On tail formation during gravure printing of electronics

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Kitsomboonloha *et al*. [1] study experimentally the deposition of femtolitre droplets by the gravure method. The substrate (gravure plate) passes under a stationary blade. Liquid placed on the substrate upstream of the blade fills the engraved wells as they enter the blade-substrate gap. Motion of the substrate beneath the blade removes excess ink, leaving liquid-filled wells. The resulting pattern can then be printed. But the sharpness of the printed pattern is limited because, as the well leaves the blade, some liquid is subtracted from the well and deposited on the substrate. The authors propose that these 'tails' form by a 3-dimensional mechanism, involving lateral wicking along the apparent contact line between the blade and substrate. By contrast, we show that tails will form even in plane flow. To do so, we analyse the behaviour for low capillary number (Ca). We assume the interface to be pinned at the leading edge A of the well. This is a good approximation if the thickness of the residual film *ahead* of the well is small compared with the well depth.

During stage I (Fig. 1, meniscus rise), the well emerges from beneath the blade. Because Ca is small, the interface is, to a first approximation, the circular arc passing through point A, making a given contact angle θ on the blade, and satisfying an obvious equal area constraint (areas above and below line OA are equal). In this hydrostatic approximation, the only length scale is the distance |OA|, and geometric similarity requires the meniscus rise height on the blade to be proportional to |OA|. The interface remains a circular arc until viscous effects modify the pressure.

As a first step to understanding the effect of viscosity, we have considered the idealized case in which θ is close to 90 degrees. Lubrication theory can now be used to derive an evolution equation governing the entire film. Solving this equation numerically shows that stage I ends when the trailing edge of the well approaches the interface, isolating the liquid between the blade and trailing edge from the well.

In stage II, this liquid is deposited onto the substrate, forming the tail (Fig. 1, tail formation). Because, at the end of stage I, a finite volume of liquid has been isolated, the tail thickness must ultimately vanish *far behind* the well; because the film thickness is also negligibly small *at the trailing edge* of the well, the function describing the interface height has two zeros as a function of distance along the substrate; such a function necessarily has a maximum. Numerical integration of the evolution equation confirms this explanation. Scaling of the evolution equation shows that tail length increases as Ca is reduced; as θ is reduced from 90 degrees, the tail also grows because the area under the meniscus at the end of stage I is increased. These results from analysis are consistent with the experimental observations.

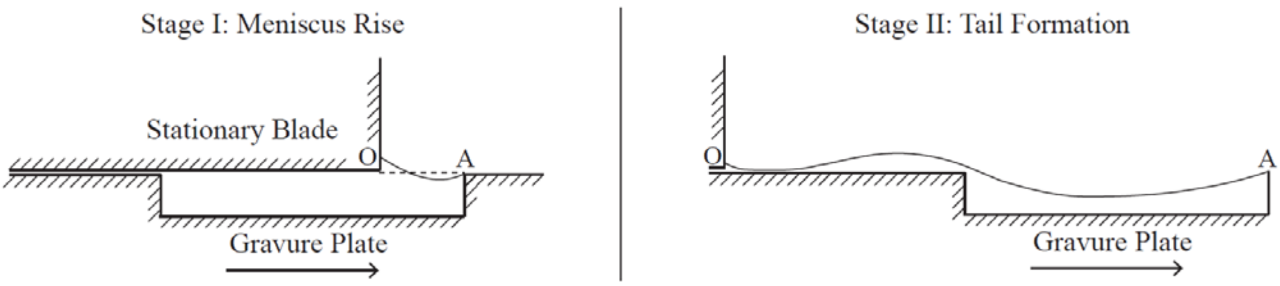

Fig. 1: Tail formation mechanism.

Our analysis suggests several related problems in lubrication theory. It also shows that at finite Ca, tail formation can be studied as a problem in plane, rather than 3-dimensional, Stokes flow.

References

1. R. Kitsomboonloha, S. J. S. Morris, X. Rong and V. Subramanian, *Langmuir*, **28**, 16711-16723 (2012).