Compact nanoscale textures reduce contact time of bouncing droplets

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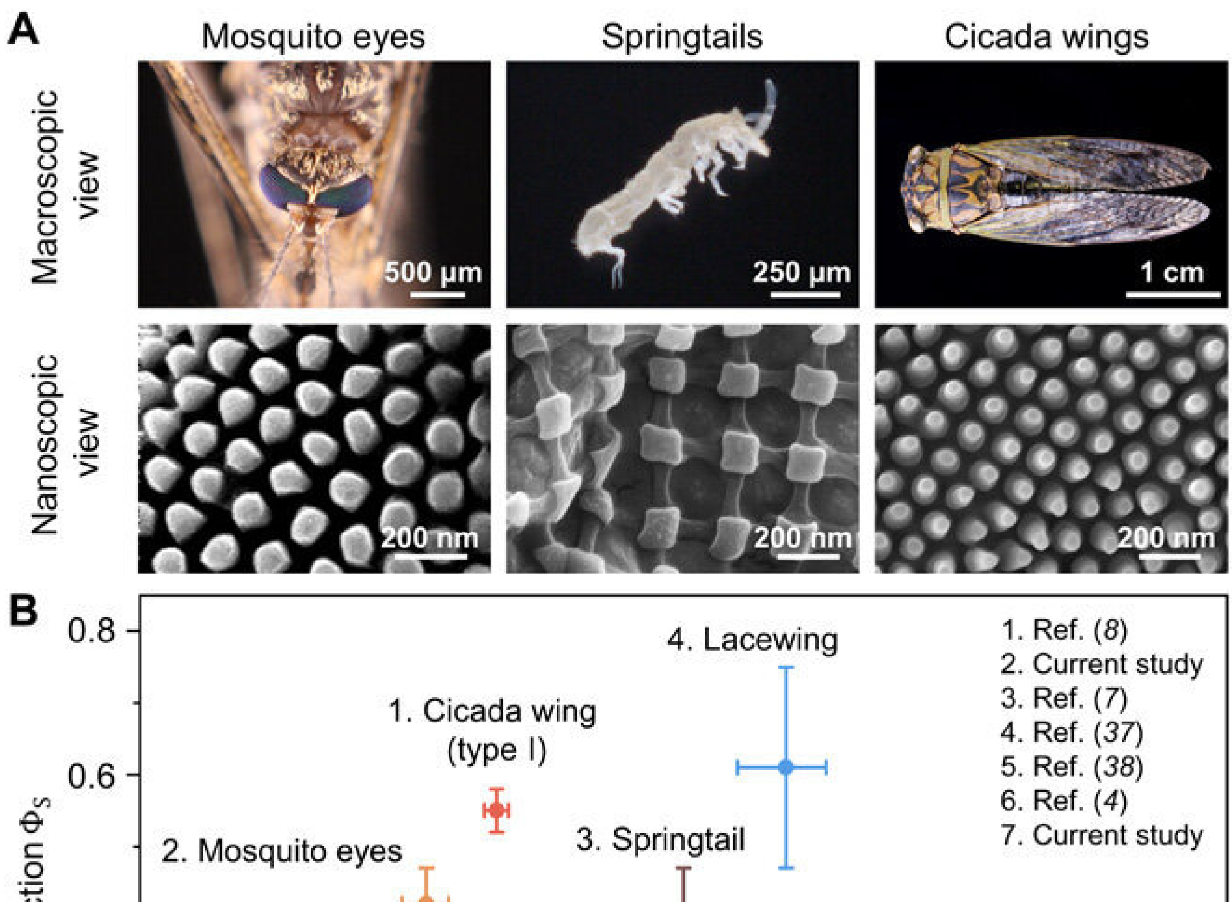
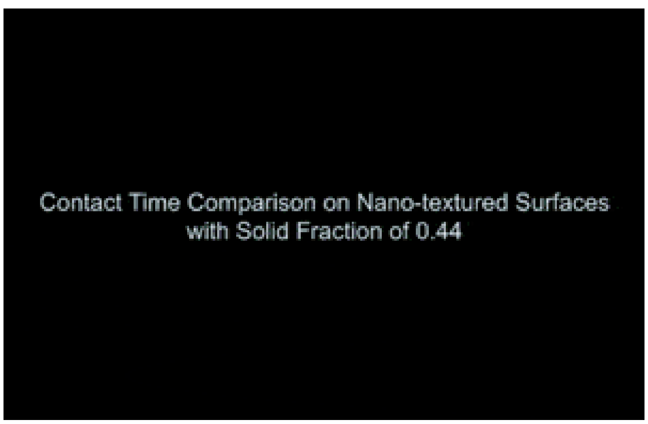


Examples of water-repellent insects equipped with high solid fraction nanoscale surface textures. (A) Optical and scanning electron microscopy (SEM) images of mosquito eyes, a springtail, and cicada wings showing the presence of high solid fraction nanoscale surface textures (Photo credit: L.W., Pennsylvania State University). (B) A plot summarizing the solid fraction Φs and the corresponding texture size D for various water-repellent insects. Note that the solid fraction of different insect surfaces is in the range of ~0.25 to ~0.64, which is substantially higher than that of the plant surfaces (e.g., Φs ~ 0.01). Error bars indicate SDs for five independent measurements. Credit: Science Advances, doi: 10.1126/sciadv.abb2307

Many natural surfaces can rapidly shed water droplets due to their water-repellent functionality. In 1945, scientists Cassie and Baxter linked the water-repellent function of natural surfaces to their surface textures. The use of low solid fraction textures (denoted Φ_s) is therefore a key principle to design water-repellent surfaces. In this work, Lin Wang and a team of scientists in materials science, biomedical engineering and mechanical engineering at the Pennsylvania State University, U.S. reduced the contact time of bouncing droplets on high solid fraction surfaces (i.e. Φs ~ 0.25 to 0.65) by reducing the surface texture size to the nanoscale. They showed how high solid fraction surfaces with a texture size below 100 nanometers could reduce the contact time of bouncing droplets by approximately 2.6 milliseconds (ms) compared to a texture size above 300 nm. The texture and size-dependent contact time reduction observed on solid surfaces is a first-in-study outcome relative to existing theories on surface wettability. Wang et al. credited the reduction in droplet contact on nanoscale surfaces to the dominant three-phase contact line tension. Based on pressure stability experiments, the team further showed how surface solid fractions were bioinspired by insects that can withstand the impact of raindrops. The results are now published on *Science Advances*.

Nanoscale surfaces have diverse roles in biological organisms with importance for insect survival, examples include anti-reflection properties of moth eyes, antifogging properties of mosquitoes, self-cleaning techniques of cicada and anti-biofouling of dragonfly. The rapid detachment of raindrops on flying insects is also critical for their survival. For instance, the impact duration of raindrops on mosquitoes approximated 0.5 to 10 ms; a time frame of combined active and passive droplet shedding mechanisms. Plants and butterfly wings can also maintain microscale patterns to break the impact of droplets into smaller pieces to reduce droplet contact time. However, materials scientists must still understand how the high solid fraction and nanoscale textures of water-repellent insect surfaces can cause rapid detachment of raindrops on impact. To explore texture size effects and liquid-solid interactions, Wang et al. engineered a series of bioinspired, insect-like textured surfaces, coated them with a silane monolayer to induce surface hydrophobicity (water-hating nature) and conducted a series of experiments.

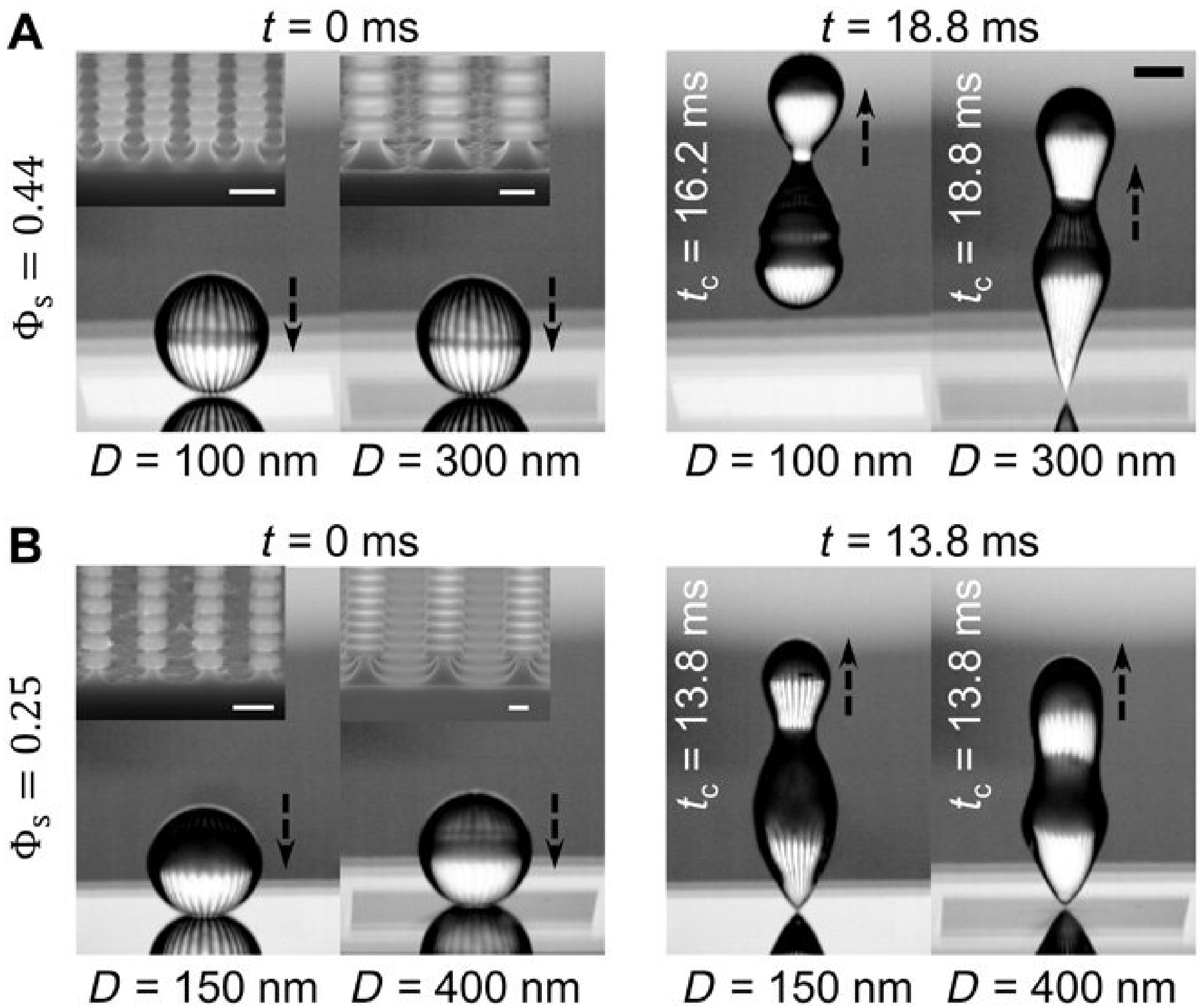


Comparison of contact times of bouncing water droplets on surfaces with different texture size at solid fraction

Measuring the contact time of bouncing droplets on textured surfaces

During the experiments, the team maintained the Cassie-Baxter state (heterogenous surface wetting) with the test liquid droplets and compared the contact time of bouncing water droplets on textured surfaces. Surfaces with a texture size smaller than 300 nm showed decreased contact time for bouncing droplets. The texture size-dependent reduction of droplet contact on solid surfaces was a first-in-study compared to existing surface wetting theories.

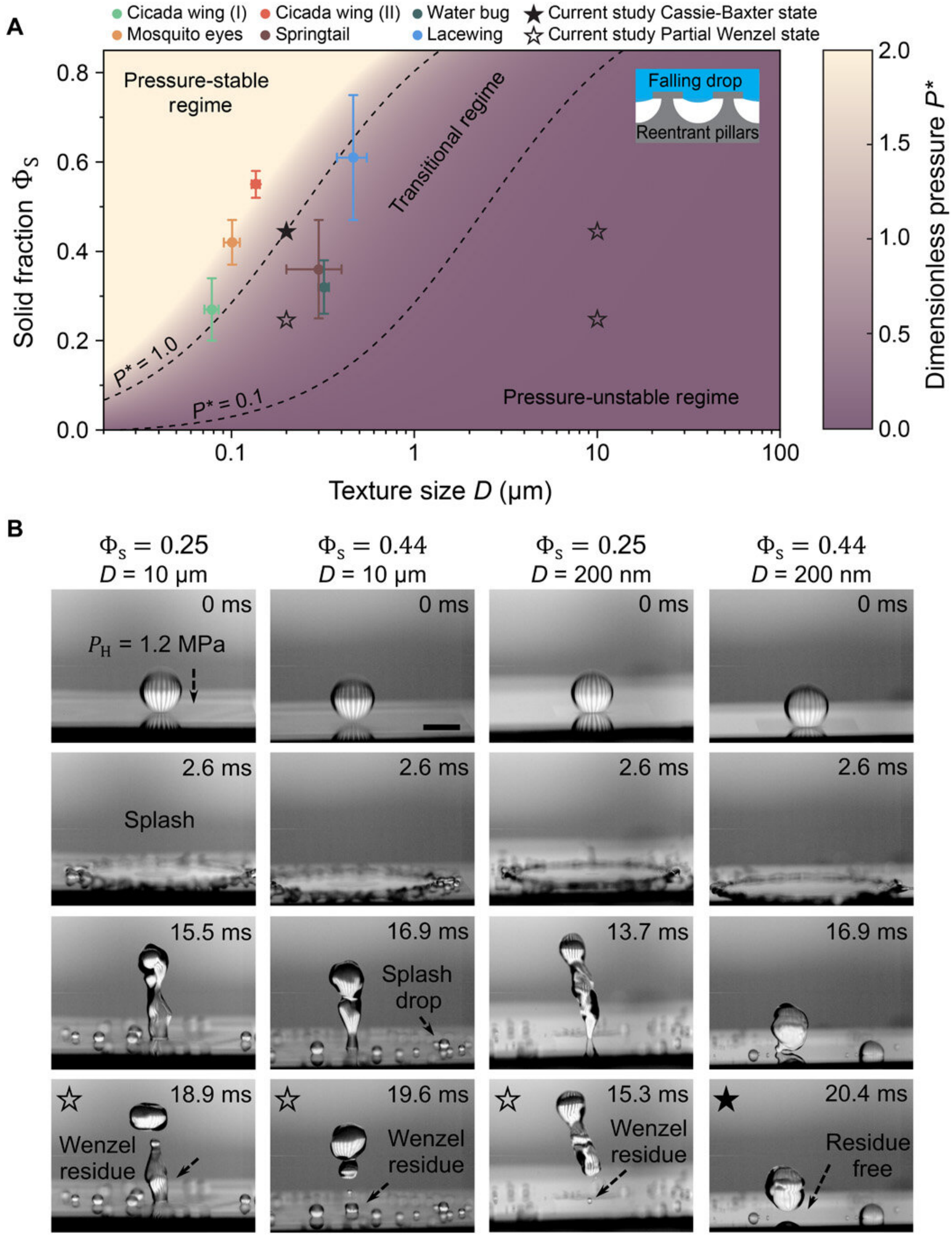
In theory, the contact time can be predicted relative to the density and surface tension of water. When a liquid droplet impacted a textured surface, it spread to a maximum diameter and retracted from the surface much like a 'liquid spring." On low solid fraction textured surfaces, the liquid-air interfacial tension of the droplet dominated the spring constant of the liquid spring. Meanwhile any contributions from liquid-solid interactions could be ignored. However, scientists could not ignore liquid-solid interactions on high solid fraction textured surfaces where Φ_s equalled 0.44, due to additional energy resulting from the formation of three-phase contact lines beneath the droplets to influence their bouncing energies. For this, Wang et al. considered the three-phase contact line tension (τ), first introduced by Gibbs in the 1870s, where the experimental measurements of τ depended on the specific system under investigation.



Comparison of contact time of bouncing water droplets on textured surfaces. (A) Time-lapse images of bouncing water droplets (diameter d0 ~ 2.3 mm, Weber number We ~ 31.6) on surfaces with solid fraction Φs = 0.44. The droplet detached faster from ~100 nm textures than the one from ~300 nm textures. D denotes the texture cap size of each re-entrant pillar, and tc denotes contact time. (B) Identical drop impact experiments on surfaces with solid fraction Φs = 0.25. Droplets detached simultaneously from both surfaces. Insets showing the SEM images of fabricated nanoscale re-entrant textures. Scale bars in all SEM images, 200 nm; scale bar in the optical image, 1mm. Credit: Science Advances, doi: 10.1126/sciadv.abb2307

Kinematics of bouncing droplets on textured surfaces and the pressure stability of surfaces

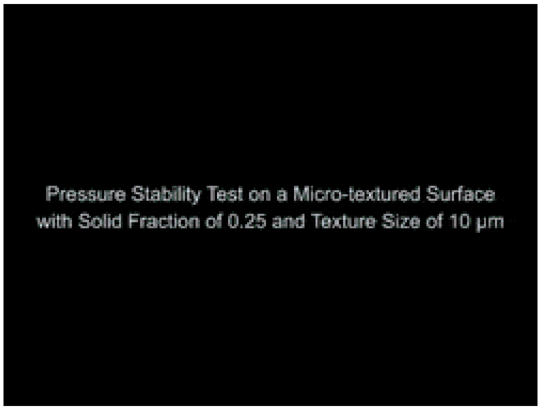
To further understand the reduction in contact time of droplets impacting nanoscale surfaces, Wang et al. investigated the kinematics of bouncing droplets based on spreading and retracting processes. While velocities of droplet spreading were similar on different surfaces, during the phase of retraction, droplets took longer to fully retract from surfaces with higher solid fractions. The work showed how increased solid fraction therefore increased retraction time. For example, a droplet on a superhydrophobic black silicon surface could retract at a consistent velocity for droplets to recede at the fastest possible pace. Unexpectedly, therefore, Wang et al. noted superhydrophobic bouncing behavior on 100 nm surface textures with a solid fraction of 0.44



Pressure stability of re-entrant textured surfaces against impacting raindrops. (A)

A phase map showing the pressure stability of re-entrant textured surfaces against impacting raindrops as a function of texture size and solid fraction. To repel impacting raindrops, it requires a sufficient capillary pressure PC on textured surfaces to withstand the raindrop hammer pressure PH. P* is defined as the ratio between PC and PH, i.e., P* = PC/PH. Note that the textured surfaces are pressure stable when texture size D is small at high solid fraction Φs. It is shown that all the geometrical parameters of the surface textures on water-repellent insects fall within or near the pressure stable regime. (B) Experimental results showing droplets impacting on re-entrant textured surfaces with different geometrical parameters. Water droplets with terminal velocity ~4.0 m/s impacted the re-entrant pillars, resulting in a water hammer pressure PH ~ 1.2 MPa and We ~ 505.5. The surface with texture size of 200 nm and solid fraction of 0.44 was able to maintain the droplet at the Cassie-Baxter state (solid star symbol), while the droplets on other surfaces were in partial Wenzel state (empty star symbols). Scale bar, 2 mm. Credit: Science Advances, doi: 10.1126/sciadv.abb2307

To understand the outcome, the scientists then developed a method to quantify the contact angle hysteresis by systematically measuring the advancing and receding contact angle on engineered surfaces. Surfaces with a higher solid fraction had delayed droplet retraction, notably deviating from the intended superhydrophobic bouncing behavior. It was therefore interesting to understand why water-repellent insect surfaces did not adopt textures with a lower solid fraction to get rid of water more effectively. For this, Wang et al. investigated the pressure stability of textured surfaces against impacting droplets when water droplets impacting a solid surface underwent two modes of impact pressures. The first mode was water hammer pressure at the liquid-solid contact surface and the second mode was dynamic pressure at the spreading stage. The team therefore showed high solid fraction to be an important requirement for insects to withstand the impact pressure of raindrops in order to completely shed them.



Pressure stability test on a reentrant micro-textured surface with solid fraction

In this way, Lin Wang and colleagues showed how nanoscale textures on high solid surfaces reduced the contact time of bouncing droplets for the first time. The findings uncovered an unprecedented strategy to reduce the contact time of bouncing droplets on solid surfaces. The team achieved superhydrophobic bouncing behavior on high solid fraction surfaces ($\Phi_s = 0.44$) with a nanoscale texture size approximating 100 nm. The findings shed light on how insects escape the high-speed impact of raindrops. The study provides experimental evidence to the necessity of high solid function textures in order to counter the impact pressure of raindrops. Technically, a compact nanoscale textured material that can repel high-speed impact of liquid droplets with reduced contact time will have a range of applications in facilitating fouling-resistant personal protective gear, for insect-sized flying robots and in miniaturized drones.

More information: Lin Wang et al. Compact nanoscale textures reduce contact time of bouncing droplets, *Science Advances* (2020). DOI: 10.1126/sciadv.abb2307

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