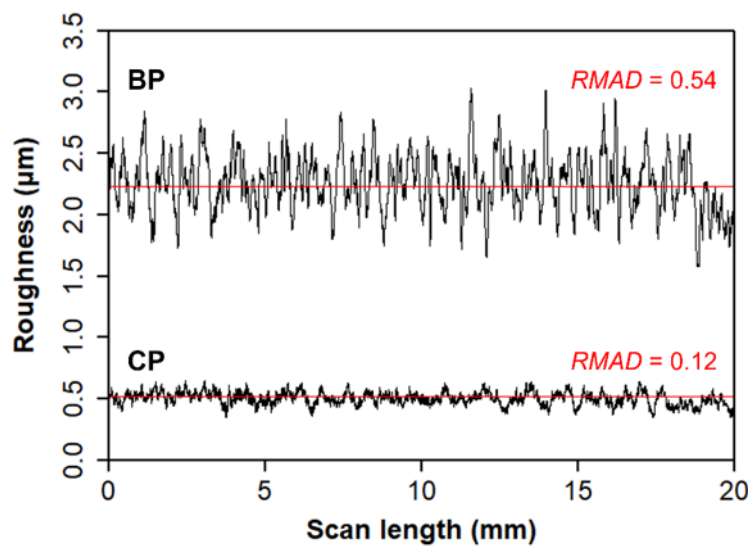


Fig. 3. Roughness profiles of BP and CP. Coating markedly reduced the fluctuation in the surface roughness profile, as reflected by the lower RMAD (0.12 for CP and 0.54 for BP).

Effect of Stylus Type on Surface Roughness: Pyramid vs. Conical

The stylus-based contact method is relevant not only for understanding papermaking processes such as printing, embossing, and coating, but also for evaluating product quality attributes including printability (Persson 2007; Buzio *et al.* 2003; Goedecke *et al.* 2013). Moreover, stylus-type contact techniques have been successfully applied to assess surface softness in textiles and hygiene paper products such as tissue and towel (Ko *et al.* 2019; Yokura *et al.* 2004; Beuther *et al.* 2012; Kweon *et al.* 2024). These applications indicate that contact profilometry provides meaningful information on functional surface properties across a range of fibrous materials.

The shape and size of styluses play crucial roles in determining the surface roughness of paper and paperboard *via* stylus-based surface profilometry (Jeong *et al.* 2019). When a spherical stylus traverses a surface asperity, the contact point shifts along the stylus tip. As a result, the measured profile becomes smoother than the actual surface geometry (Leach and Hart 2001). Although the stylus reaches its maximum vertical displacement at the crest and therefore records the true peak height, the curvature of the tip tends to smooth sharp peaks and reduce the apparent depth of valleys.

In general, a finer stylus tip is required to characterize surface features at the microscale (Poon and Bhushan 1995). The tip size governs the contact pressure at a given force because pressure is defined as the applied force divided by the contact area (Ko *et al.* 2019). Therefore, a finer tip yields higher accuracy in roughness measurements (Leach and Hart 2001). To evaluate the performance of our stylus design, which minimizes the contact

area due to its spherical contact area, a comparative analysis was conducted using a pyramidal stylus previously used for surface roughness measurements (Jeong *et al.* 2019).

Figure 4 compares the R_a (Fig. 4a) and RMAD (Fig. 4b) values measured using a pyramid stylus and a 0.5R conical stylus. The correlation for RMAD is particularly strong, with an R^2 of 0.991. This indicates that the conical stylus minimizes the contact area due to its spherical contact region (Park *et al.* 2021; Moon *et al.* 2022; Lee, Y. J. *et al.* 2023). In addition, RMAD should be evaluated directly from the surface profiles because R_a varies with not only the testing conditions but also the measurement location on the sample surface (Park *et al.* 2021; Lee, Y. J. *et al.* 2023).

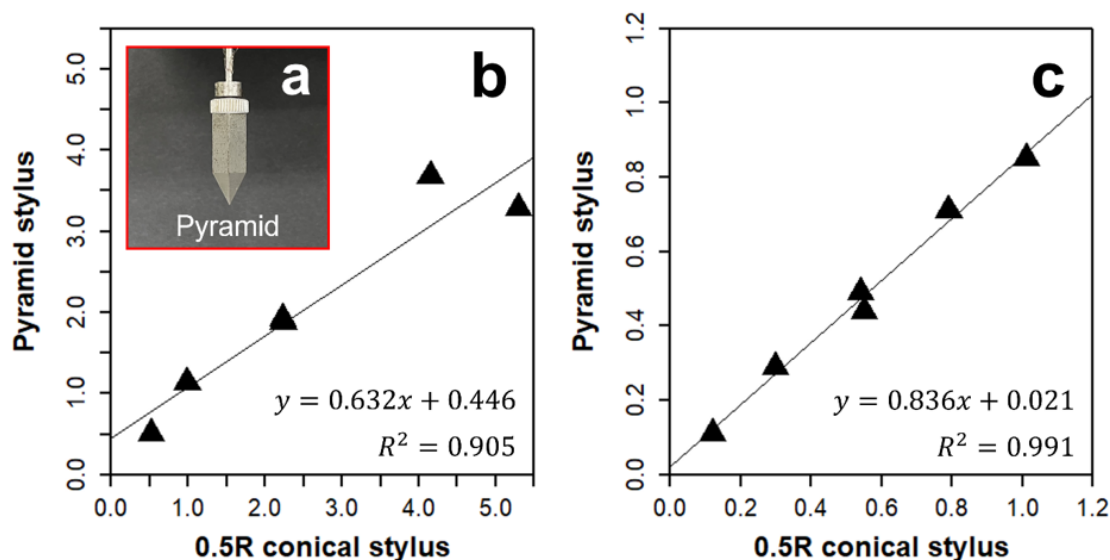


Fig. 4. Comparison of roughness values measured using a pyramid stylus and a 0.5R conical stylus. (a) Photograph of the pyramid stylus used herein. (b) Relationship between R_a values obtained using both styluses, showing a strong linear correlation ($R^2 = 0.905$). (c) Relationship between RMAD values measured using the same two styluses, exhibiting an even stronger linear correlation ($R^2 = 0.991$).

FDs of Surface Roughness of Paper Products Determined via PSD Analysis

Fractal-based methods are widely used for the characterization of complex systems, including surface morphology, porous architectures, signal analysis, and sensor technologies in biomedical applications (Kornev *et al.* 1999; Neimark *et al.* 2003; Vernhes *et al.* 2008a; Vernhes *et al.* 2008b). Fractal geometry is characterized by self-similarity across multiple length scales, forming hierarchical structures (Mandelbrot 1982; Russ 2013). As the FD increases, surface ruggedness generally becomes more pronounced. Consequently, surface profiles with similar average roughness may differ substantially in their structural organization.

A key limitation of using the average thickness or roughness and its coefficient of variation (COV) as indicators of surface quality is that they can lead to misleading interpretations. Two surfaces may have identical mean roughness and COV but exhibit considerably different mechanical behaviors, resulting in incorrect conclusions. To address this issue, Ko *et al.* (2025, 2019) suggested that surface profiles indistinguishable by conventional metrics, such as the mean and standard deviation, can be effectively differentiated using FDs.

A large number of data points are required for estimating the FDs of paper and nonwoven substrates, and PSD-derived FDs often fall within a narrow range even when

the underlying roughness profiles differ (Militký and Bajžík, 2001; Lee, Y. J. *et al.* 2023; Lee *et al.* 2025b). Herein, we collected ~200,000 data points, for the first time, to compute FD values *via* PSD analysis. The DAR of the instrument was limited to 1000 Hz (1000 points/s); however, a scan speed of 0.1 mm/s yielded an SD of 0.1 μm and enabled the acquisition of roughly 200,000 data points over a 20-mm scan.

Table 2 presents the FD values of the paper products, together with conventional roughness parameters and the indirect air-leak roughness results obtained by the PPS method. As the FD approached 2, corresponding to an areal dimension, the profile increasingly filled the surface. The representative roughness profiles and PSD spectra of BP and CP are shown in Fig. 5.

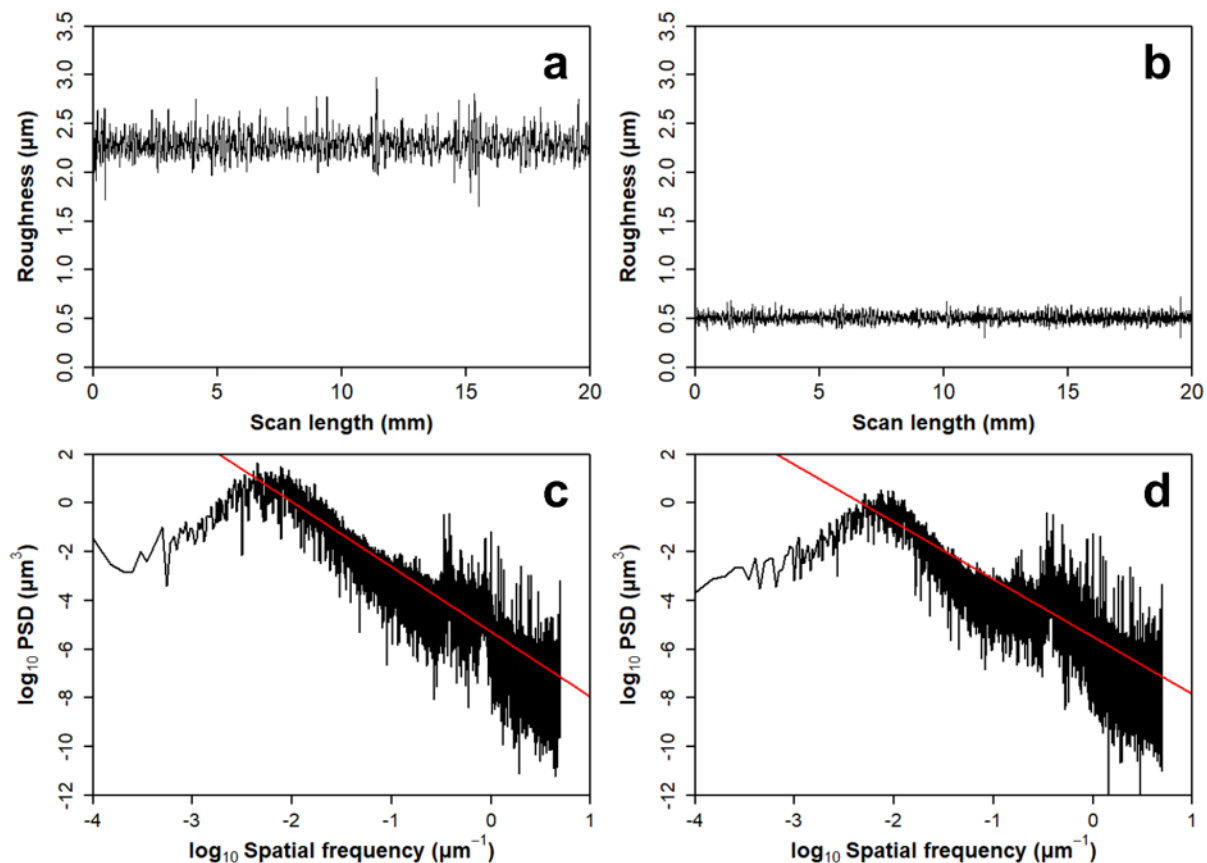


Fig. 5. Surface roughness profiles and corresponding spatial PSD analysis of the BP and CP. (a) Roughness profiles of the BP and (b) CP (coated paper using BP as the base substrate) obtained under identical measurement conditions. All line-scan profiles were acquired at a sampling rate of 1000 Hz, and the scan speed was reduced to 0.1 mm/s (1/10 mm/s), providing an effective spatial sampling interval of 0.1 μm . (c) PSD spectrum of the BP derived from the roughness profile and plotted in log–log scale. The red straight line indicates the fitted power–law region used for FD analysis. (d) Corresponding PSD spectrum of the CP.

The limitations of the air-leak method become evident in this context. Because roughness is evaluated indirectly based on air permeability, the method is primarily suitable for comparative assessment. However, it does not provide detailed morphological information, limiting its ability to interpret surface-related functional behavior.

Upon coating, the roughness profile shifts from predominantly line-based features toward more area-dominated characteristics, as reflected by the increased FD values shown

in Table 2. This trend is in line with Lee *et al.* (2025b). It should be noted that FD and conventional roughness parameters describe different aspects of the surface: roughness reflects amplitude variation, whereas FD characterizes structural complexity independent of thickness variation.

Considering the FD results, the CP surface exhibits a more composite, areal-dominated structure rather than a line-dominated one. Therefore, it can be hypothesized that the transition from line-dominated features to a more areal surface structure will be significant as the FD approaches 2, reflecting a more uniformly coated surface.

Table 2. FD Analysis Results for Paper Products

Sample	Type		R_a^c (μm)	$RMAD^d$ (μm)	FD ^e	PPS ^f (μm)
WP	P&W ^a		0.99	0.29	1.49	3.23
NP	Newsprint		2.24	0.44	1.56	4.97
LP	Liner		5.29	0.71	1.56	10.03
KP	Kraft		4.15	0.85	1.53	11.50
BP ^b	P&W	Uncoated	2.23	0.54	1.35	5.72
CP ^b		Coated	0.51	0.12	1.72	0.73

^aP&W: printing and writing

^bCP: coated paper using BP as the base substrate

^c R_a : roughness average

^d $RMAD$: the absolute mean deviation from the average for the roughness

^eFD: fractal dimension

^fPPS: Parker Print-Surf surface roughness

Although not examined in the present study, optical surface measurement techniques such as Optitopo are well documented for evaluating surface topography across multiple spatial scales (Barros and Johansson 2005). Optitopo quantifies surface deviation (OSD) by analyzing the shadow lengths generated by incident light on both sides of the sample, providing fine-scale surface variation values expressed in micrometers. Similarly, laser profilometry has been widely used to measure surface profiles by scanning the sample in a predetermined direction using a laser beam (Land 2004).

However, these optical approaches generally require sufficient surface opacity and are not suitable for low-opacity paper materials. In addition, they do not allow simultaneous evaluation of surface friction. In contrast, the stylus-based method employed in this study enables the combined assessment of surface roughness and friction under direct mechanical contact (Lee *et al.* 2023).

CONCLUSIONS

1. A series of styluses with tip radii ranging from 0.25 to 1.75 mm was used for surface roughness characterizations. Among these, the stylus with a 0.5-mm tip radius (0.5R) provided the most stable and reliable surface roughness measurements for paper products.
2. To examine the effect of coating on surface roughness, the 0.5R stylus and a predetermined contact force of 5 gf were used to obtain the surface roughness profile of the coated paper (CP). Compared with the base paper (BP), the CP exhibited

considerably reduced surface roughness fluctuations and its roughness mean absolute deviation (RMAD) decreased by 78%.

3. The reliability of the 0.5R stylus was further compared with that of a pyramidal stylus featuring a finer and sharper tip. The R_a and RMAD values for measurements with these styluses exhibited strong agreement, with RMAD yielding an R^2 of 0.991. This confirmed that the conical stylus design maintained a minimal contact area.
4. The fractal dimension (FD) values of paper surfaces were computed *via* power spectral density (PSD) analysis, demonstrating that FD can be successfully derived *via* stylus-based surface profilometry. Finally, the potential of FD as a supplementary metric for characterizing CP during coating processes was observed.

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