

Visualization Study of Flow Stability in Reverse Roll Coating

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Reverse roll coating is widely used to coat a thin liquid layer onto a moving substrate. A metered liquid layer is created within the gap between a pair of co-rotating rolls. To avoid roll damage due to roll run-out, substrate caliper change or splice passage, when the gap between the rolls is small, one of the rolls will have a compliant polymer cover. The existence of a deformable cover in the gap between a metal roll and a rubber roll creates an elastohydrodynamic flow field in that region. As the liquid passes through the converging-diverging section within the gap, it generates pressure, and this pressure can deform the elastic roll surface, which in turn alters the geometry of the gap and the flow. Therefore, the uniformity of coating is affected differently than what is observed when only rigid rolls are used.

In this study, visualizations of the flow between a reverse deformable roll and solid stainless steel roll are done to determine how the uniformity of coating in the high roll speed region is affected by operating parameters, namely, the speed ratio between the rolls, roll cover properties and liquid properties. The wavelength of ribbing is investigated to verify the effect of speed ratio, wet coating thickness and viscosity.

For these experiments, the roll coating apparatus is used with 4 inch diameter rolls installed one above the other. A high-resolution camera is used for visualizations of the flow, and the ribbing wavelength is measured from photographed images. The uniformity of coating and its dependence on capillary number is evaluated.

A numerical simulation of the flow between metal and rubber rolls enabling prediction of the ribbing wavelength is also performed.

KEY WORDS: reverse roll coating; coating defect; ribbing; flow stability.

1. Introduction

In recent years, demand for steel sheets with special surface treatments having a corrosion resistance function has expanded. Roll coating is widely used to coat a thin liquid layer onto a moving substrate. In this process, the liquid layer is taken up from a container and coated on the substrate after controlling the wet thickness. Multiple rolls are usually used. A metered liquid layer is created in the gap between a pair of co-rotating (reverse roll) or counter-rotating (forward roll) cylinders. It is necessary to clarify the flow states between the rolls in order to obtain a uniform coating appearance. Many publications discussing single-layer roll coating processes are available.

In the case of forward roll coating, these studies have focused on the coating defect called ribbing, which is caused by the rotating motion of the rolls, and concluded that the operability limits could be shown by using a dimensionless number (capillary number: Ca).^{1–6)}

In the case of reverse roll coating, experimental and analytical approaches are used to clarify the effects of the roll

speed, liquid properties and roll gap on coating defects between metal rolls.⁷⁾

However, in roll coating processes for steel sheets, a rubber covered roll is usually used to avoid roll damage due to roll run-out, substrate caliper change or splice passage when the gap between the rolls is small. The existence of a deformable cover in the gap between the metal roll and rubber roll creates an elastohydrodynamic flow field in that region. As the liquid passes through the converging-diverging section within the gap, it generates pressure; this pressure can deform the elastic roll surface, which in turn alters the geometry of the gap and the flow. Therefore, the uniformity of coating is affected differently than what is observed when only rigid rolls are used.

In this study, visualizations of the flow between a reverse deformable roll and a solid stainless steel roll are done to determine how the uniformity of coating is affected by operating parameters, namely, the speed ratio between the rolls, roll cover properties and liquid properties. The wavelength of ribbing is investigated to verify the effects of the speed ratio, wet coating thickness and viscosity. A numerical simulation of the flow between metal and rubber rolls enabling prediction of the ribbing wavelength is performed, and the results are compared with experimental results.

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2. Experimental Set-up and Procedure

The coating apparatus used for visualization of roll coating is shown in **Figs. 1** and **2**.

For these experiments, the roll coating apparatus is used with two rolls installed one above the other. A rubber covered roll was used for the top roll and a metal roll was used for the bottom roll. The bottom roll was 4 inches in diameter. The top roll diameter was 7 or 4 inches.

The small 4 inch wide slot die shown in **Fig. 2** was sufficiently wide for a two-dimensional flow to develop away from its edges and was also easy to handle in laboratory scale experiments.

As the direction of roll rotation, a reverse method in which the rolls turned in opposite directions was used.

The coating liquid was supplied from the slot die to the bottom roll in a uniform state and was then transferred to the top roll through the meniscus between the bottom roll and the top roll. Squeegee positioned on the opposite side from the liquid feed was used to remove the liquid from the top roll. The scrapped liquid was collected in order to measure the thickness of the film on each of the rolls. In this study, the liquid film surface of the meniscus between the two rolls was visualized in order to investigate how the uniformity of reverse roll coating is affected by the speeds of the two rolls, the viscosities of the liquid and the diameter of the top roll.

The camera was positioned between the two rolls in order to visualize the flow condition. Various glycerin-water solutions were used as coating liquids. The viscosity of the solutions was adjusted by dilution with water.

Table 1 shows the experimental conditions of the study. The range of the top roll speed was from 10 mpm to 300 mpm, the range of the bottom roll speed was from 2 mpm to 120 mpm, the range of the wet thickness was from 4 μm to

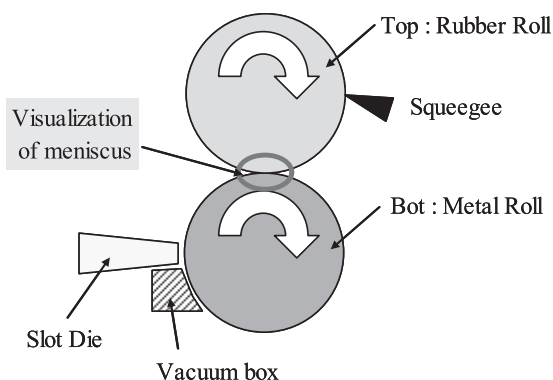


Fig. 1. Sketch of coating apparatus.

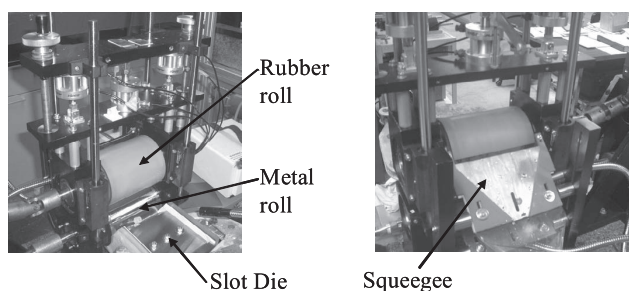


Fig. 2. Outline of coating apparatus.

13 μm and the range of the viscosity was from 1 cP to 44 cP.

This study also focused on the coating defect called ribbing, and the transition of the ribbing wavelength accompanying changes in coating conditions was investigated. **Figure 3** shows an outline of the ribbing wavelength measurement procedure. The camera was positioned at the center of the width direction, and a domain approximately 16 mm in width was photographed. The ribbing wavelength was calculated from the snapshot. A high resolution camera (Imaging Source model DFK 31 BF03H) was used for these visualizations.

The ribbing wavelength was compared under various conditions of roll speed, wet thickness, viscosity and roll diameter, respectively.

3. Results and Discussion

3.1. Visualization of Flow between Two Rolls

Figure 4 shows snapshots of the condition between the two rolls when the rolls speed and viscosity were changed. **Figure 4(a)** shows the case of low speed conditions, and **Fig. 4(b)** shows the case of high speed conditions.

It was remarkable that ribbing was generated under the high viscosity condition, and it was possible to avoid ribbing under the low viscosity condition by the uniformity of the meniscus between the two rolls.

The ribbing wavelength λ tended to be wide under the low speed condition and narrow under the high speed condition.

Figure 5 shows the stability diagrams when the roll speed

Table 1. Experimental condition.

Roll type	Top roll	Rubber covered roll
	Bottom roll	Metal roll
Roll speed range	Top roll	10–300 mpm
	Bottom roll	2–120 mpm
Roll diameter	Top roll	4 inches, 7 inches
	Bottom roll	4 inches
Coating liquid	Glycerin + water	
Viscosity	1–44 cP	
Surface tension	50–65 mN/m	

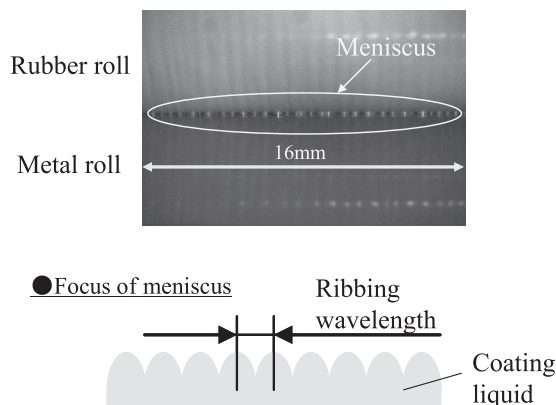


Fig. 3. Example of roll coating visualization and definition of ribbing wavelength.

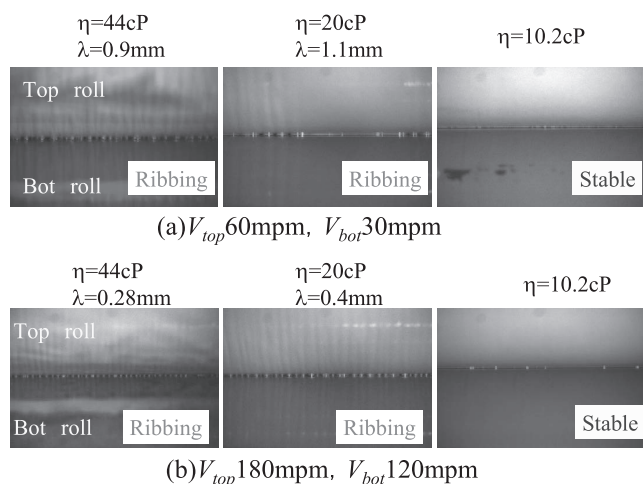


Fig. 4. Camera pictures (meniscus region).

and viscosity were changed. The horizontal axis is the bottom roll speed, and the vertical axis is the speed ratio between the top roll and the bottom roll (V_{top}/V_{bot}). The coating appearance was divided into a stable region, ribbing region and region in which the wave motion called roll bank was generated.

When the viscosity was 44 cP, as shown in Fig. 5(a), a stable coating condition was observed at low roll speeds and at a speed ratio equal to 1.0.

The stable region was expanded by decreasing the viscosity. The meniscus flow stabilized when the viscosity was 1.2 cP and the speed ratio of the rolls was about 2.5, as shown in Fig. 5(d).

From this result, it was found that reducing the liquid viscosity was effective for stabilizing the meniscus flow.

These experiments also clarified the fact that the onset of ribbing is closely correlated with the ratio between the viscous force and surface tension, which is called the capillary number (Ca).¹⁾

Ca is a dimensionless number, as shown in Eq. (1), where μ is the viscosity of the coating liquid, σ is surface tension and V is the relative velocity in reverse roll coating.

$$Ca = \frac{\mu V}{\sigma} \dots\dots\dots (1)$$

Figure 6 shows the relationship between the roll speed ratio and Ca under each coating condition. These results clarified the fact that the condition for a stable flow in the meniscus region is a low Ca condition or a speed ratio of nearly 1.0. It was also found that the onset of ribbing did not depend on the viscosity of the coating liquid and could be arranged by the roll speed condition and Ca .

In past research, the meniscus instability phenomenon called cascade was observed between rigid rolls in the high speed ratio region by Coyle *et al.*,^{1,2)} but this was not observed in the present research. It is thought that the onset of cascade is caused by air entrainment. In this research, air entrainment did not occur because the gap was narrowed and the rolls were in mutual contact.

3.2. Relationship of Ribbing Wavelength and Coating Conditions

The ribbing wavelength was investigated by changing the

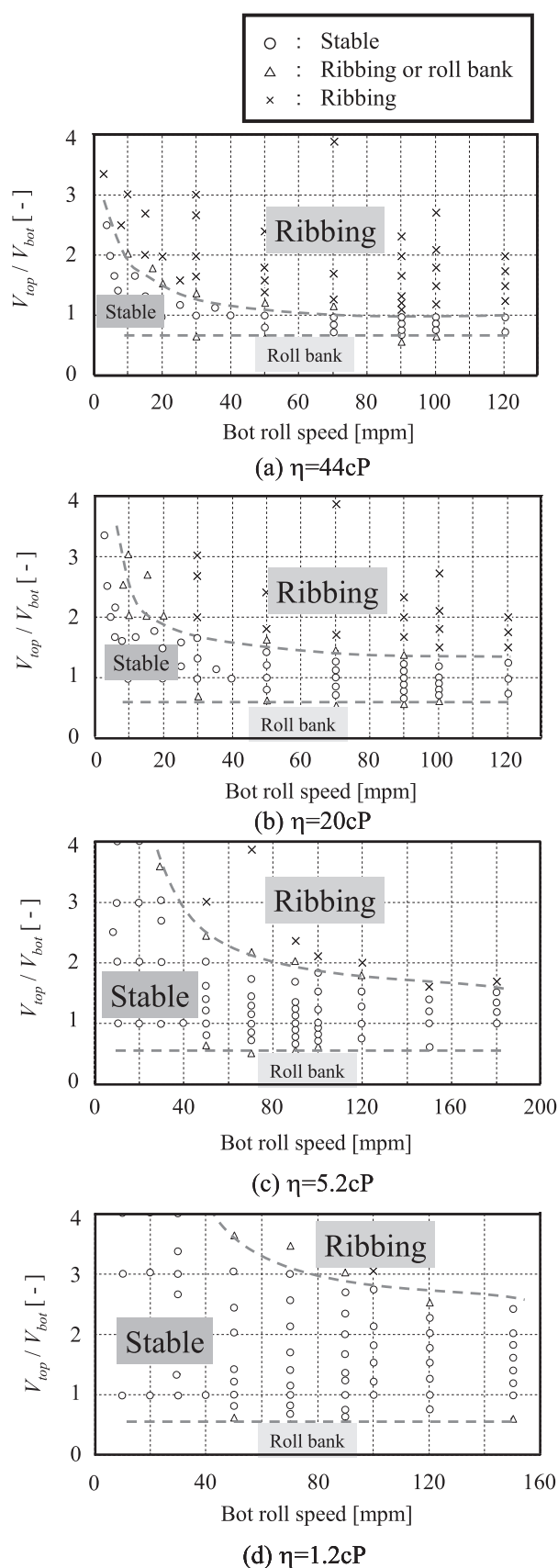


Fig. 5. Stability diagram.

roll speed condition, wet thickness and the viscosity of the coating liquid.

Figure 7 shows the relationship between the wet thickness and the ribbing wavelength at various bottom roll

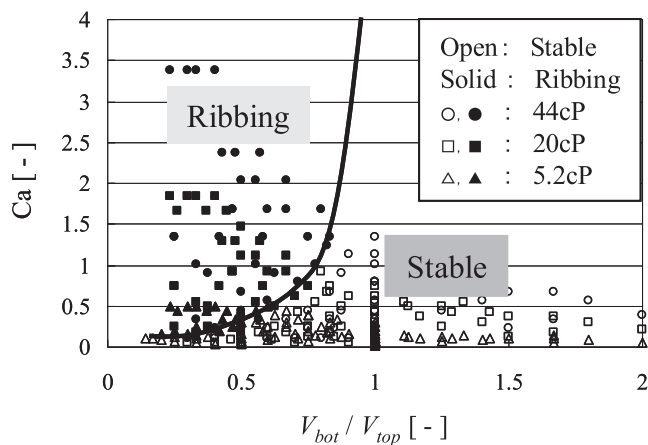


Fig. 6. Stability diagram for capillary number Ca and experimental conditions.

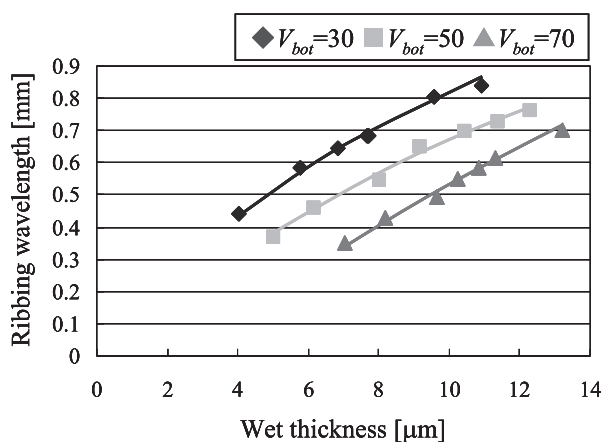


Fig. 7. Effect of wet thickness on ribbing wavelength.

speeds. The speed of the top roll was 120 mpm, the viscosity of the coating liquid was 44 cP, and the wet thickness and speed of the bottom roll were varied. The ribbing wavelength changed to the long-wavelength side when the wet thickness increased. It is thought that the frequency of ribbing changed to the long-wavelength side due to an increase in the range of oscillation in the meniscus region caused by the increased length between the roll contact and liquid surface. On the other hand, when the roll speed was increased, the ribbing wavelength changed to the short-wavelength side because the frequency of oscillation shifted to a higher frequency.

Figure 8 shows the relationship between the viscosity of the coating liquid and the ribbing wavelength. The wet thickness was 7 μm .

The results showed that the ribbing wavelength decreased when the viscosity of the coating liquid increased. The relationship between the viscosity of the coating liquid and the ribbing wavelength was estimated by using the Landau-Leibich equation, as shown in Eq. (2), where H_∞ is the final wet thickness, Ca is the capillary number and R_m is the radius of curvature. From Eq. (2), if the final wet thickness is constant, the radius of curvature of the meniscus is proportional to the $-2/3$ power of Ca , and increasing the coating viscosity leads to decrease in the radius of curvature.

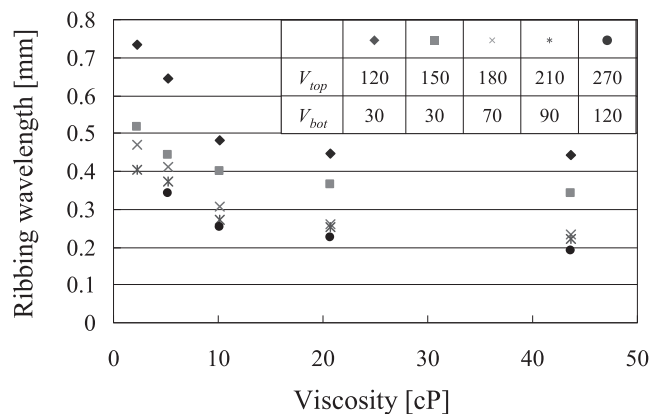


Fig. 8. Effect of viscosity on ribbing wavelength.

$$H_\infty = 1.34(Ca)^{2/3} R_m, \quad Ca = \frac{\mu V}{\sigma} \quad (2)$$

In the case of a high liquid viscosity, the quantity of coating liquid lifted from the meniscus region increases, and the length between the roll contact position and the meniscus surface is shortened. It is estimated that the ribbing wavelength changed to the short-wavelength side because the frequency of oscillation shifted to a higher frequency.

3.3. Relationship between Stability Diagram and Ribbing Wavelength and Roll Diameter

The flow state between the rolls and the ribbing wavelength were investigated when the roll diameter of the top roll was changed. Figure 9 shows the stability diagrams when the roll diameter was 4 and 7 inches, respectively. The stable region is not affected by the roll diameter. The flow stability of the meniscus is determined by the balance of atmospheric pressure, hydrostatic pressure and the surface tension of the coating liquid: therefore, it is thought that the flow stability does not change because there is no change in hydrostatic pressure when the roll diameter is changed, provided the roll speed condition is the same.

However, in this case, the contact length between the rolls will change. Figure 10 shows the relationship between the wet thickness and ribbing wavelength. The length between the contact position and meniscus surface is longer when the radius of curvature is larger. From this result, it is thought that the frequency of oscillation shifted to a lower frequency because the range of the oscillation effect became longer.

3.4. Reverse Roll Coating Analysis by Viscocapillary Model

Theoretical investigations of the pressure distribution in the meniscus region using a lubrication model and viscocapillary model were reported by Carvalho for forward roll coating and by T. J. Anderthon for reverse roll coating.^{4,10} In this experiment, reverse roll coating using a deformable roll was performed under a negative gap condition. The dimensionless equation systems and boundary conditions are given by Eqs. (3)–(11).

$$\frac{dp}{dx} = Ne \left[\frac{6(s+1)}{[h(x)]^2} - \frac{24q}{[h(x)]^3} \right] \quad (3)$$

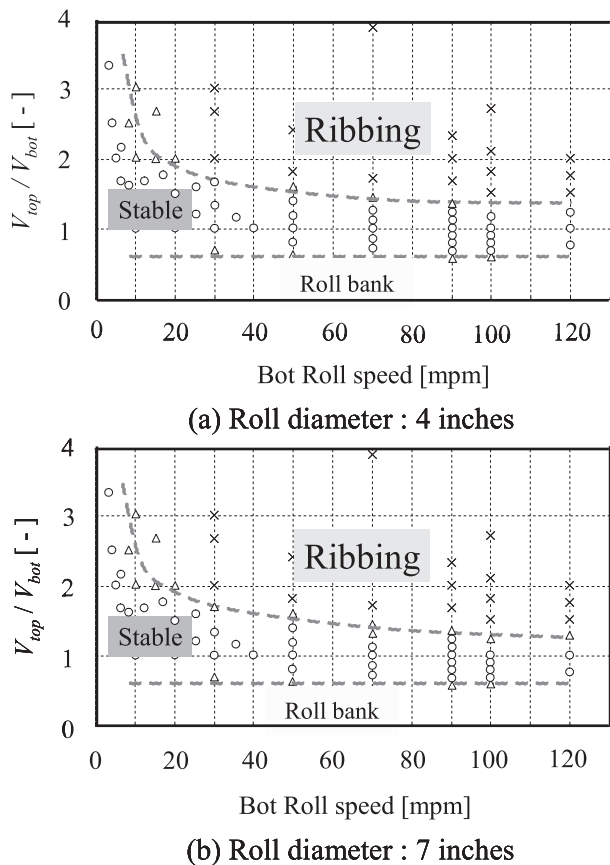


Fig. 9. Stability diagram (effect of roll diameter).

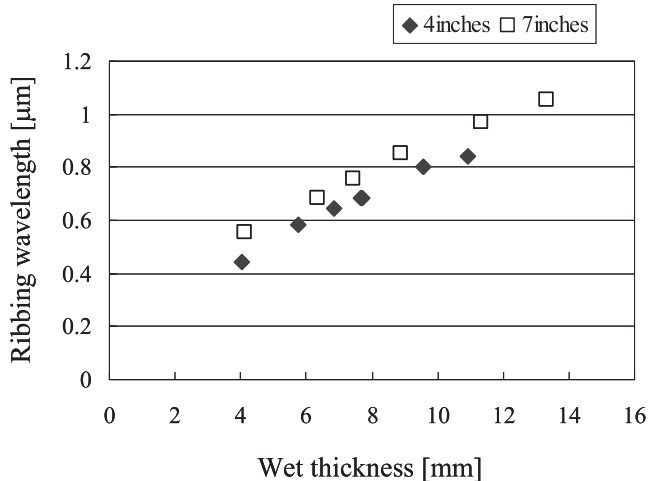


Fig. 10. Effect of roll diameter on ribbing wavelength.

$$h(x) = -2 + x^2 + d(x) \quad \dots\dots\dots (4)$$

$$Ne = E_s \left(\frac{R}{H_0} \right)^{5/2} \quad \dots\dots\dots (5)$$

$$p(x_u) = - \frac{Ne}{Ca(R/H_0)^{1/2} r_u} \quad \dots\dots\dots (6)$$

$$p(x_d) = - \frac{Ne}{Ca(R/H_0)^{1/2} r_d} \quad \dots\dots\dots (7)$$

$$d(x) = p(x) \quad \dots\dots\dots (8)$$

$$x_u = - \left[h_{1\infty} + 1.6442 \frac{(h_1 - 2q)}{|s|} + r_u \left\{ 1 + \frac{1}{(1 + 0.863(Ca|s|)^{2/3})^{1/2}} \right\} + 2 - d(x_u) \right]^{1/2} \quad \dots\dots (9)$$

$$x_d = \left[3.2884q + r_d \left\{ 1 + \frac{1}{(1 + 0.863(Ca)^{2/3})^{1/2}} \right\} + 2 - d(x_d) \right]^{1/2} \quad \dots\dots\dots (10)$$

$$\frac{x_i - x_{i+1}}{x_1 - x_{n+1}} = K \quad \dots\dots\dots (11)$$

where $K = \frac{x_1 - x_{n+1}}{n}$

q : flow rate, s : speed ratio, R : average roll radius

$h(x)$: wet thickness at x position

$p(x)$: pressure at x position

Ne : dimensionless number

E_s : elasticity number of rubber

H_0 : roll gap

x_u : upstream meniscus location

x_d : downstream meniscus location

r_d : radius curvature

The pressure distribution of the meniscus region was calculated by the matrix method. **Figure 11** shows a sketch of the simulation region. **Figure 12** shows one example of a simulation result for the ribbing condition, which shows that a positive pressure gradient was generated at the downstream side of the meniscus region. In reverse roll coating, it was found that ribbing was generated at the downstream side of the meniscus region ($x \geq 2$) due to a positive pressure gradient.

Next, the variation of the pressure gradient was confirmed when the roll speed ratio was changed. **Figure 13** shows the relationship between the speed ratio and pressure gradient in the case of $Ca=0.5$. The pressure gradient was changed from a positive value to a negative value when the speed ratio increased. Specially, the pressure gradient changed to a negative value at speed ratios above 0.5. The results of the numerical simulation were substantially similar to the experimental results, as shown in Fig. 6, demonstrating that the stability condition of the meniscus can be predicted by numerical simulation in the case of reverse roll coating.

3.5. Comparison of Ribbing Wavelength in Experiment and Prediction Model

A numerical simulation of the ribbing wavelength was performed for the effects of the roll speed, coating liquid property and wet thickness, and the results were compared with the experimental values. An analytical approach to the ribbing wavelength between rolls in the case of forward roll

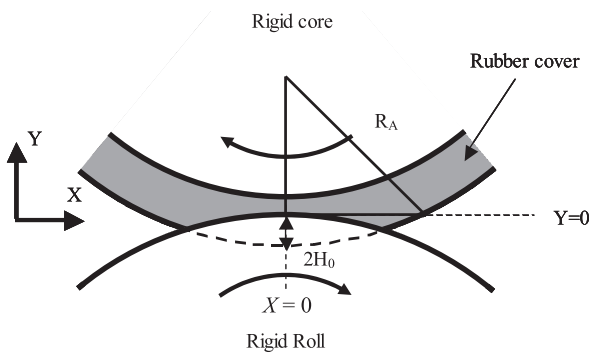


Fig. 11. Sketch of nip region between 2 rolls.

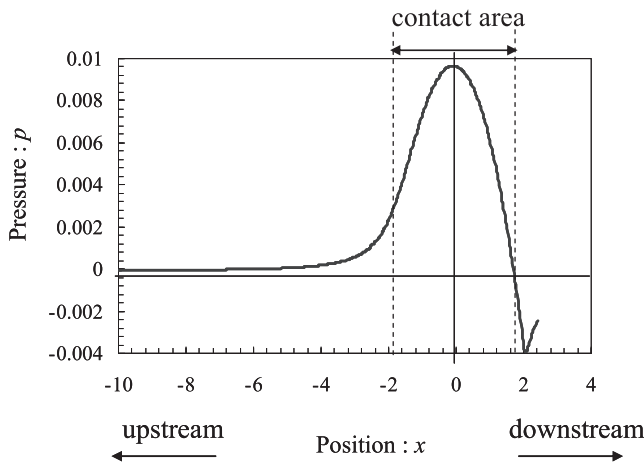


Fig. 12. Pressure distribution of meniscus region.

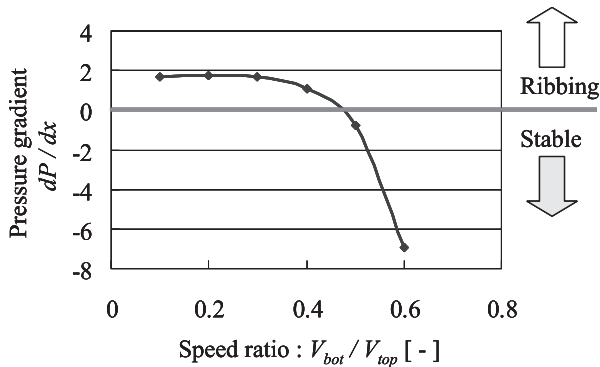


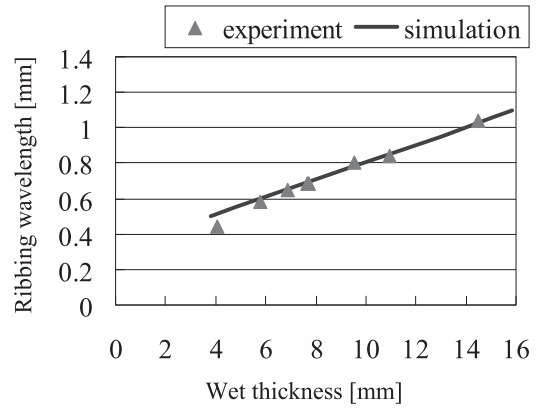
Fig. 13. Estimation of meniscus stability (Ca=0.5).

coating was examined by Carvalho *et al.*,⁴⁾ who reported an analysis of the disturbance of ribbing by the linear perturbation method.

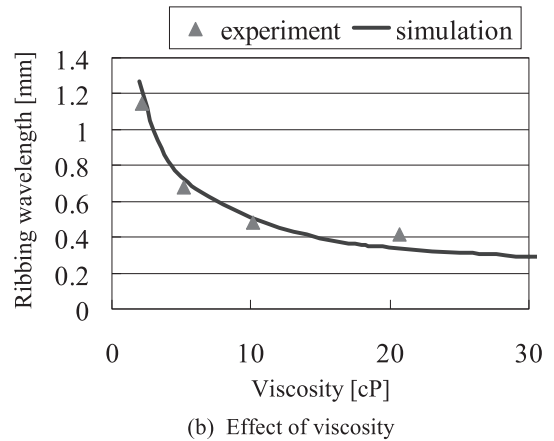
As in the micro time scale, the location of the meniscus, pressure and wet thickness are given by Eq. (12).

$$\left. \begin{aligned} x_m^*(z, t) &= x_m + \varepsilon e^{\beta t} \sin(2\pi n z) \\ p^*(x, z, t) &= p(x) + g(x) \varepsilon e^{\beta t} \sin(2\pi n z) \\ h^*(x, z, t) &= h(x) + g(x) \varepsilon e^{\beta t} \sin(2\pi n z) \end{aligned} \right\} \dots\dots (12)$$

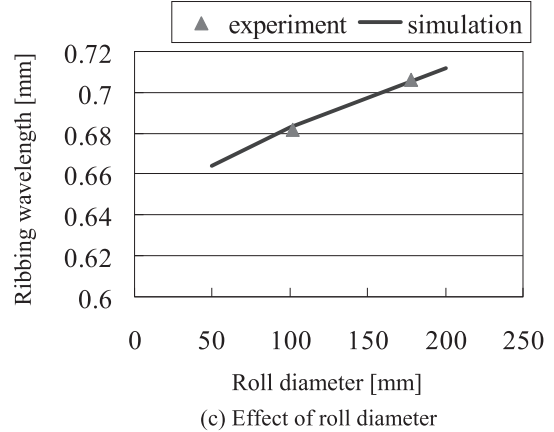
where ε is the amplitude of a transverse disturbance, n is its wavenumber, $g(x)$ is an amplitude function of disturbance and β is its growth factor. The growth factor is a function



(a) Effect of wet thickness



(b) Effect of viscosity



(c) Effect of roll diameter

Fig. 14. Comparison of ribbing wavelength between experiment and simulation.

of the wavelength. The disturbed variables must satisfy the time-dependent two-dimensional Reynolds Eq. (13). Replacing the perturbed variables, as shown in (12), results in an ordinary differential equation that governs the amplitude function $g(x)$:

$$\frac{\partial}{\partial x} \left(h^{*3} \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial z} \left(h^{*3} \frac{\partial p}{\partial z} \right) = 12 \left(\frac{\partial h^*}{\partial x} + \frac{\partial h^*}{\partial t} \right) \dots (13)$$

$$\frac{d^2 g}{dx^2} + \left\{ \frac{3}{h(x)} \frac{dp}{dx} - \frac{12Ne}{h(x)^3} + \frac{3}{h(x)} \frac{dh}{dx} \right\} \frac{dg}{dx} + \left\{ \frac{6}{h(x)^2} \frac{dp}{dx} \frac{dh}{dx} + \frac{3}{h(x)} \frac{d^2 p}{dx^2} - 4\pi n - \frac{12\beta Ne}{h(x)^3} \right\} g = 0 \dots (14)$$

The equation system governing the amplitude function $g(x)$ consists of the second order differential Eq. (14) and the boundary condition (15). The growth factor, which is given by (16), appears in one of the coefficients of (14). A Runge-Kutta method was used to solve this nonlinear system.

$$g(x_m) = \frac{-\left(\frac{dp}{dx}\right)_{x_m} + \frac{1}{Ca \cdot r_m \cdot h(x_m)} \left(\frac{H_0}{R}\right)^{1/2} \left(\frac{dh}{dx}\right)_{x_m} + \frac{4\pi^2 n^2 H_0}{Ca R}}{1 - \frac{1}{Ca \cdot r_m \cdot h(x_m)} \left(\frac{H_0}{R}\right)^{1/2}} \dots (15)$$

$$\beta = \frac{1}{F(1+S^{2/3})-1} \frac{h^2(x_m)}{12} \left\{ \left(\frac{dg}{dx}\right)_{x_m} + \left(\frac{d^2p}{dx^2}\right)_{x_m} \dots (16) \right. \\ \left. + \frac{2}{h(x_m)} \left(\frac{dp}{dx}\right)_{x_m} \left[\left(\frac{dh}{dx}\right)_{x_m} + g(x_m) \right] \right\}$$

Figure 14 shows comparison results of the analytical results and experimental results. Figure 14(a) shows the effect of the wet thickness. In this case, the top roll speed was 120 mpm, and the bottom roll speed was 30 mpm. Increasing the wet thickness leads to an increase in the ribbing wavelength.

Figure 14(b) shows the effect of viscosity. Increasing the viscosity leads to decrease in the ribbing wavelength.

Figure 14(c) shows the effect of the roll diameter. Increasing the roll diameter leads to an increase in the ribbing wavelength. These analytical results corresponded with the results of experiments.

It was found that these analytical results concerning the effect of the wet thickness, coating liquid property and roll diameter on the ribbing wavelength were similar to the results of the visualization experiments. Thus, these results clarified the fact that fluctuations of the ribbing wavelength in reverse roll coating can be predicted by using the linear perturbation method.

4. Conclusion

The behavior of a liquid film surface as it is transferred from a rigid steel roll to a deformable urethane covered roll was investigated in order to determine how the uniformity of reverse roll coating is affected by the speed ratio between two rolls, wet thickness, liquid viscosity and roll diameter. The conclusions are summarized as follows.

(1) The uniform coating region was expanded by decreasing the liquid viscosity.

(2) The uniform coating region could be arranged by the roll speed condition and capillary number Ca . In the case of reverse roll coating with a metal roll and rubber covered roll, only a stable region and ribbing region were observed.

(3) The ribbing wavelength shifted to the short-wavelength side under conditions of high roll speed, low wet thickness and high liquid viscosity.

(4) The roll diameter did not influence the stable region, but the ribbing wavelength became longer when the roll diameter was increased.

(5) The stability of the meniscus could be estimated by using a lubrication model and viscocapillary model, and it was possible to predict the ribbing condition.

(6) The analytical results of the ribbing wavelength were similar to the results of visualization. In the case of reverse roll coating, the variation of the ribbing wavelength could be predicted by using the linear perturbation method.

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