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Supporting Information

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Switchable Underwater Adhesion by Deformable Cupped Microstructures

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Supporting Information

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Section 1. Derivation of the pull-off stress

The water influx into the cavity under the cupped microstructure, $\dot{V}_{in}$ must approximately equal the volume expansion of the cavity, $\dot{V}_{cav}$, that is

$$\dot{V}_{in} \approx \dot{V}_{cav} \,. \tag{A1}$$

The cavity expands vertically at a rate

$$\dot{V}_{cav} \approx \pi R^2 \left(u - \frac{d\Delta H}{dt}\right) = \pi R^2 \left(u - \frac{H}{E}\frac{d(p_0 - p_{cav})}{dt}\right), \tag{A2}$$

where πR^2 is the area of the stalk and u is the retraction velocity of the motor. The applied force (induced by the retraction) stretches the stalk of the microstructure by $\Delta H \approx \frac{(p_0 - p_{cav})H}{E}$, where H is the length and E is the Young's modulus of the stalk, and $p_0 - p_{cav}$ is the (positive) pressure difference between the hydrostatic pressure outside the contact, p_0, and inside the cavity, p_{cav}.

The water influx is given by

$$\dot{V}_{in} = 4\pi R h \bar{v}, \tag{A3}$$

where $2\pi R$ is the perimeter of the stalk, $2h$ is the thickness of the water film between the seal and the substrate, and $\bar{v}$ is the average flow velocity, which for laminar flow is $\bar{v} = \frac{h^2(p_0 - p_{cav})}{3\mu L_r'}$, where μ is the viscosity of water, and L_r' is the radial length of the seal.

Rewriting eq. (A1) gives:

$$4\pi R h \frac{h^2(p_0 - p_{cav})}{3\mu L_r'} = \pi R^2 \left(u - \frac{H}{E}\frac{d(p_0 - p_{cav})}{dt}\right). \tag{A4}$$

Rearrangement of eq. (A4) gives the differential equation with the general form $\frac{dy}{dt} + P(t)y = Q(t)$:

$$\frac{d(p_0 - p_{cav})}{dt} + \frac{4Eh^3(p_0 - p_{cav})}{3RH\mu L_r'} = \frac{E}{H}u, \tag{A5}$$

The solution of the differential equation is

$$y = Ce^{-\int P(t)dt} + e^{-\int P(t)dt} \int Q(t)\, e^{\int P(t)dt} dt \tag{A6}$$

Substituting provides $P(t) = \frac{4Eh^3}{3RH\mu L_r'}$ and $Q(t) = \frac{E}{H}u$. Both terms were assumed to be constant, i.e. independent of time, which gives $e^{-\int P(t)dt} = e^{-\frac{4Eh^3}{3RH\mu L_r'}t}$.

Solving the integral of the second term of eq. (A6) then gives:

$$e^{-\int P(t)dt}\int Q(t)\,e^{\int P(t)dt}dt = e^{-\frac{4Eh^3}{3RH\mu L_r'}t}\int\left(\frac{E}{H}u\right)e^{\frac{4Eh^3}{3RH\mu L_r'}t}dt = \frac{3R\mu L_r'}{4h^3}u. \qquad \text{(A7)}$$

Therefore, eq. (A6) can be rewritten:

$$p_0 - p_{cav} = y = Ce^{-\frac{4Eh^3}{3RH\mu L_r'}t} + \frac{3R\mu L_r'}{4h^3}u. \qquad \text{(A8)}$$

The constant C can be determined from the boundary condition. At $t = 0\ s$, the pressure difference $p_0 - p_{cav}$ is zero, hence $C = -\frac{3R\mu L_r'}{4h^3}u$.

The solution of the differential equation (A5) is:

$$p_0 - p_{cav} = \frac{3R\mu L_r'}{4h^3}u\left(1 - e^{-\frac{4Eh^3}{3RH\mu L_r'}t}\right) = \frac{3R\mu L_r'}{4h^3}u_{eff}, \qquad \text{(A9)}$$

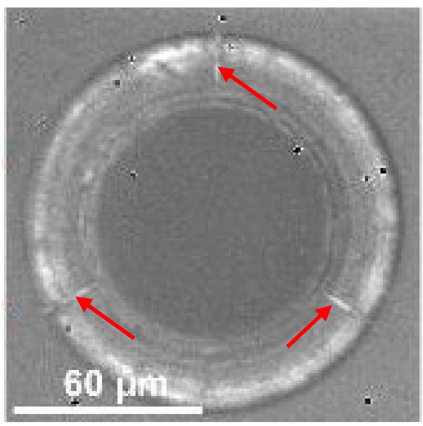
which is equivalent to the pull-off stress (based on suction):

$$\sigma_p = p_0 - p_{cav} = \frac{3\mu R L_r'}{4h^3}u_{eff}, \qquad \text{(A10)}$$

with $u_{eff} = u\left(1 - e^{-\frac{4h^3E}{3\mu L_r' RH}t}\right)$.

Section 2. Cupped microstructures with channels

We created a cupped microstructure with 30° cup angle, a 20 μm wide rim, and three channels with a width of 2 μm and depths of 0.3, 0.5, and 0.8 μm (Figure S1). For the depth of 0.3 μm (black squares), the transition velocity was 2 μm/s and for the depth of 0.5 μm (red circles), the transition velocity increased to 50 μm/s. For the deepest channels (blue triangles), the contact did not seal and therefore the cup did not adhere to the substrate in the range of the tested retraction velocities. In conclusion, deeper channels led to higher water flow rates and therefore to higher transition velocities.



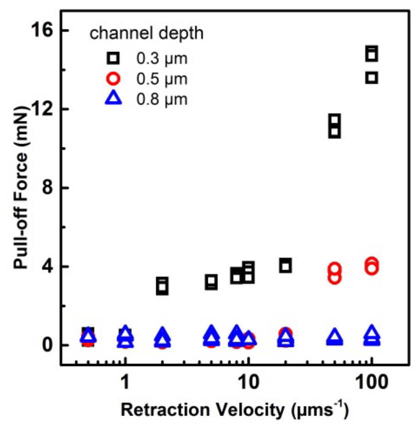


Figure S1. Underwater adhesion of a cupped microstructure with 3 channels in the rim. The cup angle was 30°. (left) Optical micrograph of the cupped microstructure with three channels marked by the red arrows. (right) Pull-off force vs. retraction velocity. The width of the channels was 2 μm and the depth varied from 0.3 (black squares) to 0.8 μm (blue triangles).