Direct thickness measurement of doctor-bladed liquid film on gravure roll surface

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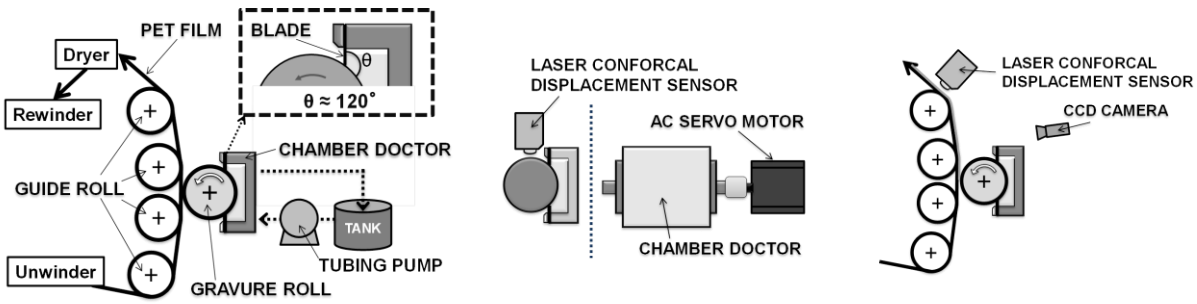
Introduction

Gravure coating is a common method in the manufacture of a wide variety of thin film coatings. Gravure roll is a cylinder patterned with cells which engraved onto the roll surface. The cells are usually filled with a liquid by rotating the gravure roll into a liquid pool (filling process), and the excess liquid on the roll surface is wiped off by a doctor blade (doctoring process). The liquid remaining in the cells is partly transferred to the substrate (transfer process). Gravure coating belongs to a class of coating method known as self-metered coating: the thickness of the coated liquid film in principle is set by the capillary number (Ca) defined as the balance between the viscous and surface tension forces. However, the previously reported and/or numerically predicted transfer ratio, i.e., a ratio of coating liquid volume to gravure cell volume, for Newtonian fluids ranged between 0.2 ~ 0.8 even at the same capillary number of Ca = 0.1[1]-[7]. This deviation for the liquid transfer ratio may stem from the difference in the amount of liquid remaining on the roll surface after the blade-doctoring process. To the best of our knowledge, no experimental data is currently available for the thickness of doctor-bladed liquid film in the literature. In this study, the direct thickness measurement of doctor-bladed liquid film on gravure roll was conducted experimentally. Furthermore, we investigate how the liquid film remaining on the roll surface influences a transfer ratio, and the coating window.

Experimental

The experimental set-up in reverse kiss mode is schematically shown in Fig. 1. The coating liquid was fed to the chamber-doctor closed coating system from a tubing pump. The stainless-steel doctor blade with the thickness of 0.2 mm, stepped tip thickness of 0.1mm and the length of 1.5 mm from the tip (Eco Blade Co., Kanagawa, Japan) was used for the doctoring. The blade angle of chamber doctor was 120 degrees (reverse angle). The tri-helical grooves of 70 lines/inch in pitch and 74 cm^3/m^2 in volume were engraved on the surface of gravure roll of 60 mm in diameter. The gravure roll surface speed ($V_{gravure}$) was varied between 0.017 and 0.833 m/s (1 ~ 50 m/min). The moving substrate (web) used was PET film of 25 μm thick and 100 mm width (type T-60, Toray Co., Tokyo, Japan). The web speed (V_{web}) was varied between 1.66 × 10^{-3} and 0.833 m/s (0.1 ~ 50 m/min). The coating liquids used were aqueous solutions of polyethylene glycol (PEG, Mw = 7300 ~ 9300, Wako Pure Chemical Industries Co., Osaka, Japan) as a

Newtonian fluid (Table 1). First, the doctor blade was pushed onto the rotating gravure roll surface to form the doctor-bladed liquid film. Second, a local distribution of the free surface position across two neighboring grooves was measured using a laser confocal displacement sensor (model LT-9010M and LT-9500SO(5883), Keyence Co., Osaka, Japan) after a quick stop of the gravure roll by the controlled servomotor. After restarting the rotation of the gravure roll, the substrate was contacted with the gravure roll in kiss mode to measure the coating thickness of liquid transferred on the web. The transfer ratio was calculated from the measured coating thickness divided by the volume of the grooves. Simultaneously, the coating film surface was observed by a CCD camera.



(a) Apparatus

(b) Measurement of liquid film thickness

(c) Measurement of coating thickness

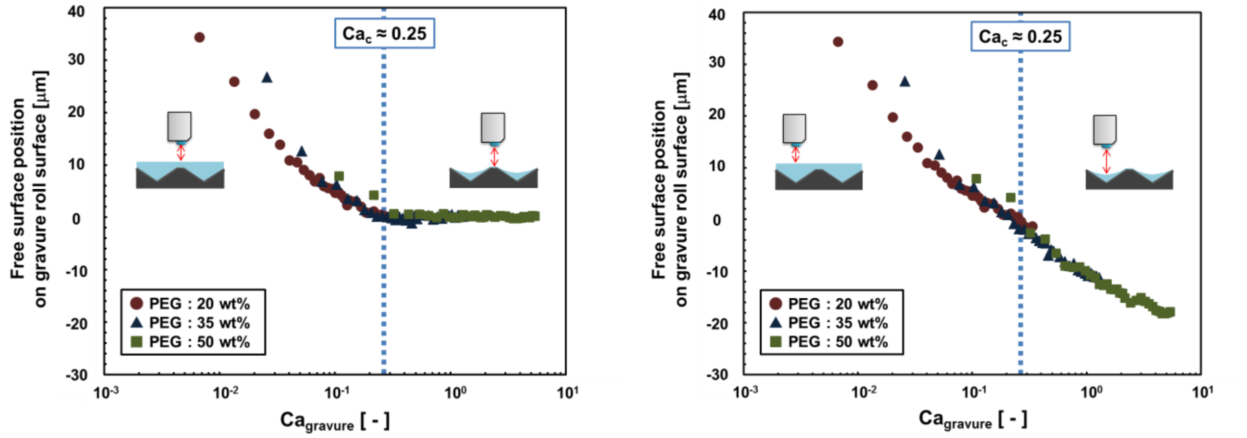
Fig. 1 Schematic of the experimental set up

Table 1 Property of PEG aqueous solution

Concentration [wt%]	Viscosity μ [mPa· s]		Surface tension σ [mN/m]
	Average	Uncertainty	
20	19	±1	58
35	87	±4	55
50	375	±25	50

Results and Discussion

Fig.2 shows the variations in measured the free surface positions with capillary number Ca_{gravue} (= $\mu V_{gravure}/\sigma$), where μ and σ are the viscosity and static surface tension of the solution, respectively. The origin of the coordinate in the thickness direction is on the surface of the land. The doctor-bladed liquid film remained on the land surface below a critical capillary number of $Ca_c \approx 0.25$. The surface positions for the fluids with different viscosities were found to obey a master curve with $Ca_{gravure}$. The local liquid film thickness on the land monotonically decreases with increasing $Ca_{gravure}$, and eventually reaches a constant value of 0.1 ± 0.6 μm at high capillary numbers, showing a complete removal of excess fluids on the gravure roll. On the other hand, the position of the free surface at the center of the groove shows negative values at $Ca_{gravure} > Ca_c$, indicating a concave free surface profile after doctoring.



(a) Surface position of liquid on land (b) Surface position of liquid at groove center

Fig. 2 Measured free surface positions on gravure roll

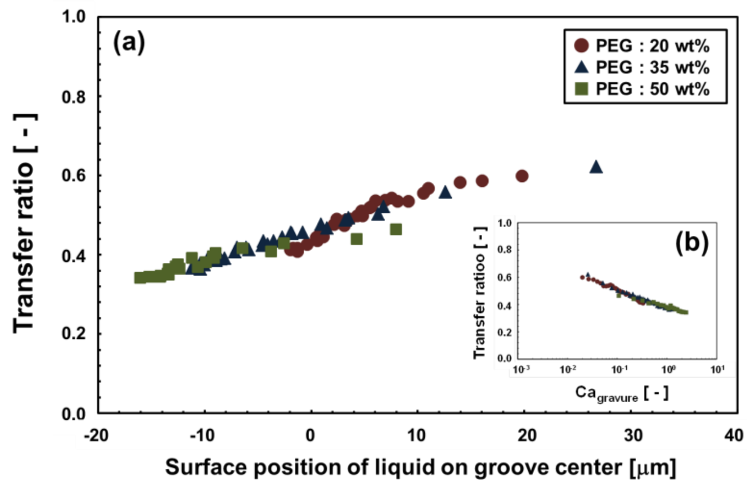


Fig. 3 Transfer ratio at $V_{web}/V_{gravure}$ = 1

To understand how the remaining liquids on the gravure roll surface affect the liquid transfer process, we measured the transfer ratio at $V_{web}/V_{gravure}$ = 1. The relationship between the transfer ratio and the position of the free surface at the center of the groove is shown in Fig. 3(a). The transfer ratio increased with increasing the amount of liquid on gravure roll, indicating that the liquid transfer from a gravure roll to the web is strongly influenced by the amount of remaining liquid on the gravure roll surface. The transfer ratio obeys a single master curve with $Ca_{gravure}$ (Fig. 3(b)). We note that the measurement was performed in the intermediate range of $Ca_{gravure.}$ The dripping and ribbing defects were observed at low ($Ca_{gravure}$ < 0.01) and high ($Ca_{gravure}$ > 2.5) capillary numbers, respectively.

To demonstrate how the doctoring process affects the stability of coating film, we observed the coating films for different $Ca_{gravure}$ and Ca_{web} (= $\mu V_{web}/\sigma$). The coating was stable at intermediate capillary numbers (Fig. 4a). A part of the coating liquid dripped at low Ca_{web} (dripping defect, Fig. 4b). The coating film formed terraces to the moving direction of web at high $Ca_{gravure}$ because of the instability of coating bead (cascade defect, Fig. 4c). The coating film showed periodic but angled thickness variations at high Ca_{web} (ribbing defect, Fig. 4d). We summarized the operable regions as a coating window shown in Fig. 5. The stable region becomes narrow with increasing $Ca_{gravure}$ and Ca_{web}. The transition between dripping and cascade modes was observed at $Ca_{gravure} \sim 0.25$, which agrees with Ca_c, above which no liquid film remains on the roll surface. This fact indicates that the doctor-bladed liquid film with a finite thickness influences not only the transfer ratio, but also the liquid stability in the transfer process.

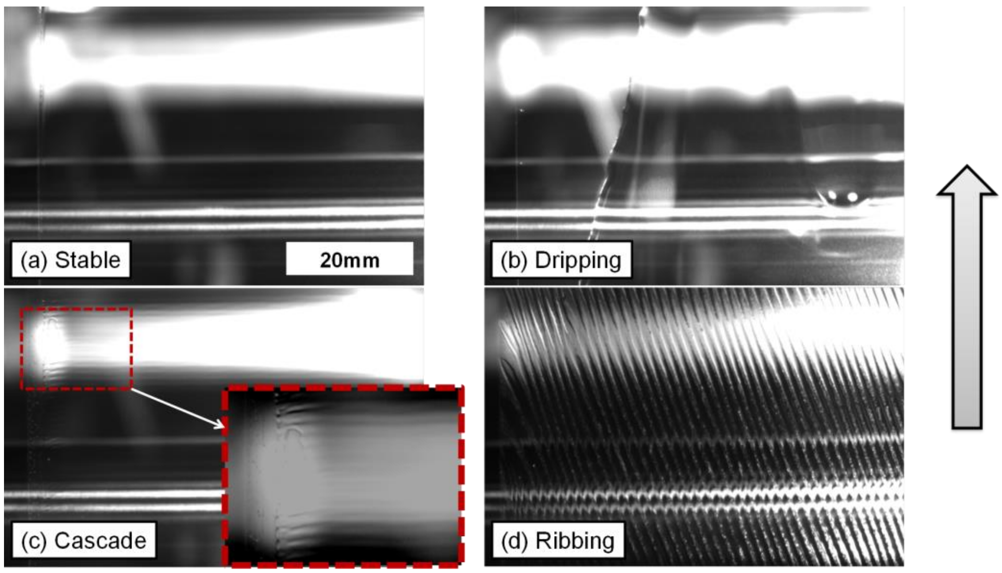


Fig. 4 Optical images of coating films. The arrow in the figure represents the coating direction.
(a) $Ca_{gravure} = 0.25$, $Ca_{web} = 0.075$, PEG - 35wt% (b) $Ca_{gravure} = 0.011$, $Ca_{web} = 0.0055$, PEG - 20wt%
(c) $Ca_{gravure} = 1.26$, $Ca_{web} = 0.0075$, PEG - 35wt% (d) $Ca_{gravure} = 0.63$, $Ca_{web} = 1.00$, PEG - 50wt%

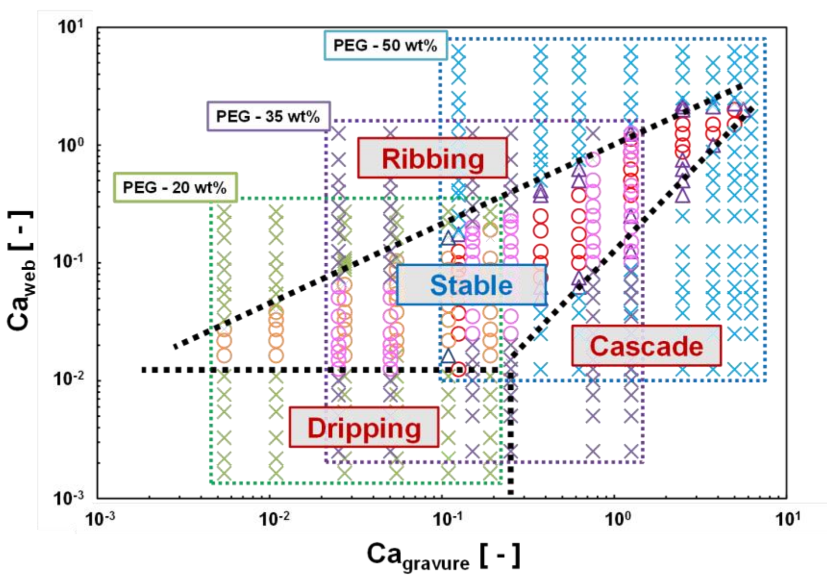


Fig. 5 Influence of Ca on coating stability (coating window)

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