Trapping Leidenfrost Drops with Crenelations

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Drops placed on very hot solids levitate on a cushion of their own vapor, as discovered by Leidenfrost. This confers to these drops a remarkable mobility, which makes problematic their control and manipulation. Here we show how crenelated surfaces can be used to increase the friction of Leidenfrost drops by a factor on the order of 100, making them decelerate and be trapped on centimetric distances instead of the usual metric ones. We measure and characterize the friction force as a function of the design of the crenelations.

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For a water drop moving on a plate, adhesion and friction are generally related to contact angle hysteresis and dissipation at the contact line [1]. Suppressing the contact line drastically modifies the picture, and liquids on superhydrophobic solids can run (or roll) typically 100 times faster than on conventional solids [2,3]. The situation is even more spectacular with Leidenfrost drops, which make strictly no contact with their support: The substrate is at a temperature much higher than the boiling point of the liquid, so that a cushion of vapor sets between the drop and the solid, which fully suppresses hysteresis and line dissipation [4–7]. The thickness h of the film on which levitation takes place is typically 100 μm [8]. Because of this film, the friction is especially low. A drop of a few millimeters of liquid nitrogen (in a Leidenfrost state at room temperature) thrown at a velocity $V = 0.3$ m/s onto the ground slows down on a distance L of a few meters. This corresponds to a friction of the order of $MV^2/L \sim 1$ μN ($M \sim 0.1$ g is the drop mass), much lower than its weight.

In this Letter, we discuss how textured surfaces can be used to enhance the friction of sliding Leidenfrost drops and even trap them. Aluminum was micromachined to a depth H varying between 150 and 730 μm, forming crenelations of wavelength $\lambda = 3$ mm (Fig. 1). The solid is heated to 450 °C, and the liquid is ethanol, with drops of controlled volume Ω between 50 and 150 μL. Using a hot incline meeting the solid tangentially, we make the drops come to the surface at a velocity V_0 [9]. We compare in Fig. 2 their trajectories on a horizontal flat surface (empty symbols) and on a crenelated surface with $\lambda = 3$ mm and $H = 480$ μm (full symbols). The typical duration of an experiment is 1 s, much smaller than the evaporation time of the liquid, which is about 1 min. We observe that the liquid decelerates much faster if the surface is textured. Its velocity V first decreases exponentially with the distance, and we deduce from the plot a characteristic deceleration length $L = 2.8 \pm 0.2$ cm. In a second regime, V drastically falls to zero, showing that textures also have the ability to trap the liquid at a well-defined distance x^*. We further discuss how drop deformations in the grooves (visible in Fig. 1) can be responsible for these effects.

Since the friction is large, we could use inclined textured surfaces to quantify it (Fig. 3). An ethanol drop deposited on a crenelated substrate tilted by an angle α slides under the action of gravity. After a few centimeters, it reaches a constant terminal velocity V, for which the friction F balances the weight $\rho \Omega g \sin\alpha$ ($\rho = 730$ kg/m^3 is the density of ethanol at boiling point, and g is the acceleration due to gravity [9]). The larger α, the larger V, so that this simple device allows us to measure the force F as a function of the velocity V, in the range $V = 4$–40 cm/s.

Figure 4(a) shows our results for three different volumes ($\Omega = 50$, 100, and 150 μL). These drops of radius R larger than the capillary length $a = \sqrt{\gamma/\rho g} = 1.6$ mm ($\gamma = 18$ mN/m is ethanol surface tension at the boiling point) are flattened by gravity as seen in Fig. 1. Consequently, their thickness is $2a$ and $\Omega \approx 2\pi R^2 a$ [8]. The corresponding frictions were found to vary between 20 and 300 μN. We observe that the force increases with the volume Ω and with the velocity V. More precisely, F is proportional to V^2, as emphasized by the dashed lines of slope 2 in this logarithmic plot. In addition, we changed the height H of the crenelations. Figure 4(b) shows the friction F as a function of H for different velocities. F is seen to

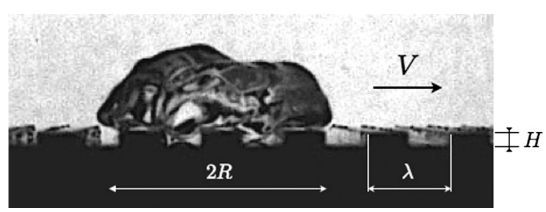

FIG. 1. Ethanol drop ($\Omega = 150$ μL) sliding on aluminum crenelations of wavelength $\lambda = 3$ mm and height $H = 480$ μm. The solid is at a temperature of 450 °C, and the drop moves at a velocity $V = 19$ cm/s.

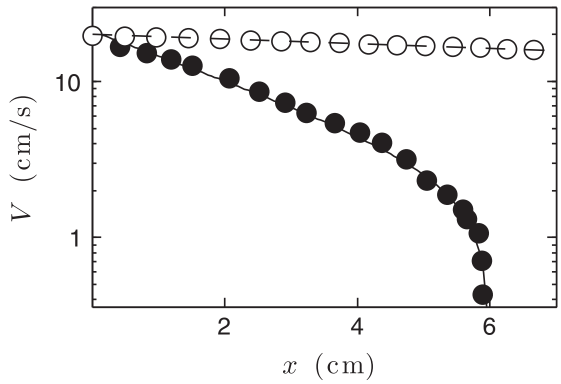

FIG. 2. Velocity V of a Leidenfrost drop ($\Omega = 90\ \mu$L) as a function of its position x, either on a flat surface (○) or on a crenelated one with $\lambda = 3$ mm and $H = 480\ \mu$m (●), for an initial velocity $V_0 = 21$ cm/s. On the crenelated surface, the drop velocity first decreases exponentially [Eq. (4)], from which we deduce a trapping length $L = 2.8 \pm 0.2$ cm. For $V < 3$ cm/s, the velocity critically falls to zero, which defines a trapping distance $x^* \approx 6$ cm. The solid line is Eq. (6) with $V^* = 2.5$ cm/s. By contrast, a similar drop on a flat surface hardly decelerates (empty symbols). The temperature of both solids is 450 °C.

increase linearly with H (dotted lines): The more textured the surface, the higher the friction.

In order to interpret these experiments, we propose a mechanism based on the drop deformations. As seen in Fig. 1, the bottom of the liquid gets deformed into the grooves. If the groove were infinitely deep, the amplitude ϵ of the bump would result from a balance between hydrostatic pressures (scaling as $\rho g a$) and Laplace pressure (scaling as $\gamma\epsilon/\lambda^2$ for $\epsilon \ll \lambda$). This yields $\epsilon \sim \lambda^2/a$, that is, a few millimeters. Therefore, the liquid reaches the bottom of the grooves if the height H is smaller than λ^2/a, which is the case for our crenelations of a depth of a few hundreds micrometers. Hence the volume of liquid trapped per groove scales as $RH\lambda$.

These bumps can generate friction for two reasons. First, they hit the crenelation sides and lose kinetic energy in these soft impacts. The energy loss per crenel scales as $\rho V^2 RH\lambda$, and it must be multiplied by the number R/λ of bumps. The total loss W_1 is $\rho V^2 R^2 H$, and it corresponds to the work $F_1\lambda$ of a friction force F_1. Second, the

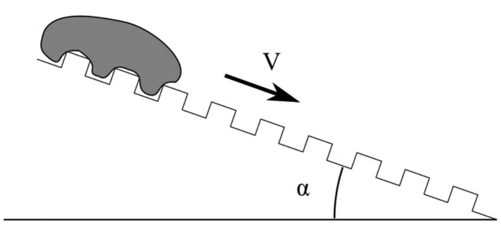

FIG. 3. Drop of volume Ω sliding on a crenelated surface inclined by an angle α; for each α, we measure the terminal velocity V.

sliding liquid has to overcome potential energy barriers $W_2 \sim \rho g R^2 H^2$, and, again, this energy can be lost when the liquid falls into the groove. The corresponding friction force F_2 scales as W_2/λ, from which we deduce the total friction force $F = b_1 F_1 + b_2 F_2$:

$$F = b_1 \rho R^2 V^2 \frac{H}{\lambda} + b_2 \rho g R^2 \frac{H^2}{\lambda}, \tag{1}$$

where b_1 and b_2 are numerical coefficients. For shallow crenelations, the dominant term in Eq. (1) is the inertial one F_1. Then the friction force is linear in crenel height and quadratic in velocity, which is consistent with the experimental observations in Figs. 4(a) and 4(b). With $R \sim 3$ mm, $H/\lambda \sim 0.1$, and $V \sim 0.3$ m/s, we predict $F \sim 100\ \mu$N, on the order of the measurements. The agreement between this law and the experimental data can be checked quantitatively: We plot in Fig. 5(a) the measured force F as a function of F_1. We observe that the data with $H < 400\ \mu$m collapse on a straight line of slope $b_1 = 1.4 \pm 0.3$. This implies that we can build substrates exerting an enhanced and tunable friction on Leidenfrost drops, by adjusting the ratio H/λ.

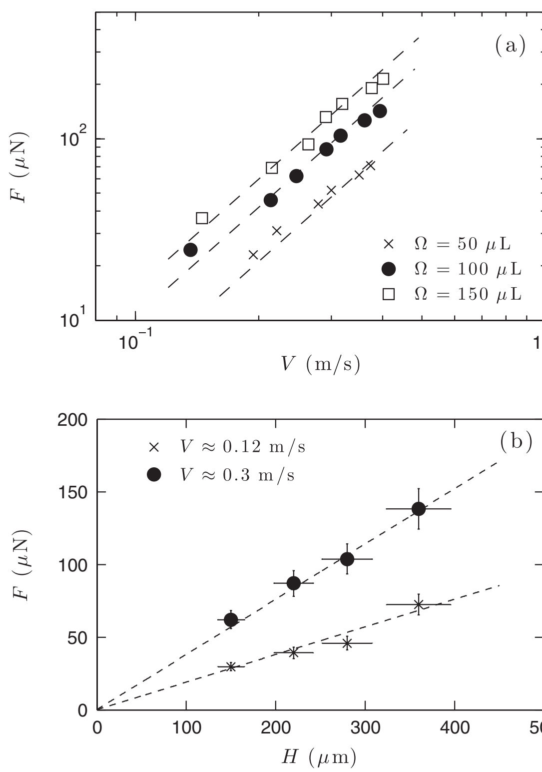

FIG. 4. (a) Friction force F as a function of the velocity V for different volumes Ω. The velocity is varied by changing the angle α of textured inclines between 3° and 12°. Dashed lines show $F \propto V^2$. Crenelation properties are $\lambda = 3$ mm and $H = 280\ \mu$m. (b) Friction force F as a function of crenel height H, for different velocities, $\Omega = 100\ \mu$L, and a fixed wavelength $\lambda = 3$ mm. The dotted lines have slopes of 0.19 and 0.38 N/m, respectively.

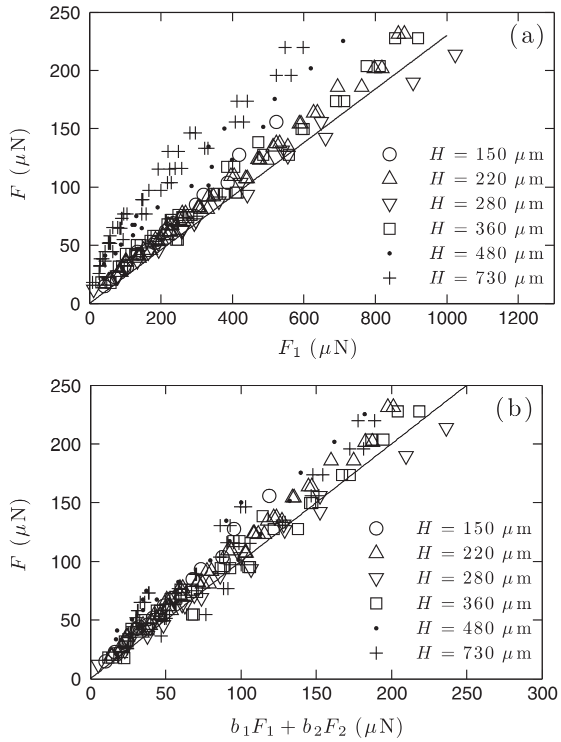

FIG. 5. (a) Measured friction force F as a function of $F_1 = \rho R^2 V^2 \frac{H}{\lambda}$; the straight line has a slope of $b_1 = 1.4$. (b) Friction force F as a function of $b_1F_1 + b_2F_2$ with $b_1 = 1.4$ [deduced from (a)], $F_2 = \rho g R^2 \frac{H^2}{\lambda}$, and $b_2 = 2.9$. The straight line has a slope of 1.

However, the friction on deeper crenelations in Fig. 5(a) is clearly not described by the sole inertial term F_1. The friction then becomes higher than expected due to the gravitational term in Eq. (1). Considering the total friction (1) indeed allows us to understand the whole set of data. We plot in Fig. 5(b) the same data as a function of the force $b_1F_1 + b_2F_2$ (with $b_1 = 1.4$) and find a fair agreement between the model and the observations with $b_2 = 2.9 \pm 0.3$.

The gravitational correction in Eq. (1) can also explain the trapping of the drop observed in Fig. 2, at a well-defined position x^*. This can be understood by discussing how Leidenfrost drops get decelerated on horizontal substrates, from an initial velocity V_0. We balance the drop inertia MdV/dt with the friction force:

$$\rho R^2 a V \frac{dV}{dx} \sim -\rho R^2 V^2 \frac{H}{\lambda} - \rho g R^2 \frac{H^2}{\lambda}, \tag{2}$$

where x is the distance travelled by the drop. The dominant term in the friction is the inertial one at high velocity, i.e., for $V > V^*$ with

$$V^* \sim \sqrt{gH}. \tag{3}$$

For $H \sim 100\ \mu$m, V^* is a few centimeters per second. For drops faster than that, the solution of Eq. (2) simply is

$$V = V_0 \exp(-x/L), \tag{4}$$

where L is the characteristic distance of slowing down given by

$$L \sim a \frac{\lambda}{H}. \tag{5}$$

The length L is found to be independent of the drop initial velocity and mainly fixed by the crenel design. It is expected to be typically $10a$, i.e., about 1.5 cm for ethanol, in agreement with Fig. 2, where the drop velocity is first found to decrease exponentially, with a characteristic distance $L = 2.8 \pm 0.2$ cm.

As the drop slows down ($V \rightarrow V^*$), the gravitational term in Eq. (2) becomes more and more significant. A general solution of Eq. (2) is

$$V^2 = (V_0^2 + V^{*2}) \exp(-2x/L) - V^{*2}. \tag{6}$$

Equation (6) is drawn with a solid line in Fig. 2, where it is found to fit the data for $L = 2.8$ cm and $V^* = 2.5$ cm/s. It also predicts the trapping of the drop ($V = 0$) at a well-defined distance x^*. For $V_0 \gg V^*$, we expect

$$x^* \approx L \ln\left(\frac{V_0}{V^*}\right). \tag{7}$$

The distance x^* is a few times L, as observed in Fig. 2, where $x^* \approx 6$ cm $\approx 2L$. Remarkably, it only logarithmically depends on the initial velocity V_0, and it appears to be mainly fixed by the design of the texture, via L. In this scenario, trapping occurs when the drop velocity becomes of the order of V^*, because the liquid does not have enough kinetic energy to climb the next crenel. The transition to the trapped state is sharp (Fig. 2); expanding Eq. (2) for $x \rightarrow x^*$, we find that the drop velocity critically falls to zero [$V \sim V^* \sqrt{2(x^* - x)/L}$] as it approaches x^*. Other factors can cause the brutal stop of the drop after a distance of the order of L. In some cases we observed that defects on the solid surface can generate local pinning. Conversely, drop oscillations or local boiling can help the drop to reach the next crenel. The trapping distance remains of the order of L, but uncertainties of the order of λ exist for the distance x^*.

We also displayed in Fig. 2 the deceleration of a similar Leidenfrost drop on a flat surface, for which the velocity hardly decreases on similar distances. For such a drop, the balance of inertia and inertial friction in air can be written $MV^2/L \sim \rho_a V^2 R^2$ (with ρ_a the air density), which yields a slowing distance $L \sim a\rho/\rho_a$ on the order of 1 m, instead of 1 cm for our traps [Eq. (5)]. Crenelations increase the friction by a factor $\rho/\rho_a \times H/\lambda$, and the efficiency of the trap relies on the fact that dissipation mostly takes place in the liquid and only marginally in the surrounding air. Because the density of a liquid is 3 orders of magnitude higher than the one of air, the resisting inertial force is greatly increased, compared to the one on a flat solid.

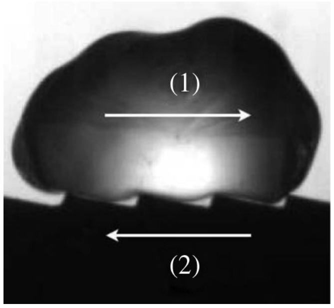

FIG. 6. Linke's device: A Leidenfrost drop made of water or ethanol on a hot surface with asymmetric teeth self-propels in direction (1). The teeth are 1.5 mm wide and 200 μm high, and the surface temperature is 350 °C. After accelerating for a few centimeters, the drop reaches a constant velocity $V = 14$ cm/s, fixed by the friction in direction (2) [7].

Textures can also be asymmetric, and it was shown by Linke *et al.* that Leidenfrost drops on asymmetric teeth get self-propelled (Fig. 6) [6]. Using this observation, Goldstein *et al.* were recently able to design traps made of concentric teeth [10]. Self-propelled drops can reach terminal velocities of approximately 10 cm/s [6,11], resulting from the balance between a production of vapor and friction. We saw here that friction might arise from the steps on which the liquid bumps impact. For typical values of the teeth height and length (see Fig. 6), we expect from Eq. (1) friction forces on the order of 10 μN in agreement with observations [7].

According to our scenario in which the dissipation is due to the liquid hitting the crenel, asymmetric teeth should provide an anisotropic friction. We measured the friction on ratchets ($H = 0.2$ mm and $\lambda = 1.5$ mm), following the experiment sketched in Fig. 3. The tilting angle was taken large enough ($\sim 10°$) to neglect the self-propulsion force. For each tilting angle, we measured two drag coefficients $C = F/(\rho V^2 R^2)$, corresponding to the directions 1 and 2 defined in Fig. 6. We found $C_1 = 0.09 \pm 0.02$ and $C_2 = 0.05 \pm 0.01$, respectively: The loss of kinetic energy is larger when the drop hits the sharp edge of the step than when it follows the smooth slope, as expected from our dissipation mechanism. For this ratchet, the two drag coefficients differ by a factor of 2 (strong anisotropy): Linke's drops self-propel in the direction of the larger friction, which raises the question of the optimal design to be given to a ratchet to get the fastest self-propulsion.

Hence, submillimetric textures were found to deeply affect the friction of levitating drops, as they do for marbles running down rough substrates [12]. This makes it possible to slow down and even trap efficiently these ultramobile drops, which we characterized by a trapping length, a function of the texture design. It would be interesting to study whether these ideas also apply on superhydrophobic surfaces decorated with similar patterns. For instance, butterfly wings and man-made ratchets were observed to show anisotropic wetting properties [13,14]. As discussed in this Letter, these materials might also exhibit an anisotropic friction, when water drops run on them.

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[9] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.107.114503 for high-speed movies showing Leidenfrost drops decelerating on a crenelated surface, running down crenelated inclines, and losing elasticity as they hit crenels.
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