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Operability limits of slide coating

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ABSTRACT

Slide coating is one of the pre-metered methods used for high precision single and multilayer coatings. The thickness of each liquid layers is set by the flow rate and web speed only and it is independent of other process parameters. The uniformity of the deposited layer, however, is affected by the operating conditions. In the design of coating processes, it is crucial to know the set of conditions at which the deposited layer is adequately uniform, i.e. to define the operability window of the process. We developed a theoretical model of slide coating flow by solving the full two-dimensional Navier–Stokes equations and used it to uncover the mechanisms of coating bead breakdown at low vacuum, high vacuum, and low flow limits. With full understanding of the bead breakup processes, we then constructed a theoretical coating window as a function of coating thickness, web speed, and applied vacuum. A simple stability criterion was used to predict the onset of ribbing instability and deployed to add the onset of ribbing limit inside the coating window.

1. Introduction

Slide coating is commonly used in manufacturing of products that require precision single and multilayer coating, such as photographic films, magnetic storage media, and optical films in flat panel displays. The coating liquid is pumped to a coating die and exits through a narrow slot, ideally with a uniform flow rate per unit width. As sketched in Fig. 1, the liquid flows down an inclined plane before filling the gap between the die and the moving substrate to be coated. Unlike slot coating, the free surface that defines the interface between the surrounding air and the coated liquid layer is not confined; it stretches all the way from the static contact line near the feed slot exit. The competition among viscous, capillary, gravitational and pressure forces, and in some cases inertial and elastic forces, sets the range of operating parameters in which the viscous free surface flow of the liquid can be two-dimensional and steady, which is the desired state.

The thickness of each layer can be precisely controlled due to the pre-metered nature of the process, it depends solely on the flow rate delivered to the slide die and the speed of the substrate or web, and it is independent of other process conditions and liquid properties. The uniformity of the layers, however, can strongly depend on the process conditions. Understanding how coating flows respond to a set of operating condition and liquid properties is essential in producing defect-free coating. The range of operating conditions in the parameter space at which the product is within uniformity specification is usually referred to as coating window.

Like in slot coating, many process limits of slide coating come from flow instabilities in the coating bead region. The operating parameters that define these flow limits set the boundaries of the process coating window. As discussed by Carvalho and Kheshgi (2000), low flow limit is the most relevant critical condition in pre-metered coating of low viscosity liquids. It is defined to be the minimum thickness that can be achieved at a given coating speed or the maximum coating speed that can be achieved at a given coating thickness. Most of slide coating windows reported in the literatures came from experiments. Tallmadge et al. (1979) reported experimental values of lower and upper coating speed limits under different flow rates, gap widths and viscosities. They did not apply vacuum underneath the coating bead, which limited the applicability of their results to industrial coating operations. Gutoff and Kendrick (1987) improved the analysis by incorporating vacuum in their studies of slide coating operability limits at different viscosities and gap widths. They demonstrated that thinner coating can be achieved when vacuum is applied underneath the bead. Chen (1992) reported experimental values of vacuum limits at different coating thickness, but he did not investigate low flow limits.

Before the coating bead breaks into stripes of coated and uncoated substrate, known as rivulets, the flow may become unstable with respect to periodic cross-web disturbances, leading to a defect called ribbing. Hens and Abbenyen (1997) determined experimentally the critical operating conditions at the onset of

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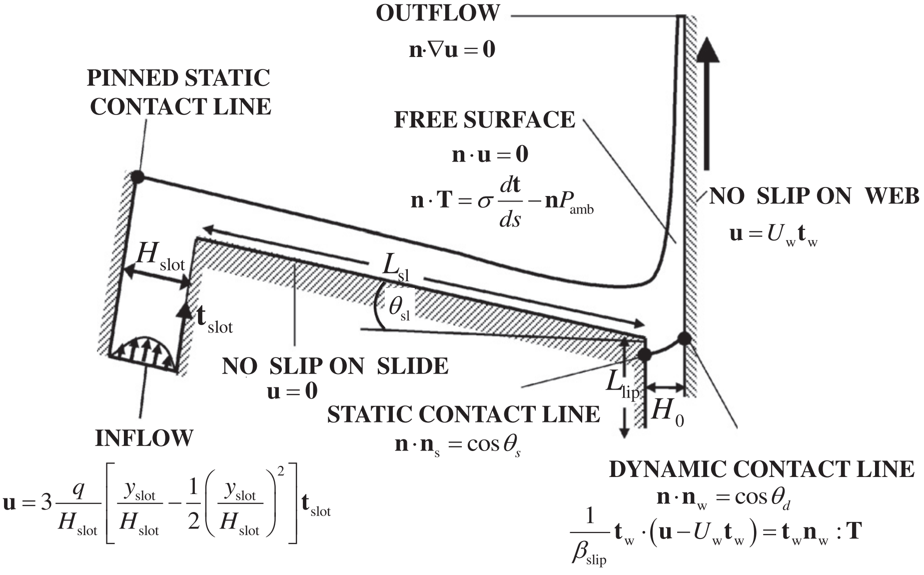

Fig. 1. Two-dimensional model of slide coating.

ribbing and rivulets. Schweizer and Rossier (2003) expanded the range of parameters explored in the previous work to high speed coating. They showed that, like in slot coating (Carvalho and Kheshgi, 2000), at a range of operating conditions, the minimum thickness for uniform coating can be lowered by raising the web speed. Expanding the coating window to thinner coating and faster web speeds is the goal of many coating researches. Lin et al. (2005) explored the possibility of combining slot and slide coating in order to achieve two layer coating with a thin top layer.

Even if the flow is two-dimensional and the coated layer uniform, recirculations in the coating bead may lead to coating defects. The center of vortices tend to collect small particles and bubbles that eventually get discharged in the final product. Therefore, knowing the conditions at which recirculations are present is also very important in the design of robust processes. Schweizer (1988) improved visualization technique of coating flows with the use of dye and hydrogen bubbles and he was able to capture streamlines and vortices in slide coating flow. With those tools, he was able to report critical flow rates corresponding to the onset of vortex birth at the downstream meniscus at a given coating speed.

Most of the previous studies discussed above did not study in detail the different coating bead breakup mechanisms. Theoretical modeling allows for fundamental understanding on how the coating bead breakup occurs and for the theoretical predictions of the critical conditions associated with each one of them.

Advances in theoretical modeling of coating flow, especially in slide coating, has been made by Christodoulou and Scriven (1989). They solved the full two-dimensional steady Navier–Stokes with the Galerkin finite element method. However, due to high computation cost in that time, they only made few excursions in the parameter space and therefore, did not perform systematic exploration to study operability limits. The goals of this work are to study the mechanisms of slide coating failures and defect formation and to predict critical operating conditions corresponding to the onset of those failures. Effects of gap width, slide inclination, and die-lip geometry were investigated.

2. Mathematical model

Successful coating operation requires the flow to be steady, two-dimensional except at the edges, and stable to small disturbances. Therefore, the appropriate mathematical model used to describe the flow in the coating bead is laminar, steady state, two-dimensional Navier–Stokes equations with the appropriate boundary conditions for free surface flows with contact lines. The mathematical formulation and solution method used here are similar to those used by Christodoulou and Scriven (1989). It is briefly summarized here.

2.1. Governing equations and boundary conditions

The die configuration and flow domain considered in this analysis is shown in Fig. 1. The slide length was $L_{sl} = 20$ mm, its inclination with respect to the horizontal plane was $\theta_{sl}=10^\circ$, the die-lip length was $L_{lip}=5$ mm and the coating gap, $H_0=0.3$ mm. The laminar, steady state, two-dimensional Navier–Stokes equation system that governs liquid flow in slide coating is

$$\rho\mathbf{u}\cdot\nabla\mathbf{u}=\rho\mathbf{g}+\nabla\cdot\mathbf{T} \quad \text{and} \quad \nabla\cdot\mathbf{u}=0, \tag{1}$$

where ρ is the liquid density, $\mathbf{g}$ is the gravitational acceleration, $\mathbf{T}=-p\mathbf{I}+\mu[\nabla\mathbf{u}+(\nabla\mathbf{u})^{\mathrm{T}}]$ is the total stress tensor, p is the pressure, and μ is the liquid viscosity.

The conditions at each flow boundary sketched in Fig. 1 are:

1. *Inflow: fully developed velocity profile.* At inflow boundary with width of H_{slot}, a parabolic velocity profile is imposed

   $$\mathbf{u}=3\frac{q}{H_{\text{slot}}}\left[\frac{y_{\text{slot}}}{H_{\text{slot}}}-\frac{1}{2}\left(\frac{y_{\text{slot}}}{H_{\text{slot}}}\right)^2\right]\mathbf{t}_{\mathbf{slot}}, \tag{2}$$

   with specified volumetric flow rate per unit width q.
2. *Slide and web surfaces: no slip, no penetration.* $\mathbf{u}=\mathbf{0}$ at slide surface and $\mathbf{u}=U_{\text{w}}\mathbf{t}_{\text{w}}$ at the web surface, where U_{w} is the web speed and the $\mathbf{t}_{\text{w}}$ is the unit vector tangent to the substrate in the flow direction.
3. *Free surface: force balance and kinematic condition.*

   $$\mathbf{n}\cdot\mathbf{T}=\sigma\frac{d\mathbf{t}}{ds}-\mathbf{n}P_{\text{amb}} \quad \text{and} \quad \mathbf{n}\cdot\mathbf{u}=0. \tag{3}$$

   σ is the liquid surface tension, s is the arc length coordinate along the free surface, and P_{amb} is the ambient pressure, set to zero at the top free surface and to a sub-ambient pressure (vacuum pressure) at the bottom free surface.
4. *Static and dynamic contact lines.* The static contact line at the feed slot exit is pinned at the corner of the elevated block