Drop friction on liquid-infused materials

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Supplementary information

We provide in this section complements to the main text, supplementary experiments, and captions for the four accompanying movies.

1. Description of our surfaces

Our surfaces were obtained using SU8 photolithography, resulting in regular arrays of square pillars, as sketched in figure 1 and shown in table 1. In the table, we also provide the geometrical characteristics of the samples, together with the tilt angle α^* above which a water drop with volume Ω = 20 μL moves. These values are given for smooth pillars filled with a silicone oil of viscosity 10 mPa.s. For nano-rough pillars (Glaco treatment), the angle α^* cannot be measured ($\alpha^* \approx 0$) whatever the pillar density ϕ.

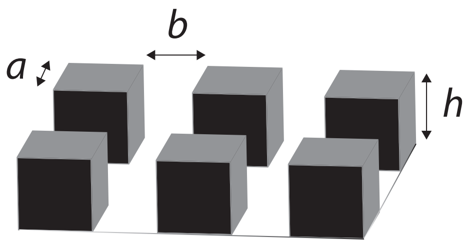


Figure 1. Sketch of our textures, and definition of the geometrical parameters.

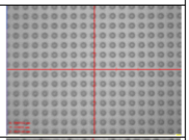
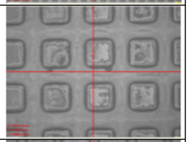
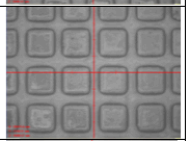
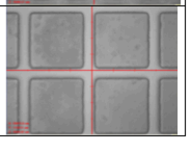
	a (μm)	b (μm)	h (μm)	ϕ	α^*	
1	18	15	18	23%	15°	
2	90	60	22	36%	23°	
3	90	35	22	52%	30°	
4	185	40	23	67%	40°	

Table 1. Pillar dimensions, as defined in figure 1. ϕ designates the pillar density ($\phi = a^2/(a+b)^2$) and α^* is the tilt angle above which a water drop with volume $\Omega = 20\ \mu$L moves once the texture is filled with silicone oil. Its value is given here only for smooth pillars (on rough pillars, we get $\alpha^* \approx 0$). The last column shows top views of the samples obtained by profilometry (Veeco, Wyko NT9100).

2. Measurement of the drop position and speed

Water drops ($\Omega = 20\ \mu$L) are placed on a sample tilted by an angle α larger than α^*. Positions X are deduced from high-speed movies shot from the side, after 5 cm of descent. The velocity is observed to be constant, and its value is extracted from the derivation of the curve $X(t)$, as shown in the example displayed in figure 2.

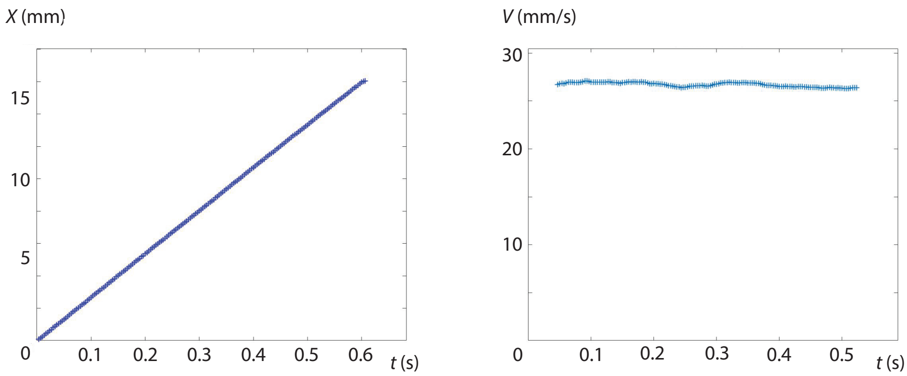


Figure 2. Position X and speed V of a drop (Ω = 20μL, η_w = 3 mPa.s) descending a lubricant-impregnated surface (smooth pillars, ϕ = 23%, η_o = 50 mPa.s) tilted by an angle α = 40°, as a function of time. The movie is recorded at 800 fps. Despite the high value of the velocity, the regime of descent is observed to be stationary.

In order to test the repeatability of the experiment and to check that the passage of a drop does not modify the substrate (by extracting its oil), we measured the velocities of large series of drops (up to 50) dropped every 5 seconds at the same place of a tilted sample (with ϕ = 23% and η_o = 100 mPa.s), and following the same trajectories. As shown in figure 3 for low and high drop viscosities (η_w = 2 mPa.s and η_w = 500 mPa.s), the velocity is observed to remain roughly constant as a function of the drop number.

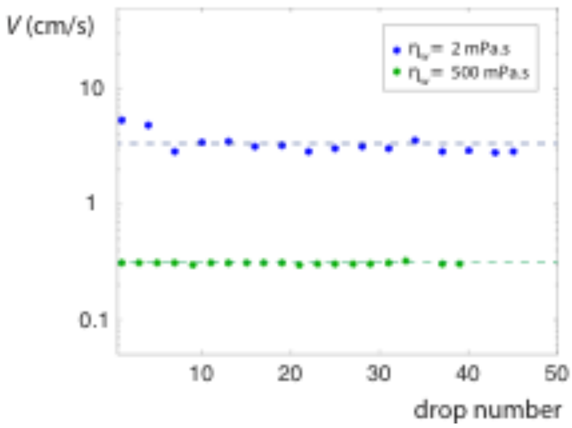


Figure 3. Series of water/glycerol droplets (Ω = 20µL) with low viscosity (η_w = 2 mPa.s, blue) or high viscosity (η_w = 500 mPa.s, green) and separated from each other by roughly 2 cm on a sample (with ϕ = 23% and η_o = 100 mPa.s) tilted by α = 40°. The speed of the drops is hardy affected by the repetition (apart from the very first non-viscous drops).

3. Further experiments in the stationary regime of descent

As shown in the main text (figure 3d), a unique equation can capture the speed for different viscosities of water and glycerol for drops running down a plate inclined by 40°. To check the robustness of our model, we also did some experiment at lower (α = 20°) and higher (α = 65°) tilting angle, on a surface with solid fraction ϕ = 23% and critical roll-off angle α^* = 15°. Results are shown in figure 4, where data are compared with the velocity obtained by balancing the effective gravitational force $\rho\Omega g$ ($\sin\alpha - \sin\alpha^*$) with the sum of oil and water frictions given by eqs. 2 and 3, with respective coefficients 13 and 11. This unique set of adjustable parameters is found to describe the whole set of data in a satisfactory way, with speeds varying by more than two orders of magnitude.

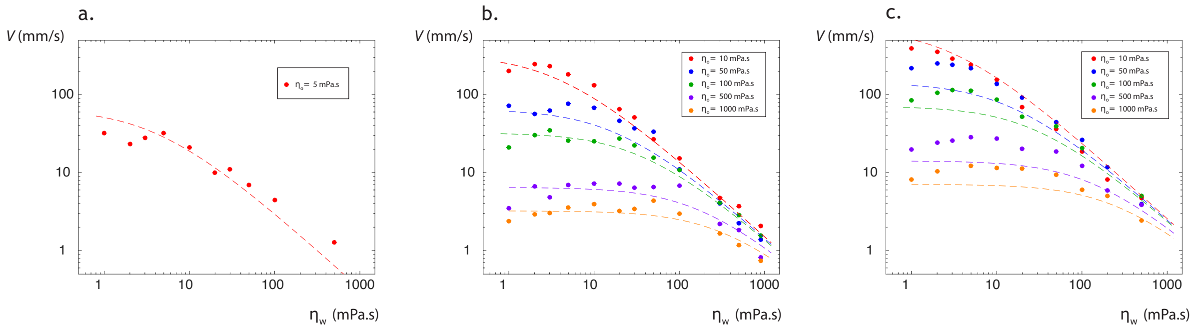


Figure 4. Speed V of descending drops (Ω = 20μL, ϕ = 23%) as a function of their viscosity η_w for tilting angle **(a)** α = 20°; **(b)** α = 40°; **(c)** α = 65°. Coloured dotted lines are obtained by balancing the effective gravitational force $\rho\Omega g$ (sinα – sinα*) with a friction of the form $13F_o + 11F_w$, where the oil and water frictions F_o and F_w are given by eqs. 2 and 3.

The main discrepancy observed between the fits and the data corresponds to high water viscosity and low slope (figure 4a), that is, low speeds on a non-viscous lubricant. This might be linked to the fact that the slip number σ in this regime becomes non-negligible, which leads to underestimate the speed. At high angle (figure 4c), data are well fitted at high viscosity η_w, but deviate at low η_w – the case where the model underestimates the speed, as discussed in the main text (figure 1e at large slope).

Some complementary remarks may be done on the shape of moving drops. When speed is small enough, the drop keeps a quasi-hemispherical shape. Yet, we observe that the angles for fast drops deviate from their static values (figure 5). This slight change of shape is not taken into account in the models, since it should modify neither the scaling law for the viscous dissipation inside the drop nor the oil meniscus dissipation.

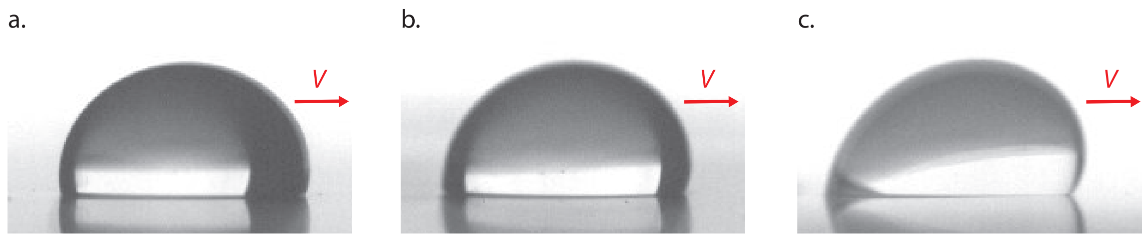


Figure 5. Shape of a 20μL-drop (η_w = 2 mPa.s) descending a lubricant-impregnated surface (ϕ = 23%, Glaco treated and infused with silicone oil of viscosity η_o = 100 mPa.s). The surfaces are tilted by α = 5° (a), α = 15° (b) and α = 40° (c), which yields respective velocities of 1.4 mm/s, 7.8 mm/s and 45 mm/s. The camera is tilted by the same angle as the plate, which explains the apparent horizontality of the experiment.

4. Captions for the supplementary movies

We provide four videos of drops going down incline planes, corresponding to the three regimes and to figure 1b in the main text. Movies 1, 3 and 4 are shot using Glaco-treated surfaces. In all cases, the camera is tilted by the same angle as the plate.

Movie 1: Three drops of a water-glycerol mixture ($\Omega = 20$ µL, $\eta_w = 2$ mPa.s) on a surface textured by pillars with height 20 µm, size 18 µm, and spacing 15 µm. The surface is impregnated with a silicone oil ($\eta_o = 100$ mPa.s) and tilted by an angle $\alpha = 2.5°$. The movie is accelerated by a factor two. The speed of the three drops is found to be uniform and equal to $V = 0.5$ mm/s. In this regime ($\eta_o >> \eta_w$), friction mainly occurs in oil and it is assumed to take place in the oil meniscus bounding the drop (eq. 2).

Movie 2: Drop of a water-glycerol mixture ($\eta_w = 3$ mPa.s) on a surface textured by smooth pillars with height 20 µm, size 18 µm, and spacing 15 µm. The surface is impregnated with silicone oil of viscosity $\eta_o = 50$ mPa.s and tilted by an angle $\alpha = 20°$ (slightly larger than the critical angle of roll off). The movie is in real time. The speed of the drop is $V = 1.2$ mm/s.

Movie 3: Drop of a water-glycerol mixture ($\Omega = 20$ µL, $\eta_w = 500$ mPa.s) on a surface textured by pillars with height 20 µm, size 18 µm, and spacing 15 µm. The surface is impregnated with silicone oil ($\eta_o = 10$ mPa.s) and tilted by an angle $\alpha = 4°$. The movie is accelerated by a factor two. The speed of the drop is $V = 0.8$ mm/s. In this regime ($\eta_w >> \eta_o$), friction mainly occurs in the drop (eq. 2).

Movie 4: Drop of a water-glycerol mixture ($\Omega = 20$ µL, $\eta_w = 2$ mPa.s) on a surface textured by pillars with height 20 µm, size 18 µm, and spacing 15 µm. The surface is impregnated with silicone oil ($\eta_o = 100$ mPa.s) and tilted by an angle $\alpha = 70°$. The movie is slowed down ten times. The speed of the drop is $V = 120$ mm/s. In those conditions, dissipation still occurs in the oil, but is not dominated in the wedge of oil anymore.