Analysis of slot coating flow under tilted die

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INTRODUCTION

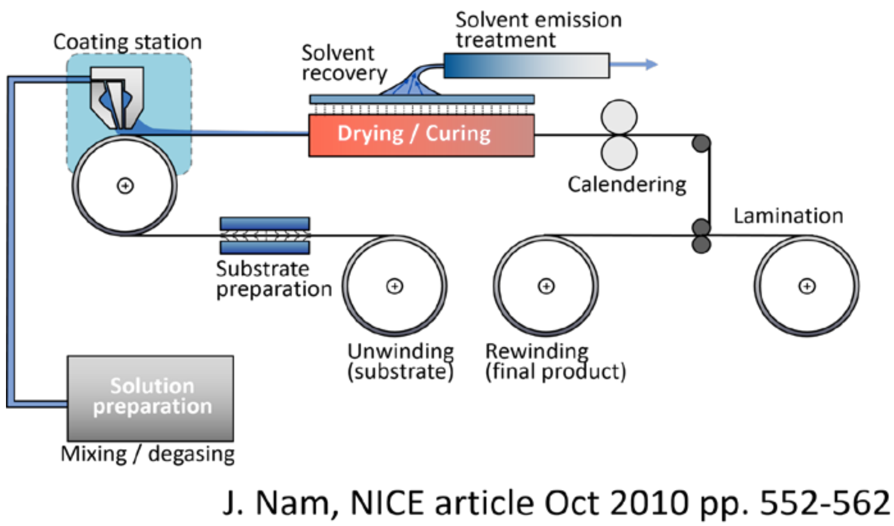

Figure 1. Schematic diagram of continuous liquid coating process

The continuous liquid coating process (Fig. 1) is the method of choice for manufacturing products such as adhesives, magnetic tapes, and optical films. When a highly uniform thin film is produced at a relatively high speed, slot coating is typically preferred (Fig. 2). The Slot coating is classified as a *pre-metered coating*, i.e. the final wet film thickness is precisely determined by the flow rate and the production speed and is independent of other process parameters.

For a successful coating, the coating flow need to be two-dimensional, steady-state and stable. The map with ranges of desirable operating conditions is called the *coating window*, and most steady-state coating flow analyses are performed to provide such windows. Rushack (1976) and Higgins and Scriven (1980) did theoretical research to create coating window. Recently, direct tracking method, which generates the window automatically, was developed by Nam at al. (2009) and applied to various slot coating system (Nam and Carvalho, 2010).

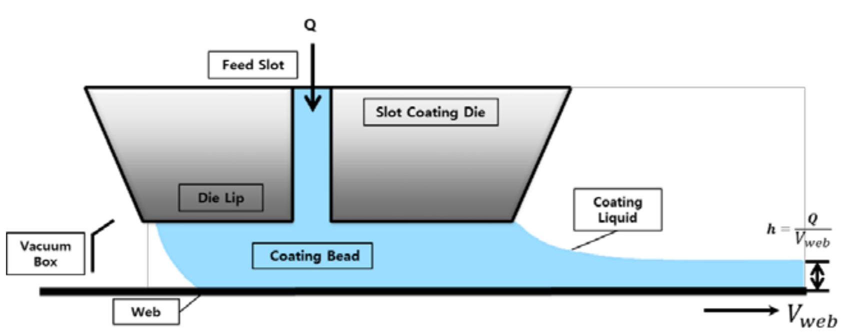

Figure 2. A schematic diagram of slot coating flow.

However, the coating flow is always surrounded by small-scaledisturbances generated by equipment which have rotating elements, suchas pumps, substrate-driving mechanisms, roll run-outs, *etc*. Because thickness and uniformity requirements of films becomesevere, effects of such small disturbances could be critical inmaintaining film uniformity. Therefore, the sensitivity analysis of coating flows under suchperiodic disturbance is important for minimizing film thickness variations. Although some researcher tried to do frequency response analysis experimentally (Joos, 1999), it is hard to select a target frequency that we want to test. Therefore, theoretical or computational methods are preferred. Tsuda et al. (2010) used a transient visco-capillary model to predict the flow response to periodic perturbations. Romero and Carvalho (2008) solved transient two-dimensional Navier-Stokes system.

Here, we performed frequency response analysis for the slot coating flow under the tilted die. This type of die layout is usually called the angle-of-attack configuration. Comparing with the normal layout that has parallel channels between the die lip and moving web, a slight inclined die lip can alter the pressure profile due to a lubrication effect. When the difference between the upstream and the downstream gap heights are considered, angle-of-attack configurations are similar to underbite/overbite configurations, which are classified as normal layouts. Therefore, it is worthwhile to examine in detail the effect of angle of attack to understand the pros and cons.

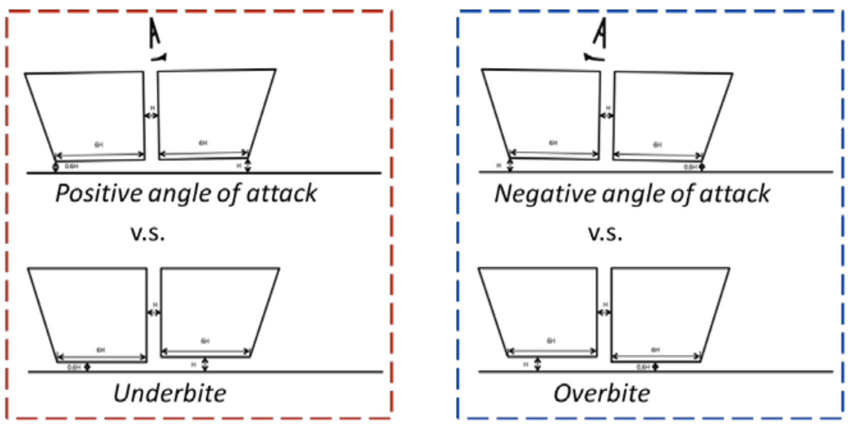

Figure 3 Tilted layout (positive and negative angle configurations) and normal layout (underbite and overbite configurations). They are grouped by comparable geometries.

RESULTS

Here, we consider two types of disturbances: flow rate and gap oscillations. To quantify thickness variations with respect to those perturbations, wedefine amplification factor:

$$\alpha_{\mathrm{q}} = \frac{h_{\mathrm{m}}/h_0}{q_{\mathrm{m}}/q_0}\text{for the flow rate oscillation;}\alpha_{\mathrm{H}} = \frac{h_{\mathrm{m}}/h_0}{H_{\mathrm{m}}/H_0}\text{ for gap oscillation,}$$

where q_0 is a steady-state flow rate, q_{m} is an amplitude of sinusoidal disturbance in flow rate oscillation, H_0 is a base gap height, H_{m} is an amplitude in gap oscillation, $h_0$is a steady-state wet film thickness and $h_{\mathrm{m}}$is an amplitude of thickness variation. Note that q_{m}/q_0 and H_{m}/H_0 are input oscillations for the computational modeland h_{m}/h_0 is a result of the analysis. These amplification factors represent how the input disturbances grow or decay inside the coating flow.

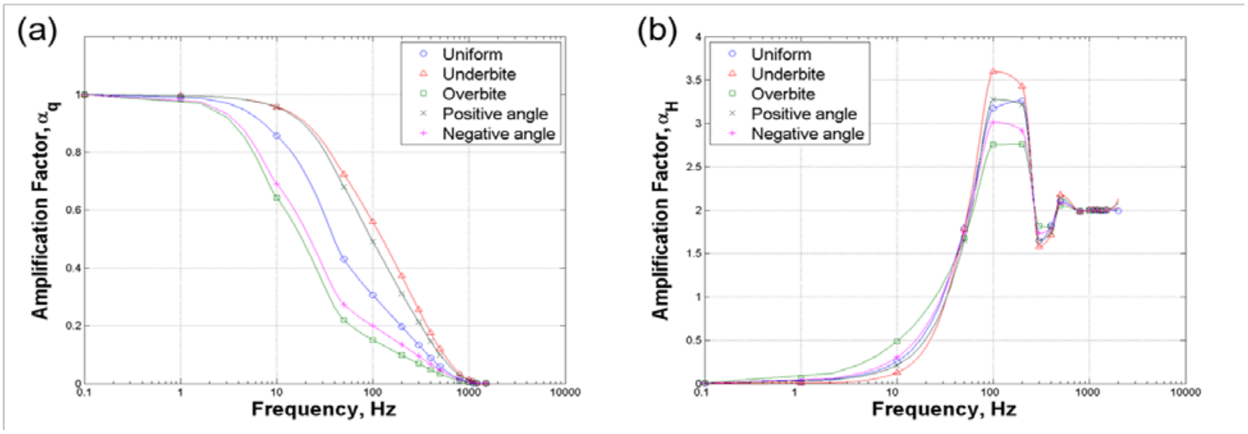

Figure 4 Amplification factor for flow rate oscillation (a) and gap oscillation (b) as a function of frequency.

FLOW RATE OSCILLATION

Figure 3(a) shows amplification factor for flow rate oscillation. This analysis was performed at $N_{\mathrm{Ca}} = \mu V_w/\sigma = 0.2$ (capillary number), $N_{\mathrm{Re}} = \rho V_w H_0/\mu = 1.33$ (Reynold number), $R_{\mathrm{gt}} = H_0/h_0 = 5$ (gap-to-film thickness ratio) and $q_{\mathrm{m}} = 0.05q_0$, i.e. 5% flow rate disturbance. To maintain the same upstream coating bead size, the dimensionless vacuum pressure $P_{\mathrm{vac}}^* = P_{\mathrm{vac}} H_0/\sigma$ is 13.33, 26.33, 21.87, 9.93 and 10.05 for uniform, underbite, positive-angle, overbite and negative angle configurations, respectively.

As mentioned in Romero and Carvalho (2008), both upstream and downstream menisci fluctuate to accommodate the surplus and deficit of coating liquid caused by the flow rate disturbance. They explained that the flow resistance under the upstream coating bead, which can be controlled by die configuration, affects the amplification factor.

In this study, we foundthat the amount of flow rates toward upstream, q_{u}, and downstream coating bead, q_{d} affect fluctuation of the upstream and the downstream menisci, respectively. Consequently, q_{u} is inversely proportional to the film thickness variation, whereas q_{d} is directly proportional to the variation. We found that the die lip configurations can change the amount of these flow rates and corresponding pressure gradient under die lips as well, which can eventually affects the film thickness variation.

GAP OSCILLATION

Frequency response analysis of the gap oscillation was performed at $N_{\mathrm{Ca}} = 0.2$, $N_{\mathrm{Re}} = 1.33$, $R_{\mathrm{gt}} = 2$ and $H_{\mathrm{m}} = 0.05H_0$, i.e. 5% gap disturbance. P_{vac}^* is 7.42, 20.33, 14, 3.83 and 5.08 for uniform, underbite, positive-angle, overbite and negative angle configurations, respectively.

The upstream and downstream menisci oscillate as the web approaches and move away from the die due to pressure field changes, as discussed in Romero and Carvalho (2008). Unlike the flow rate oscillation, the film thickness variation is determined from not only the downstream free surface oscillation, but also the vertical oscillation of the web. Figure 4 shows the film thickness variation at $f = 200$Hz: (a) shows maximum, middle and minimum outflow web location in a cycle and (b) shows the corresponding film thickness variation at outflow boundary. Note that free surface does not oscillate in phase with the web. Although the web approaches its maximum position in the cycle, free surface does not reach its maximum position. In this specific case, the motionof the free surface is almost opposite to that of the web: phase lag between two oscillations reaches π. This phase lagcauses large film thickness variation.

Amplification factor for gap oscillation is shown in Fig. 3 (b). As one can expect, amplification factor shows the highest value near 200Hz. But the trend of amplification factor with respect to different die configurations at high frequency is different to that at low frequency. This is because different die geometry shows different phase lag and amplitude of free surface oscillation as frequency increases.

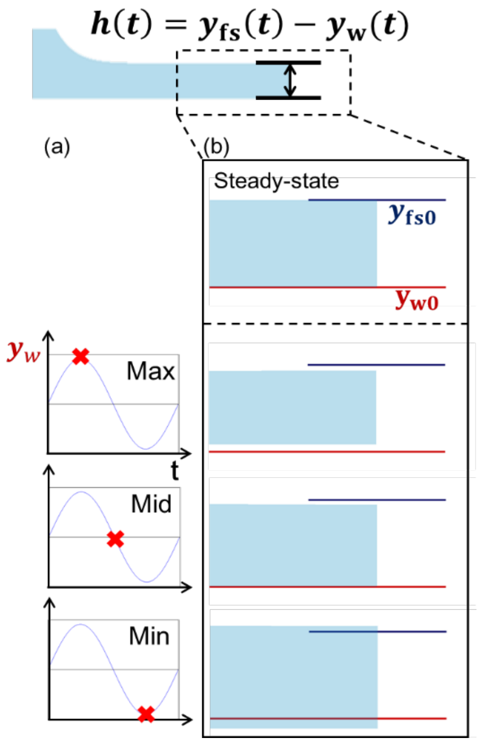

Figure 5 Location of oscillated web with time (input boundary condition) and response of free surface location at the outflow boundary (200 Hz)

CONCLUISION

In this study, frequency response analysis forvarious slot die configurations is doneto check the effect of die tilting. According to flow rate oscillation, additional pressure gradient due to sloped die lips from tilted slot die does not have strong effect on film uniformity. Therefore, one can achieve a similar effect of underbite or overbite configurationsby tilting slot die. To understand flow response to gap oscillation, the movements of the free surface and the web should be separately considered. The free surface oscillation response is similar to the flow rate oscillation. However,when both oscillations are considered, the effect of die configurations on the film thickness variations is different from the flow rate oscillation.

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