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Experimental Study on Friction Characteristics between Plastic Film and Steel Roller

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Abstract

To establish the new technology named Roll-to-Roll Printed Electronics, which can be applied to manufacture the high functional thin film based devices such as flexible displays, batteries and electric skins, it is needed to combine the roll to roll transportation system and coating technology effectively. For that purpose one of important factors to be considered is the improvement of transportation accuracy of thin film. The film is transported by traction between film and roller surface. Therefore, it is very important to understand the friction characteristic between film and roller surface. In this paper, the static and kinetic frictions between the plastic film (polyethylene terephthalate film) and steel roller were measured while changing the film thickness and web tension. As a result, the static friction coefficient was increased with the decrease in the film thickness. On the other hand, the kinetic friction coefficient was decreased the decrease in the film thickness. Moreover, the tendency can be pronounced with the decrease in the web tension.

Keywords: roll-to-roll, web handling, friction coefficient, plastic film

1 Introduction

In recent years, a product development system for manufacturing of high functional thin film based devices such as flexible displays, thin-film solar cells, batteries and electric skins is being promoted. These devices are manufactured by Printed-Electronics (PE) manufacturing which is one of the most remarkable systems of manufacture at present. PE can manufacture a wide variety of flexible devices. However, the system is not yet capable of manufacturing mass products because of a high cost associated with making of large-area devices. On the other hand, Roll-to-Roll (R2R) transportation system has been applied to the manufacture of thin and flexible materials which is called a web, such as plastic films, papers, thin metal plates at low cost. R2R system can transport the web using a large number of rollers and several processes are performed on the web, such as recording, coating, drying, laminating during transportation of the web. Therefore, it is needed to establish the new technology named Roll-to-Roll-Printed-Electronics (R2RPE) manufacturing system which combines with the R2R transportation system and PE manufacturing system as shown in **Fig.1** to manufacture a large amount of high functional thin film based devices. However, the application of this system is being limited to the manufacturing of only a few products because R2RPE manufacturing system has many problems. For example, as the manufacturing devices require high precision, registration for printing is very important during the transportation of the web. During the web transports on rollers, web defects such as wrinkling, slippage, sagging, unwanted meandering on rollers are occur [1]-[2]. In order to prevent the defects, it is important to understand the friction characteristics between a web and rollers. In previous studies, the effect of the entrained air between a web and roller on friction characteristic was examined, in which the air film thickness was modeled by the foil bearing equation [3]-[11]. Hashimoto presented new theoretical modeling of friction coefficient between uncoated paper-web and steel roller under mixed lubrication by using contact mechanics, and the model was verified compared with the measured results [12]. However, higher accuracy of the transportation technology for the web is being required to establish the R2RPE manufacturing system. Therefore, it is necessary to investigate friction characteristics between the web and roller surface including effects of various factors in more detail. For example, webs used in the R2R are being thinner and low web tension is applied in the transportation of the web.

In this paper, fundamental experiments, in which the static and kinetic friction forces between plastic film and steel roller are measured, are conducted to clarify the effect of the difference of film thickness on friction characteristics.

2 Experimental apparatus and procedure

2.1 Static friction

Figure 2 shows the experimental apparatus for measuring the static friction force between the plastic

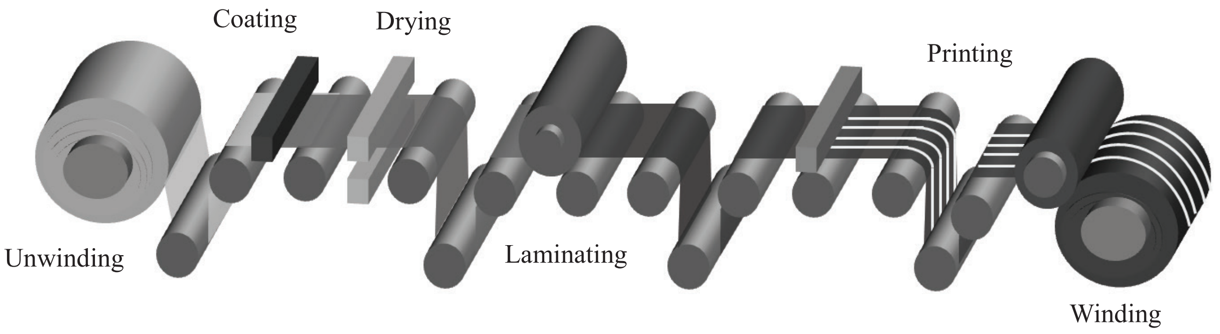


Fig. 1 Roll-to-Roll-Printed-Electronics (R2RPE) manufacturing system

film and steel roller surface. The experimental apparatus consists of a roller, test film and weight, and these components comprise a simple system in which a pulley method is implemented for friction measurement. The test roller is cylindrical which is fixed in the experiment. Five specimens of polyethylene terephthalate (PET) film were used in tests, each of a different thickness. **Table 1** and **Table 2** show the specifications of the test films and test roller, respectively.

In this experiment, first a piece of the test film is put on the roller and then identical weights were set up at the ends of the film as shown in Fig. 2. After that, the weight (T_{exit}) was increased at one end of side by slowly adding water to a container suspended from film's end. The exit tension T_{exit} increase was continued until the test film started to slide on the test roller. After obtaining the inlet and exit tensions, the static friction coefficient, μ_s, was calculated by the following the Euler's belt formula;

$$\mu_s = \frac{1}{\Theta}\ln\left(\frac{T_{\mathrm{exit}}}{T_{\mathrm{inlet}}}\right) \tag{1}$$

where Θ is wrap angle. In the experiment, wrap angle was determined as $\Theta = 180°$. Furthermore, inlet tension is changed within range of $T_{\mathrm{inlet}} = 6, 12, 25, 50$ [N/m]. The experiments were conducted under the temperature between 24.9 ~ 26.4 **°C** and with the relative humidity between 40.1 ~ 45.2 %.

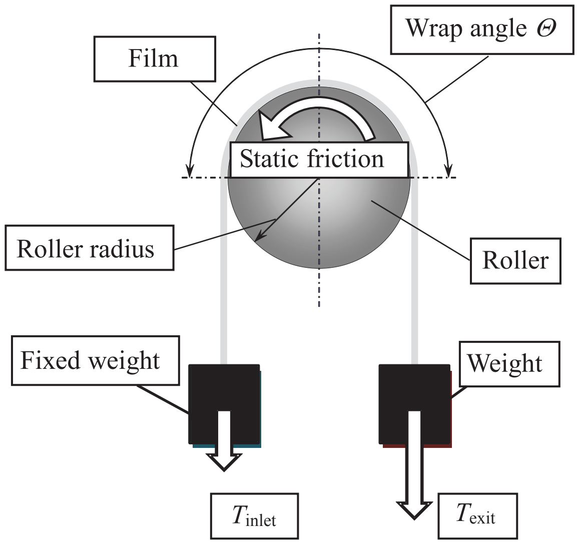


Fig. 2 Experimental apparatus for measuring static friction

2.2 Kinetic friction

Figure 3 shows the overview of experimental apparatus for measuring the kinetic friction force between the plastic film and steel roller. The experimental apparatus consists of a steel roller, driving

Table 1 Specifications of test film

Parameters			Values				
Width	w	[mm]	20~30				
Thickness	t_w	[μm]	6	12	25	38	50
R.M.S roughness	σ_w	[nm]	42	41	57	44	52

Table 2 Specifications of test roller

	Parameters			Values
Static	Material of test roller			SCM-440
	R.M.S roughness	σ_{r1}	[nm]	370
	Roller radius	r_1	[m]	0.040
Kinetic	Material of test roller			SCM-440
	R.M.S roughness	σ_{r2}	[nm]	751
	Roller radius	r_2	[m]	0.055

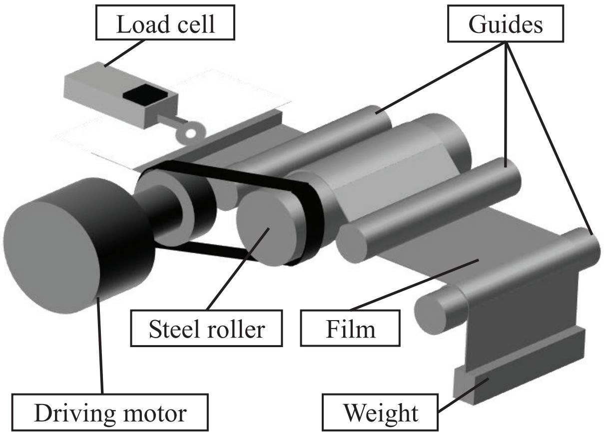


Fig. 3 Experimental apparatus for measuring kinetic friction

motor, guides, film, weight and load cell. Structure of the apparatus is different from the R2R transportation system. The film was stationary and the roller was rotated with the driving motor. The amplitude of rotating roller is less than 1 μm. Web tension can be changed by changing the hanged weight. Moreover, wrap angle can be changed within range of 30°~ 120°. In the experiments, PET film is used for measurement.

First, the film was set on the steel roller. After that, the load cell was attached at the edge of the film. The weight was also attached at the opposite edge. After obtaining the tension increase when the motor was driven, ΔT, the kinetic friction coefficient was calculated by the following Euler's belt formula;

$$\mu_k = \frac{1}{\Theta}\ln\left(\frac{T+\Delta T}{T}\right) \qquad (2)$$

where, T is initial tension when the steel roller is not rotating and ΔT is the tension increase obtained by load cell. In this system, the influence of between guides and the film on the friction coefficient is negligible because the guides were stationary. In the measurements, the three operation parameters, film tension T, film thickness t_w and roller velocity U_r, were changed. The experiments were conducted under the temperature between 23.6 ~ 24.8 **°C** and the relative humidity from 46.8 ~ 53.2 %. In addition, wrap angle was fixed to 60°.

3 Experimental results

3.1 Static friction

Figure 4 shows the relationship between the static friction coefficients and the film thickness. Plots and error bar indicate the averaged value of five times measured date and variation of measurements. As can be seen in the figure, the static friction coefficient was increased with the decrease in the film thickness. This results obtained are considered to be influenced by deformation of the film. When the tension was applied the film, the film was deformed along with the roller surface asperities. The bending stiffness of the film is proportional to the cubic of the film thickness. As a result, thin film is deformed more, as compared to thick film, and it covers more closely the roller surface asperities. When the film is pulled tangentially, the asperities behave as an anchor. The static friction coefficient in the case of thin film was increased than in the case of thick film due to an "anchor effect" between the deformed film and asperities as shown in **Fig. 5**.

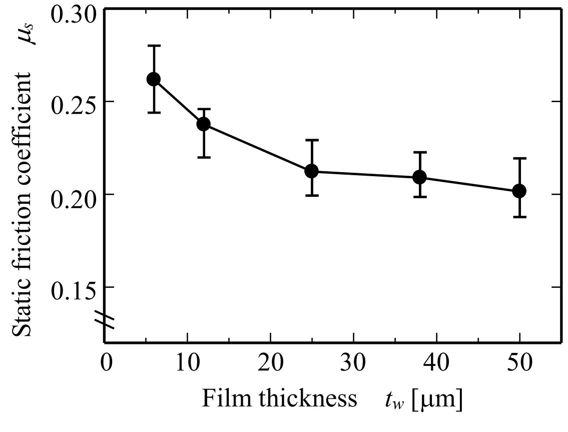
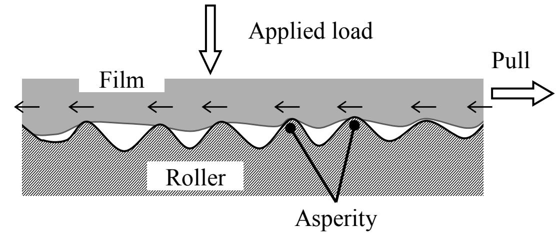
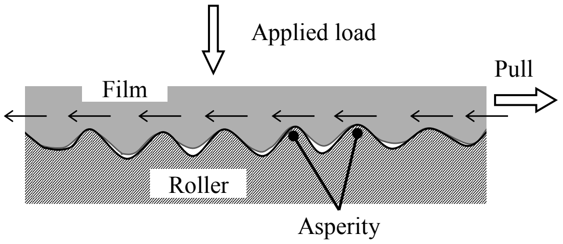


Fig. 4 Relationship between static friction coefficients and film thickness (T_{inlet}=12 [N/m], T_r=24.9~26.4[°C], H=40.1~45.2 [%])

Figure 6 shows the relationship between the static friction coefficient and film tension. In the figure, plots of □, ▲ and ○ indicate the difference of film thickness. As can be seen in the figure, the static fiction coefficient of each film thickness was moderately decreased with the increase in the film tension. The static friction is independent of applied load and the static friction coefficient stays constant with an increase the applied load according to the Amonton's-Coulomb's law. However, the different tendency, in which the static friction coefficients is increased with the decrease in the applied load, was shown because the contact areas between the film and roller surface asperities was more widely under low tension. This is, anchor effect



(a) Case of thick film



(b) Case of thin film

Fig. 5 An increase of resistance due to "anchor effect"

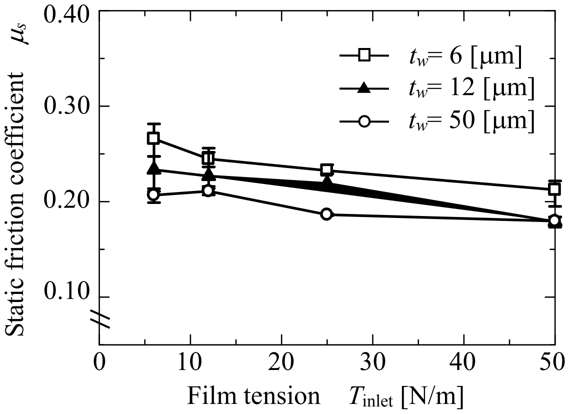


Fig. 6 Relation between static friction coefficient and film tension (T_r=24.9~26.4[°C], H=43.5~45.5 [%])

probably become lower due to high web tension.

3.2 Kinetic friction

Figure 7 shows the relationship between the kinetic friction coefficient and roller velocity by changing film tension. From the all results, the kinetic friction coefficient was decreased gradually with the increase in the roller velocity. The reason for this behavior is probably the influence by air between the plastic film and steel roller. The air between surfaces was increased with the increase in the roller velocity because the film is deformed, and then lubrication state between the film and steel roller was changed from boundary lubrication to mixed lubrication as shown in **Fig. 8**. Moreover, at the range of roller speed from 1.0 m/s to 2.0 m/s, the kinetic friction coefficient became approximately-constant. The results show that the film floated by fluid lubrication effect of air pressure, and space between the film and the steel roller became fluid lubrication as shown in **Fig. 8 (c)**. However, the kinetic friction coefficient was not zero because there was viscous friction by fluid.

On the other hand, comparing the results of differencing the film thickness, even though the static friction coefficient was increased with the decrease in the film thickness, the kinetic friction coefficient was decreased with the increase in the film thickness. The air film thickness between the film and roller was larger because the film was deformed more, compared to thick film by air pressure. As a result, the kinetic friction coefficient was decreased because the contact areas between the film and roller surface asperities were smaller. Moreover, the tendency can be pronounced with the decrease in the film tension as in the case in results of static friction coefficient as shown in **Fig. 6**.

4 Conclusions

In this paper, the static and kinetic friction forces between plastic film and steel roller surface were measured by changing film thickness and film tension. From the experimental results, the static friction coefficient was increased with the decrease in the film thickness. On the other hand, the kinetic friction coefficient was decreased with the decrease in the film thickness because of changing the interface between the film and steel roller. Moreover, the tendency can be pronounced with the decrease in the film tension.

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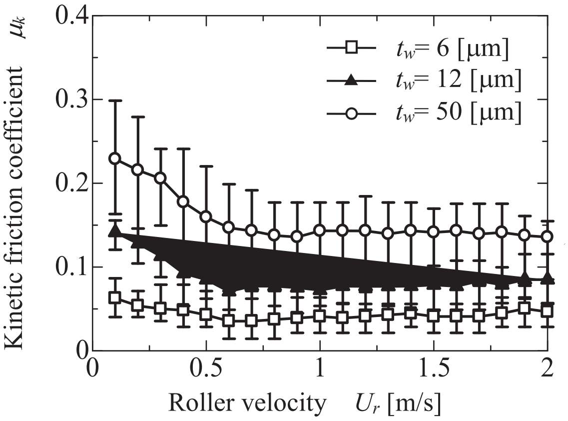
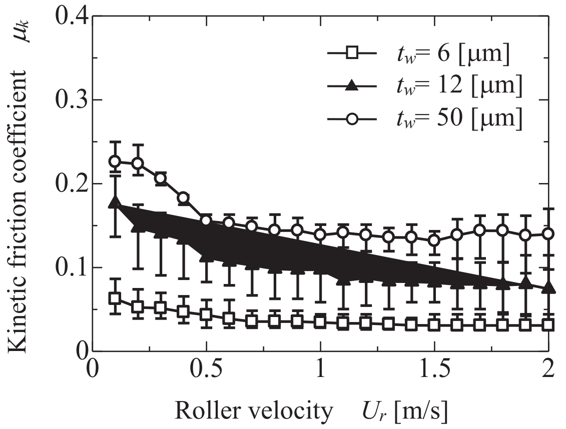
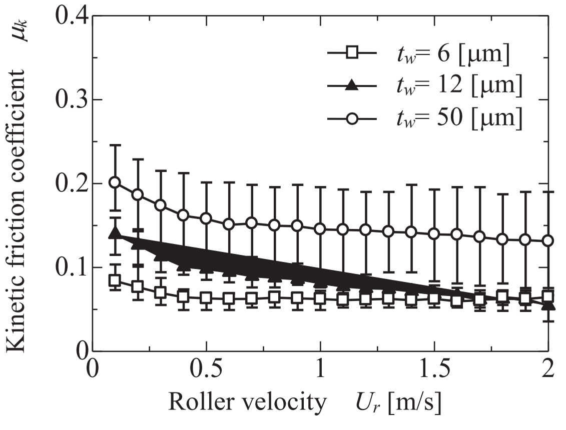


(a) T = 40 [N/m]

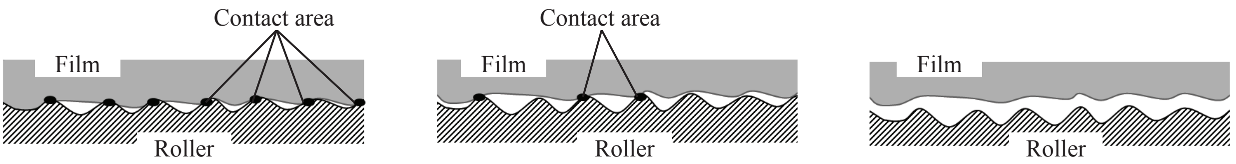


(b) T =80 [N/m]



(c) T = 120 [N/m]

Fig. 7 Variation of friction coefficient with roller velocity as a parameter of film tension (T_r=23.6~ 24.8[°C], H=46.8~53.2 [%])



(a) Boundary lubrication (b) Mixed lubrication (c) Fluid lubrication

Fig. 8 Lubrication state between plastic film and steel roller

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