Fundamentals of Directional Spreading of Lubricants over Multi-Scale Textured Surfaces

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1. Motivation and introduction

The following physical factors essentially govern free-surface flow of lubricants over solid substrates, commonly and with satisfactory accuracy treated as incompressible creeping flows: their rheological behaviour dictating viscous friction, here taken as strictly Newtonian, external body forces such as gravity and/or a centrifugal force, the macroscopic contact angle (i.e. on the continuum scale) and surface tension. Whilst the latter aids to keep the lubricant in the intended region of application, temperature gradients, either imposed externally and/or produced by friction, can result in the Marangoni effect that tends to drive the lubricant out of the frictional region. To counter this problem, identifying and controlling the governing forces involved in promoting or impeding lubricant migration in engineering applications becomes decisive. To achieve this goal, we focus on the influence of surface micro-texturing. However, the arising complex physics is still poorly understood and a successful flow control not mastered yet. We build on our previously gained experience and expertise in devising an effective “lubricant guidance” as an engineering challenge by surface texturing [1] to study in-depth the physical mechanisms that govern the wetting and spreading properties of lubricants as a (bio-inspired) multi-scale phenomenon.

A typical application is the control of oil rings formed by the interplay of capillarity and centrifugal forces at the suitably textured faces of the bush of journal bearings. More tentatively, one could consider to minimise the consumption of oil during the long-term operation of reciprocating piston compressors via its controlled storage on the textured liner outside the piston and rider rings. More generally, accomplishing the controlled storage of lubricants in the unloaded environment of tribological contacts requires the provided fundamental understanding of the migration process. These demands point to the formidable challenges of “green tribology” as an upcoming key thrust in the tribological research.

Our approach is a threefold one:

(i) We carry out experiments resorting to novel sensing methods to measure the propagation of the liquid height and the contact angle;

(ii) here we adopt texturing patterns produced by laser cutting of previously unmatched fineness;

(iii) a theoretical and numerical analysis based on rigorous methods of scale separation accompanies the experimental effort so as to complete existing the semi-rational flow descriptions.

As the ultimate overall goal, the theory shall predict the migration of a droplet on a textured substrate with experimentally verified fidelity, at least for times where the typical thickness of the liquid layer is still much larger than the depths and widths characteristic of the micro-texturing. We subsequently give a brief synopsis of the achieved first results; specifically, some benchmark measurements under isothermal conditions and their targeted confirmation by dimensional analysis.

2. Experiments

Our novel experimental setup to optically measure the shape of a droplet spreading under gravity in time is first validated for stationary droplets on a smooth untextured surfaces. Here the measured and theoretical results [2] are in exceptionally good agreement. Figure 1 shows perfectly axisymmetric shapes of these droplets by evaluation of the approximate theory, solely parametrised by the Bond number $B = \rho g L^2/\gamma$, (ρ: density, g: gravitational acceleration, L: characteristic length scale, initially given by the largest radius of the cross-section, γ: surface tension); figure 2 displays the comparison with the measurements. These form the initial conditions for the migration.

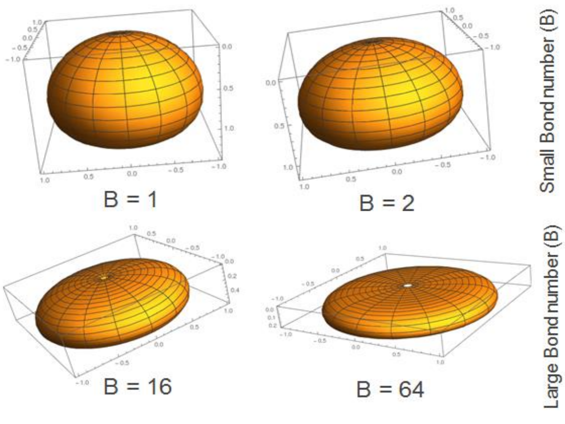

Figure 1 Shapes of sessile droplet as predicted by the asymptotic theory for large and small Bond numbers B

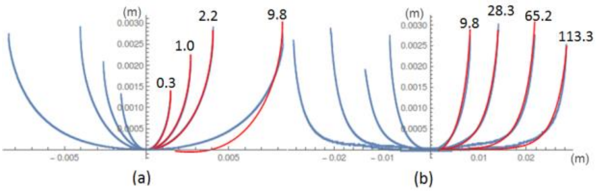

Figure 2 Measured (blue) and theoretically predicted (red) shapes of a stationary droplet (apex at the origin, gravity acting upwards): asymptotic results for (a) very small and (b)very large B (measured values indicated)

Figure 3 presents a snapshot of the initial spread of a 10-µl droplet of Polyalphaoelifin on a textured substrate with unidirectional ribs of square cross-section.

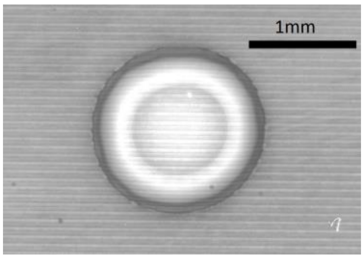

Figure 3 Droplet over a textured substrate consisting of horizontal ribs of 2µm x 2µm spread 100µm apart

Accordingly, the shape of a droplet for two different times ($t = 0$, $t = 75$ s) is shown in figure 4(a). The droplet becomes more and more asymmetric as it is elongated in the direction of the ribs by viscous forces whereas capillarity tends to maintain the initial shape. The *asymmetry*, i.e. the ratio of the major- (*length*) to the minor-axis (*width*) of an ellipse fitted to the experimentally extracted shape, is plotted over time in figure 4(b). Its initially nearly linear growth is clearly visible.

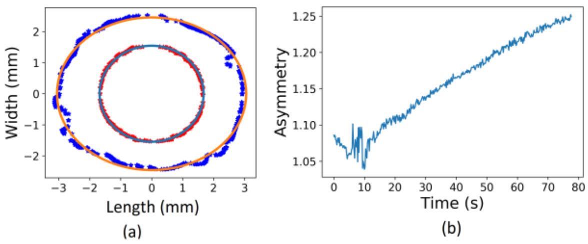

Figure 4 (a) Measured shape of droplet at t = 0 s (red dots) and t = 75 s (blue dots) superposed over fitted ellipses (red solid lines); (b) temporal variation of asymmetry (fluctuations at the initial stage are due to uncertainty in measurements)

3. Theory: dimensional considerations

A Stokes problem entered by body forces describes the lubricant flow. Its physical properties are taken as uniform, apart from the temperature-dependence of the surface tension. In turn, the kinematic and dynamic boundary conditions met at the free surface introduce respectively its unsteadiness, the capillary pressure jump and the Marangoni shear stress. For a stationary droplet, the solid-liquid interface is uniquely described by B and the static wetting angle. However, it differs distinctly from the dynamic one, α, observed on the macroscopic length scale due to the propagation of the contact line over a textured surface. In a first step, Cassie‘s classical rule in the limit of the Wenzel state, i.e. under the neglect of air pockets trapped within the microscopic surface topography (Cassie–Baxter state), provides the dynamic contact angle as a boundary condition and sole semi-empirical input.

The crucial questions are whether and how a droplet of a certain volume attains a steady state, independent of the initial conditions of its release at the substrate. However, a first comparison with experiments suggests dimensional analysis as the proper means, giving the generic dimensionless relationship

$$R(t)/L = f(B, C, L/l, \alpha), \quad C = L\mu/(t\gamma). \qquad (1)$$

Herein t denotes the time, $R(t)$ the mean distance from the center of the initial shape, C a capillary number, i.e. $1/C$ the dimensionless time, and l a microscopic length scale characteristic of the texturing. If $B >> 1$ and the droplet is relatively large as in our measurements and t being so large that the viscous flow is no longer reminiscent of its initial stage, (1) implies the law $R/t \sim a(\alpha)\gamma/\mu$ (a: universal function), confirming the linear dependence seen in figure 4(b). Contrarily, the increasing flattening of the droplet and action of capillarity casts (1) into a modified Lucas–Washburn law at later stages: $R^2/t \sim b(\alpha)\gamma l/\mu$ (b: universal function); cf. [1].

4. Further outlook

The ongoing steps include a rationally founded identification of four stages in the temporal evolution of the lubricant patch, an improved model governing the dynamics of the contact line (cf. the recent full simulations [3,4]) and how the flow in a sublayer adjacent to the substrate of vertical extent l controls the bulk flow (method of matched asymptotic expansions).

5. Acknowledgements

This work was supported by the Austrian Comet program (Project XTribology, no. 849109) and by the concerned program management institutions, viz the Österreichische Forschungsförderungs-Gesellschaft mbH, on behalf of the Federal Government, as well as by the Government of Niederösterreich, Wien, and Vorarlberg.

6. References

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