Characterization of Paper Surfaces by Friction Profilometry

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Friction profilometry is a powerful technique that is suitable for the surface characterization of paper products. In this technique, a stylus-type contact method that resembles papermaking processes is used for evaluating the quality attributes of products. The surface characterization requires both surface roughness and friction measurements. At present, however, few reports have been available regarding characterization of the friction by the surface profilometric method. The objective of this study was to provide guiding principles of a stylus-type contact surface profilometry for determining the friction properties of paper. Another objective was to introduce the concept of the mean absolute deviation (MAD) from the average coefficient of friction as a new friction parameter.

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INTRODUCTION

Surface roughness and friction are the two main components of surface properties. The former is static and describes the topography while the latter is dynamic or mechanical and determines the interaction between two objects. An interest in a stylus-type contact surface profilometric technique is continuously growing for the paper industry because the technique resembles papermaking processes such as creping, coating, printing, lamination, calendaring, and embossing (Pino *et al*. 2010; Samyn *et al*. 2011; Schlegel *et al*. 2011). It also is similar to the method used for evaluating the quality attributes of paper products such as softness, wettability, printability, and absorption (Ko *et al*. 1981; Hollmark 1983a, 1983b; Hodgson and Berg 1988; Ampulski *et al.* 1991; Modaressi and Garnier 2002; Kuilenburg *et al*. 2013; van Wang *et al*. 2018; Ko *et al*. 2020). To this end, the friction component has been recognized as more relevant because the roughness component may not be able to identify the differences in the quality attribute.

Figure 1 illustrates this point, as it shows the two surfaces (A, B) have the same average roughness. However, the image makes it instinctively clear that Sample A should perform better for the handfeel or in the wear resistance. (Leach 2014). Such differences may be readily identified if the frictional properties had been determined with a stylus-type contact profilometer. Although the contact-type surface profilometry has such powerful techniques for determining the friction of paper products and have wide applications in the paper industry, surprisingly very few works have been available on this technique.

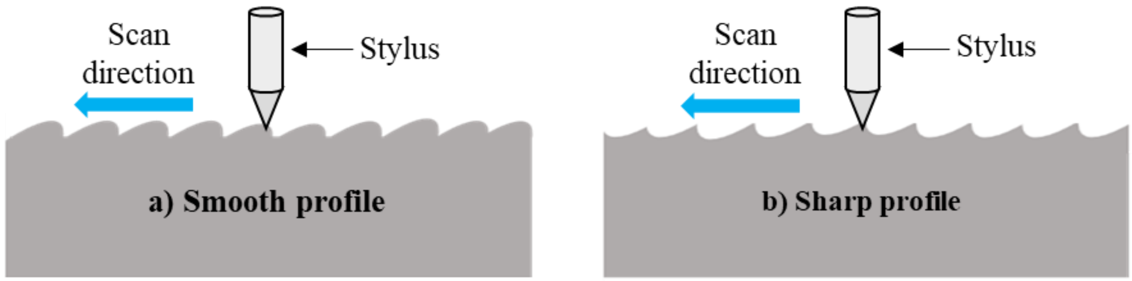

Fig. 1. Roughness vs. Friction (inspired by Leach 2014)

For the friction component, a coefficient of friction (COF) has been commonly measured to determine an average of COF with its standard deviation calculated from multiple measurements as a means of checking the uniformity of sample. Most commercial friction instruments are designed in this way. They are generally referred to as COF testers (Park *et al*. 2021). The COF testers have been applied for process control and product evaluation. However, such results seldom provide direction of developing a process or of improving the quality attributes of a product.

Surface profilometry is a technique to quantify the surface profiles of a sample. Both non-contact type and contact type methods are available. As the contact type, a stylus-type contact surface profilometer has been used to determine a surface roughness profile. In the stylus-type contact method, a probe (or stylus) scans a sample surface along the predetermined direction to generate a profile of the height variation against the scan length, being referred to as a roughness profile (Jeong *et al*. 2019; Ko *et al*. 2020; Park *et al*. 2021). In this method, stylus shape and size, contact force, and scan speed have been identified as the key variables responsible for generating surface profiles (Kawabata 1980; Yokura *et al*. 2004; Beuther *et al*. 2012; Hanaor *et al*. 2013; Zhai *et al*. 2016; Zhai *et al*. 2017; Jeong *et al*. 2019; Ko *et al*. 2020). In contrast with the roughness-profile, very few works on characterizing the friction component from friction profiles have been available.

This study is intended to provide the guiding principles of a stylus-type contact profilometry for determining the friction properties of paper products. To this end, a prototype of a friction profilometer was made, and the parameters responsible for generating friction profiles were examined. This article also introduces the term of the mean absolute deviation (MAD) from average of COF calculated from the friction profiles and suggests it as the friction parameter for paper products.

EXPERIMENTAL

Materials

Table 1 shows a list of the samples, as well as their basis weight, thickness, and density values. To investigate the influence of the contact force, 15 commercial samples (K1 ~ C5) were used. To study the effect of tip size of the stylus among these samples, three samples (K1, N3, C1) were selected and tested. Furthermore, to analyze the friction characteristics according to the surface coating, samples of uncoated paper and its coated paper with polyethylene were used. For a convenience, in Table 1, the former is denoted by base paper (B) and the latter by release paper (R), to identify the samples that were used. The samples were conditioned for more than 48 h at a temperature of 23 ± 1 ℃ and a relative humidity (RH) of 50 ± 2% according to ISO 187 (1990).

Table 1. Physical Properties of Samples

Type	Code	Basis Weight (g/m^2)	Thickness (μm)	Density (g/cm^3)
Kraft paper	K1	78.9	123	0.64
	K2	119	127	0.93
	K3	82.9	168	0.49
	K4	118	165	0.71
	K5	120	161	1.35
Newsprint	N1	46.0	67	0.69
	N2	46.7	65	0.72
	N3	46.1	66	0.70
	N4	46.6	65	0.72
	N5	45.9	63	0.73
Copy paper	C1	80.7	110	0.73
	C2	76.0	105	0.72
	C3	76.4	101	0.76
	C4	76.4	111	0.69
	C5	76.3	106	0.72
Base paper	B	69.6	126	0.63
Release paper*	R	109.0	66	0.70
*It was coated paper with polyethylene using sample B as a base paper.				

Design of a Friction Profilometer

A prototype of a stylus-type contact friction profilometer was made by QMESYS (Gyeonggi, Korea) and it is shown in Fig. 2. This profilometer is designed with replaceable stylus, and the stylus scans the sample as the sample plate passes under it at a constant speed in the scan direction.

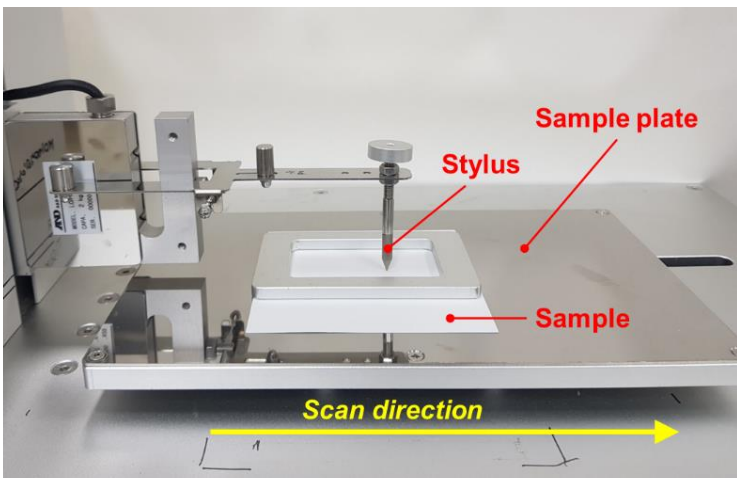

Fig. 2. A prototype of the friction profilometer

Design of Styli

A stylus was designed according to KS M 4057 (2021). The stylus was made of stainless steel specified in ASTM A681-08:2015. A series of stylus whose radius of tip (R_{tip}) ranging from about 0.25 mm to 1.75 mm were made.

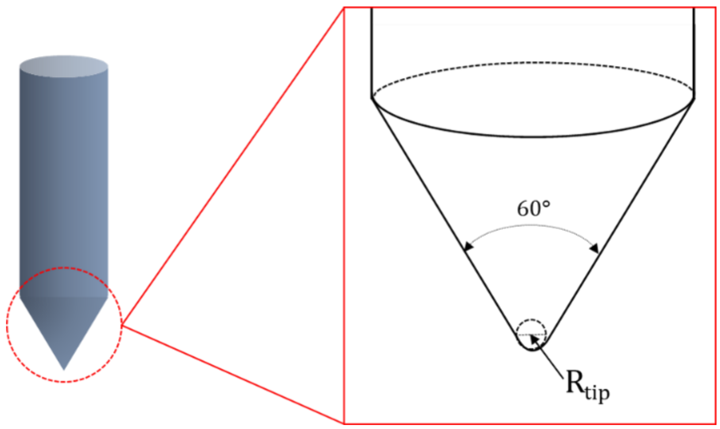

Fig. 3. Design of stylus

Surface Friction Measurements

The testing conditions were as follows: scan length 25 mm; scan speed 1 mm/min; and data acquisition rate 240 to 260 Hz. Here, *dar* indicates the points collected per second (*i.e.*, points/s). To study the effects of contact force, various contact forces (*i.e.*, 30, 50, 100, 150, 200 mN) were applied. Then, the effect of stylus size was investigated using styli with varying radius of curvature of tip (R_{tip}) (*i.e.*, 0.25, 0.35, 0.50, 0.75, 1.00, 1.25, 1.75 mm) by applying the most optimal contact force selected. Finally, the applicability of friction profilometry in the coating of paper was explored.

For each sample, 10 measurements were taken in the machine direction (MD) and the cross-direction (CD). To eliminate any contamination from the sample. The stylus has been cleaned by ethyl alcohol after each measurement. The surface friction testing was performed at 23 ± 1 °C and at a RH of 50% ± 2%.

The test results were expressed as the average of COF ($\bar{\mu}$) and the mean absolute deviation from the average coefficient of friction (MAD) according to Eqs. 1 and 2,

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

$$MAD = \frac{1}{N} \sum_{1}^{N} |\mu_i - \bar{\mu}| \tag{2}$$

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 *MAD* is the mean absolute deviation from the average of COF (Park *et al*. 2021). A graphical representation of averages of COF and MAD is shown in Fig. 4.

Here, N is calculated from Eq. 3,

$$N = dar \times L/V \tag{3}$$

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).

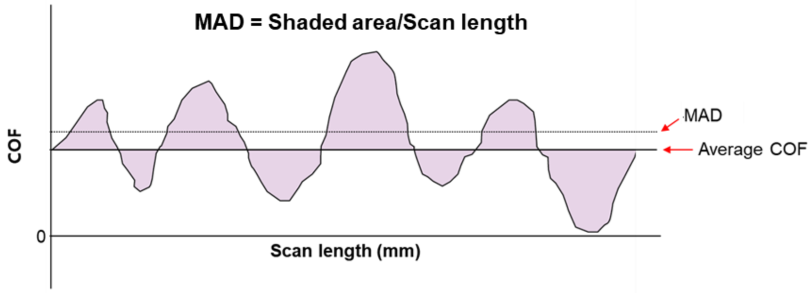

Fig. 4. A graphical representation of friction parameters (Park *et al*. 2021)

The spacing distance (*SD*) between adjacent points can be calculated from Eq. 4,

$$SD = (L \times V)/(V/dar) = V/dar \quad (4)$$

As a numerical illustration, for example at *dar* is 2500 Hz, *L* is 25 mm, and *V* is 1 mm/s, which results in *N* = 2500 x 25/1 = 2500 point/mm, and *SD* = 1 mm/2500 = 0.4 micron (Park *et al*. 2021).

RESULTS AND DISCUSSION

Effects of the Contact Force

Figures 5 to 7 shows the average values of COF and MAD of each product with the stylus of the R_{tip} of 0.5 mm.

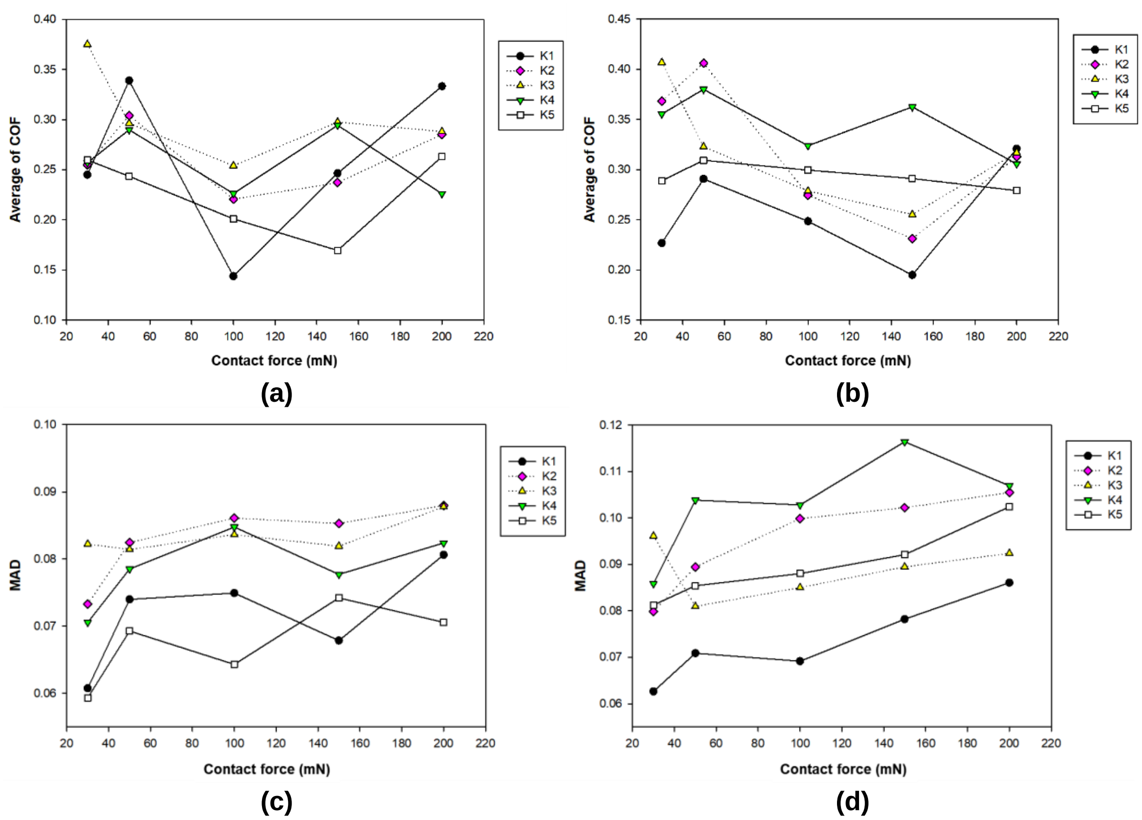

Fig. 5. Results of surface frictions of kraft paper (a, c: MD; b, d: CD)

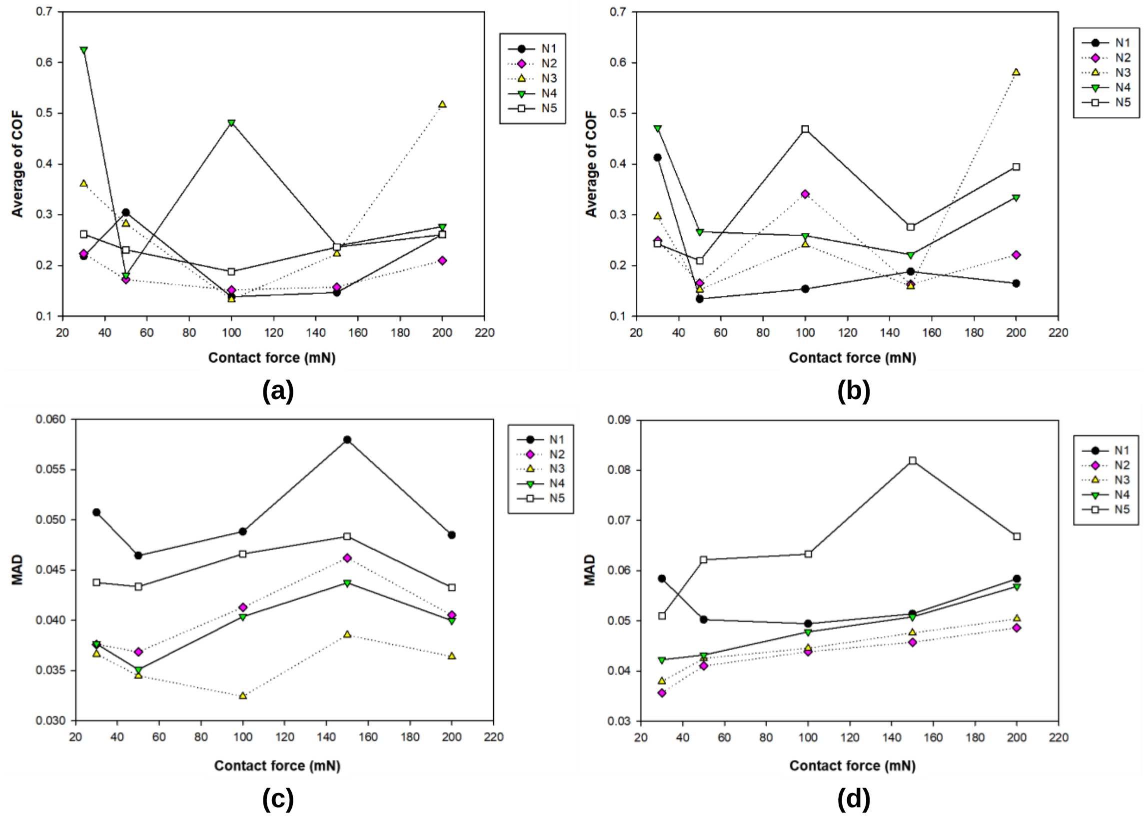

Fig. 6. Results of surface friction of newsprint (a, c: MD; b, d: CD)

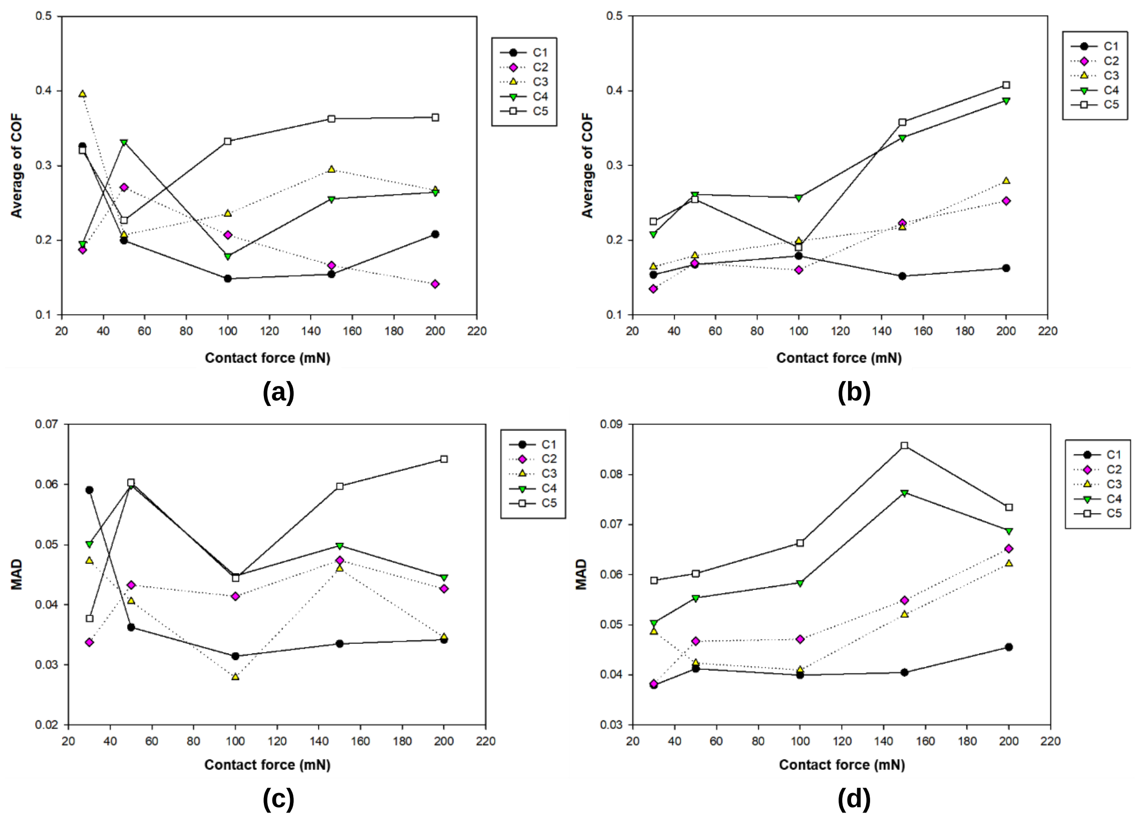

Fig. 7. Results of surface friction of copy paper (a, c: MD; b, d: CD)

It is generally observed that at the two end points of 30 mN and 200 mN the friction profiles are most unstable. This is presumably because the 30 mN may be too low to contact with the surface whereas the 200 mN may be too high to cause some structural damage during the testing. It seems that the 50 mN provides the most stable profiles for all the samples tested in the present study. Accordingly, this contact force was selected to examine the effects of other parameters.

Effects of the Tip Size of the Stylus

To investigate the effect of tip size of the stylus among these samples, three samples (K1, N3, C1) were selected and tested. Contact force was applied at 50 mN according to previous results. A series of styli whose R_{tip} ranged from about 0.25 mm to 1.75 mm were used.

The plots of average of COF and MAD against the R_{tip} are shown for each product in Figs. 8 to 10, respectively. It is generally observed that when R_{tip} was smaller than 0.50 mm the average of COF and the MAD was unstable. Additionally, when R_{tip} was 1.75 mm, it was also unstable. Meanwhile, when R_{tip} was 0.5 to 1.25 mm, the results showed no significant differences in all samples and they seemed to be stable.

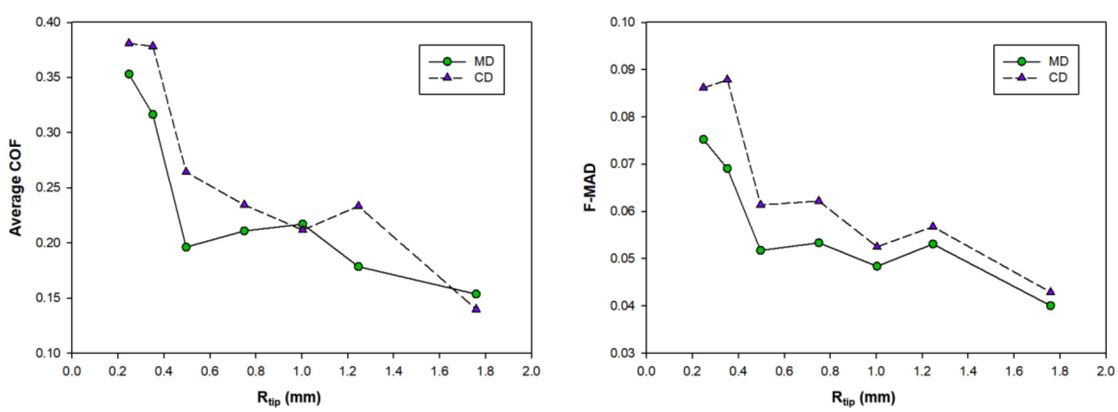

Fig. 8. Results of surface friction of kraft paper (K1)

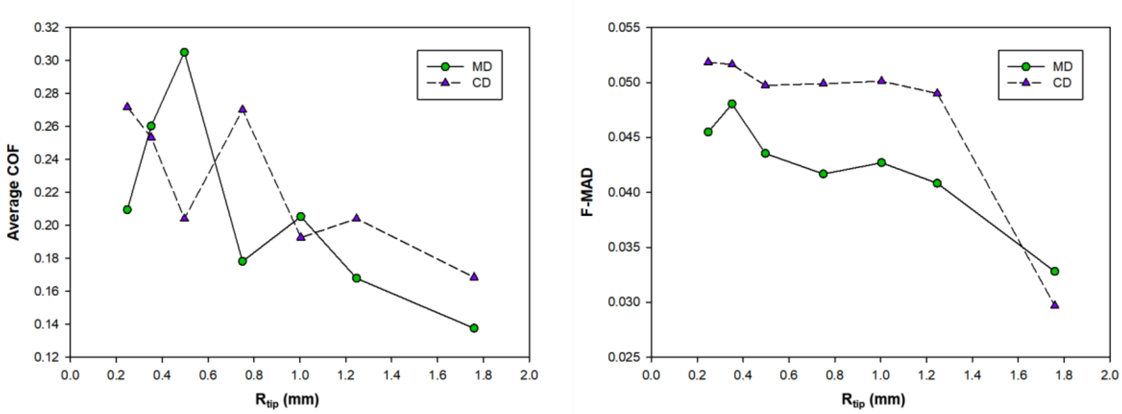

Fig. 9. Results of surface friction of newsprint (N1)

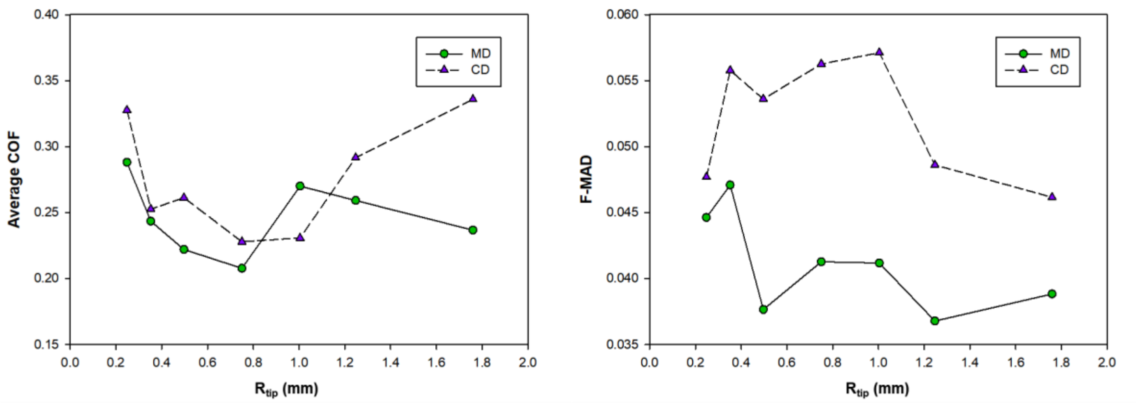

Fig. 10. Results of surface friction of copy paper (C1)

A series of styli whose R_{tip} ranged from about 0.25 to 1.75 mm were made. It is, however, critically important to note that the contact area with the sample surface should be the same. In fact, the contact area should be theoretically a point, since the end of the tip is spherical which does not provide the contact area on the surface. In this study, however, the R_{tip} being too small (*i.e.*, smaller than 0.50 mm) will make the stylus tip too sharp, which resulted in the sample tending to be damaged or torn off. In addition, when R_{tip} was 1.75 mm, the results were significantly different from those of styluses with different R_{tip}. Therefore, it was determined that the R_{tip} value of 0.50 to 1.25 mm was suitable for surface friction measurement. A tip with R_{tip} equal to 0.5 mm was selected for further experimentation.

Correlation between average of COF and MAD

Figure 11 shows the plots of the MAD *vs.* the averages of COF of the samples. It shows no clear relationship between averages of COF and the MAD. It is expected that the former is the measure of the resistance between the stylus and the sample, which should depend on the instrument and its testing conditions. Meanwhile the MAD should represent the variation of the friction relative to its average of COF, which may be treated as a constant. This explains why the MAD values should be less variable.

It is one of the most significant findings from this study that the MAD should be used as a novel crucial parameter as the friction parameter and that it can only be determined by using a friction profilometer.

Applications of the Friction Profilometry

As a potential application for coating purposes, the averages of COF and MAD of the two samples (B, R) were determined under the optimal testing conditions mentioned above. The result is shown in Table 2. Changes in averages of COF and MAD before and after coating were calculated according to Eq. 5,

$$Change = \frac{C_2 - C_1}{C_1} \times 100 \tag{5}$$

where C_1 is the average of COF or the MAD value before coating, C_2 is the average of COF or the MAD value of after coating.

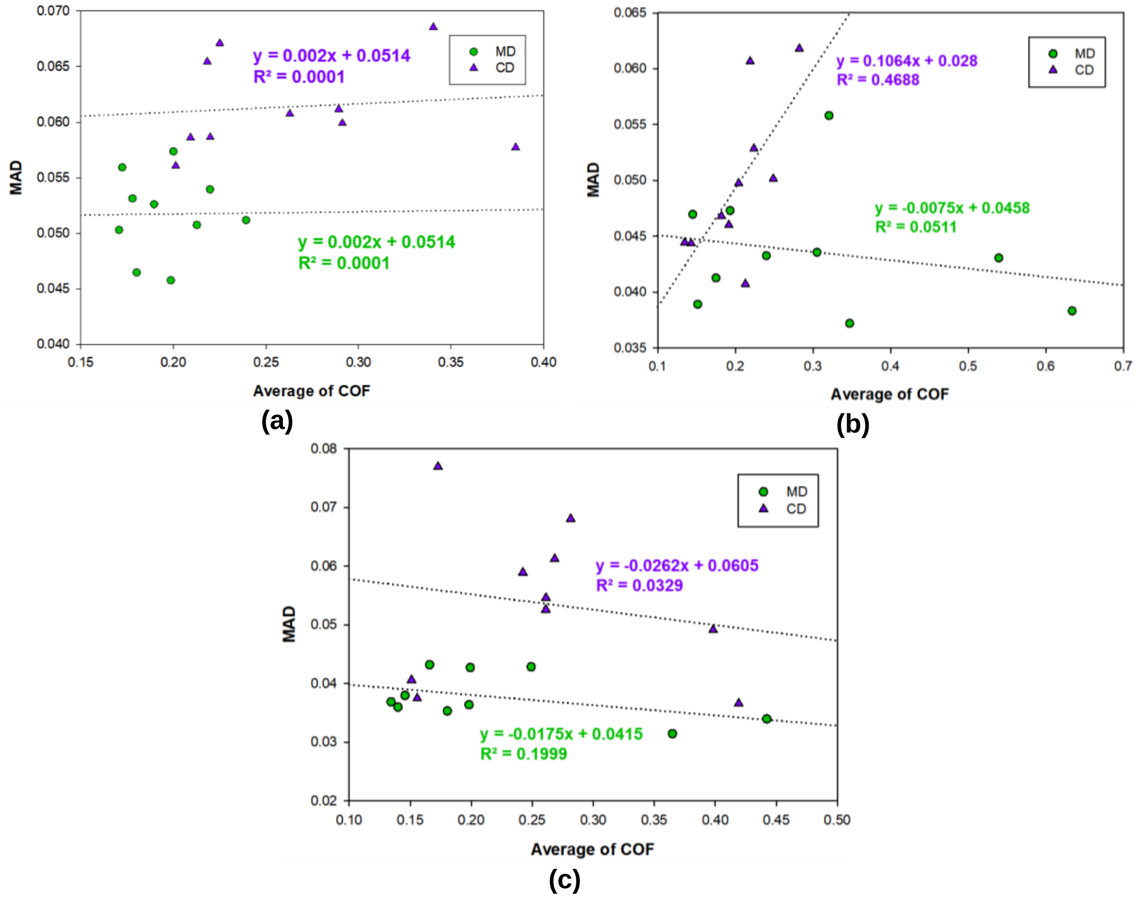

Fig. 11. Correlation between average COF and MAD (a: kraft paper; b: newsprint; c: copy paper)

Table 2. Effects of Coating on Friction

Sample code	Average of COF		MAD	
	MD	CD	MD	CD
B	0.180	0.168	0.0340	0.0313
R	0.273	0.242	0.0153	0.0347
Change (%)	51.5	44.1	-55.0	10.9

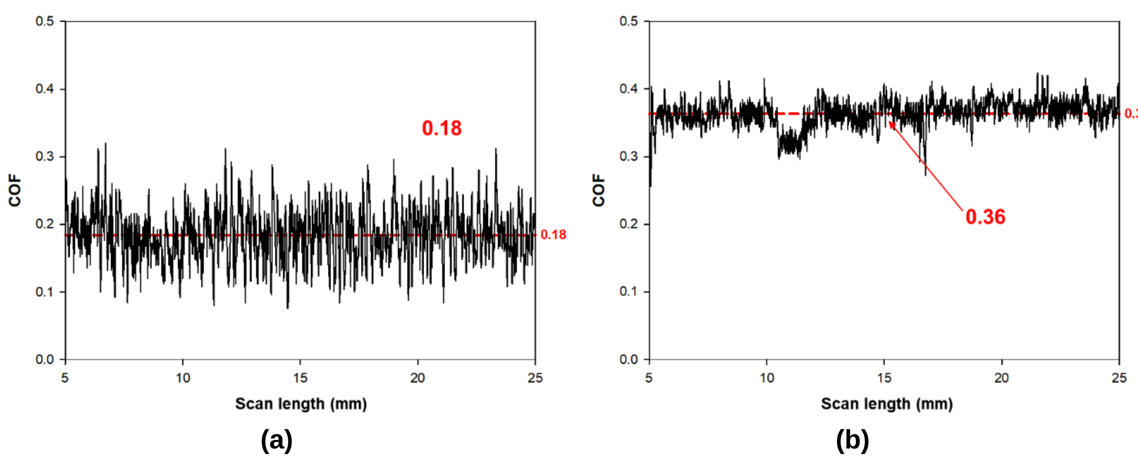

Fig. 12. Effects of coating on friction profiles in MD (a: base paper (B); b: coated paper (R))

The averages of COF and the MAD in the MD changed by 51.5% and -55.0%, respectively, but in opposite directions. That is, the averages of COF in the MD increased, and after coating while the MAD has been decreased. Figure 12 shows the friction profiles of the paper samples B and R. It shows clearly that the fluctuation in the friction profile is much reduced by coating, which could not be shown by the conventional COF tester. This strongly supports the argument that the MAD should be used as the friction parameter instead of average of COF.

CONCLUSIONS

1. A prototype of a stylus-type contact friction profilometer was successfully designed. For the profilometer, a conical stylus is used, whose design is shown in Fig. 3. It was found to be effective and R_{tip} of 0.50 mm worked well on several paper grades.
2. In the friction profilometry technique, the contact force, the scan speed, and the data acquisition rate are also important parameters. If the contact force is too low, then the stylus may not be able to touch the sample surface. If the forces are too high, then the sample surface may be damaged during testing. The scan speed and data acquisition rate influence the degree of the fluctuation of the profiles and determines the resolution in the axis, according to Eq. 4.
3. The concept of the mean absolution deviation (MAD) from average of COF has been introduced as a new friction parameter. Its usefulness and validity has been demonstrated by comparing the averages of COF and MAD of an uncoated paper with those of its coated- paper.
4. Against the common belief that a trade-off relation should exist between the size of the stylus and the spacing distance (or resolution) in a way that the smaller size is necessary for the smaller scale of the roughness, it was found that the spacing distance should be independent of the size and it can be reduced simply by increasing the data acquisition rate.
5. It is safe to conclude that the optimal testing conditions applicable to all grades of paper may not exist. However, it should not be difficult to find the optimal conditions specific to each grade by applying the principles discussed in this paper.

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