Drying-induced surface deformation of coatings on a moving web

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Capillary and/or gravitational forces tend to reduce uneven surface topographies, whereas the viscous stress opposes the leveling The previous modeling examples for isothermal coatings include the deformation of polymeric solution layers on horizontal [1] and curved [2] substrates, crater defect [3] formations in drying layers, the leveling of multiple stratified layers [4] and that in shear thinning fluids [5].

In non-isothermal coatings, liquid layers are subject to thermo-capillary stresses that drive a flow from a low surface tension region to a high surface tension region. When the surface tension is a decreasing function with respect to the temperature, a localized heating at a trough drives fluids away from the depressed region and further deepens the trough against the pressure-driven leveling. The competing feature between the surface-tension-driven and leveling flows often leads to a characteristic surface deformation in volatile polymeric solutions [6], and in the presence of a surfactant monolayer [7]. However, most of the previous work has been restricted to the thermo-capillary instability in non-uniform but steady temperature variations. In this article, we consider a temperature profile that travels along the gas/liquid interface at a constant speed. Because the surface tension gradient can change its sign as the temperature profile moves, the resultant thermo-capillary stress can thin and thicken the liquid layer with time in a complicated manner, leading to an inherently different film evolution compared to that in steady temperature fields.

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In order to make the idea concrete, we will consider an industrial air-impingement drying process of a volatile, Newtonian liquid layer on a horizontal substrate as shown in Figure 1. The air impingement from a slit nozzle promotes a localized higher solvent evaporation rate, and thus a cooler surface temperature at the impinging point. As the substrate moves at a constant speed, the temperature variation travels in the opposite direction to the moving coating and promotes a surface deformation via the thermo-capillary effect. Here we derive the governing equations for describing the drying-induced surface roughness formation based on the simple lubrication theory, and discuss how the traveling temperature profile influences the characteristic growth and decay in surface topography.

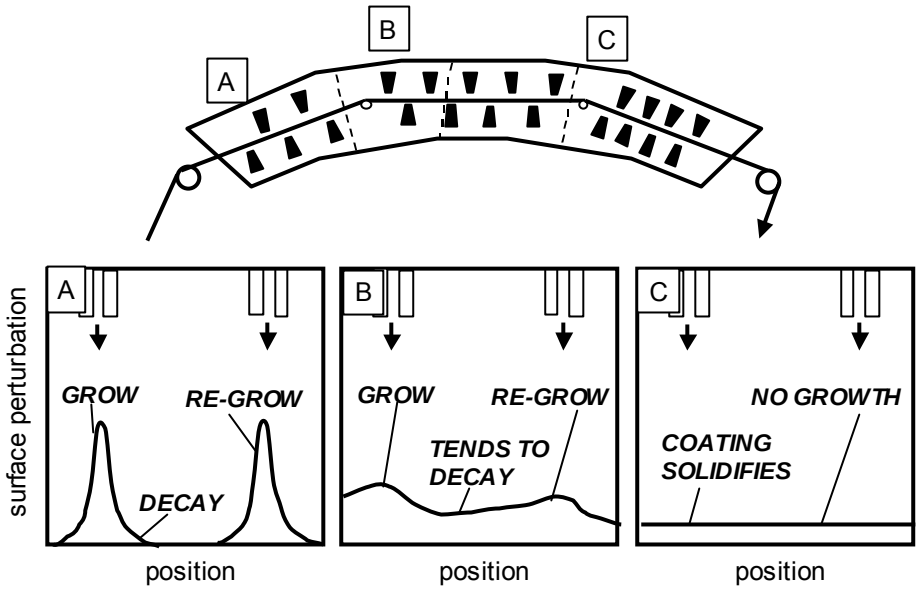

Fig. 1 Schematic diagram of roughness growth in drying oven

Consider a thin liquid film of incompressible Newtonian polymeric solution of viscosity μ coated with a uniform thickness of h on a horizontal substrate. The deformable air-liquid interface locates at $z=h(x, t)$ where z and x are the Cartesian coordinates in the thickness and transverse directions, respectively. The velocity distribution within the film is defined as $u(x, z)$ with origin on the film–substrate interface. Using a linear approximation for the surface tension with respect to temperature, we obtain $\sigma=\sigma_0-\gamma\,(T-T_0)$,

where T_0 and σ_0 denote the reference temperature and surface tension. The surface tension gradient, χ, is a positive constant in the temperature range of interest. Using the lubrication approximation and neglecting inertia and gravity, and assuming a small topographic change in the surface profile yields a non-linear evolution equation for the film thickness h as:

$$\frac{\partial h}{\partial t} = -\frac{\partial}{\partial x}\left[\frac{h^3}{3\mu}\frac{\partial}{\partial x}\left(\sigma\frac{\partial^2 h}{\partial x^2}\right)+\frac{h^2}{2\mu}\frac{\partial \sigma}{\partial x}\right] - Ev. \qquad (1)$$

where the third term on the right hand side represents the layer shrinkage due to the solvent evaporation and simply expressed as the product of the mean specific volume of the layer, $v(t)$ [m^3/kg], and the evaporation rate of the solvent, $E(t)$ [kg/(m^2·s)]. The film evolution is opposed by the viscous shear stress, which increases with the liquid viscosity as the solvent evaporates. For simplicity, we assume that the viscosity is taken to depend exponentially on the polymer mass fraction, C, as:

$$\ln(\mu / \mu_0) = mC + n, \qquad (2)$$

where μ_0 , m and n denote the pure solvent viscosity and the power law index, respectively. The surface temperature is given by the energy balance across the gas/liquid interface. Calculations given here use a uniform mesh with 200 intervals along the gas/liquid interface. In order to simulate the film evolution on a moving substrate, the temperature profile was numerically moved at each time steps in the opposite direction to the coating motion. The temperature traveling to the neighboring grid point was conducted at a constant speed, U, ranging between 0 m/s and 0.9 m/s. The film evolution Eq. (1) was discretized and solved using the finite difference method. In order to ensure the numerical stability, the fully explicit scheme with sufficiently small time steps of 10^{-7}s was used for the time integration.

The growth/decay in asymmetric surface topography is one of the major interesting features for the film evolution induced by the travelling temperature profile. Figure 2 shows the distributions of the surface temperature and layer thickness along the gas/liquid interface. The surface temperature travels at a constant speed of U=0.5 m/s as the coating

moves in the positive *x* direction. The computed temperature profile involved two distinct regimes: a flat plateau near the stagnation point and positive/negative gradients in the wall jet region. The resulting local thickness variation was found to exhibit a ridge in downstream and a depression in upstream, showing a particular asymmetric surface topography.

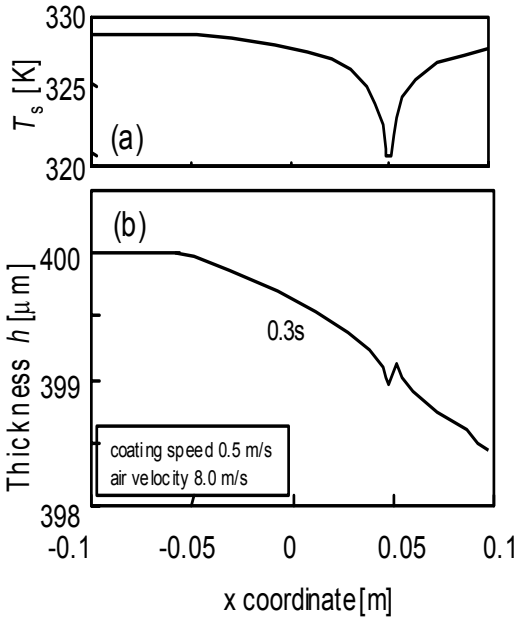

Fig. 2 computed temperature/thickness profiles

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