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Electric Supplement Information

Extraordinary Drag Reduction Effect of Superhydrophobic Coating on Macroscopic Model Ships at a High Speed

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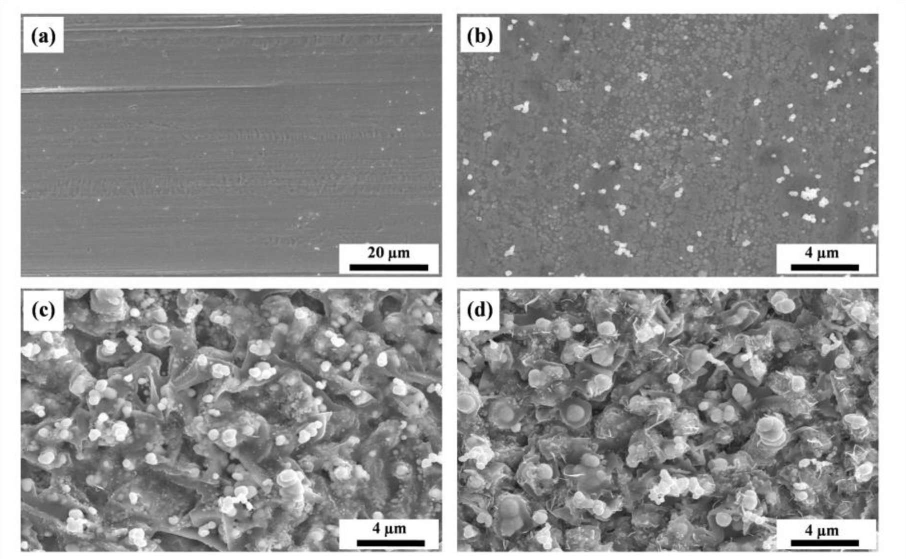
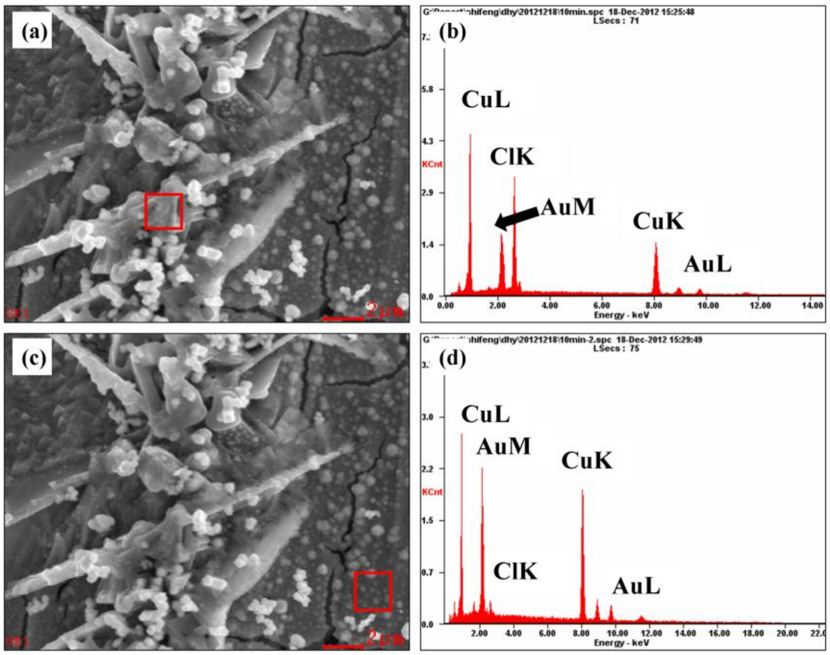
S1. The surface morphology of the copper foil deposited in $HAuCl_4$ at different concentration.

As shown in E. S. I. Fig. 1, the surface morphologies of the copper foils were characterized by SEM after they were immersed in $HAuCl_4$ aqueous solution at different concentration of 0, 1, 2 and 4 mg mL^{-1} for 10 min, respectively. In E. S. I. Fig. 1a, the bare copper foil presents a smooth and flat surface. After deposited in $HAuCl_4$ of 1 mg mL^{-1} for 10 min, one kind of particles with bright color distributed randomly on the surface of another kind of particles with a dark color underneath (E. S. I. Fig. 1b). When increased the concentration to 2 mg mL^{-1}, rough three dimensional structures forms with large accumulations accompanied by small particles on them. At a concentration of 4 mg mL^{-1}, particles aggregate to large bundles and contribute to high roughness. Since the roughness of the surface formed in the solution of 2 mg mL^{-1} is enough for the fabrication of a superhydrophobic coating, we chose the concentration of $HAuCl_4$ to 2 mg mL^{-1}.



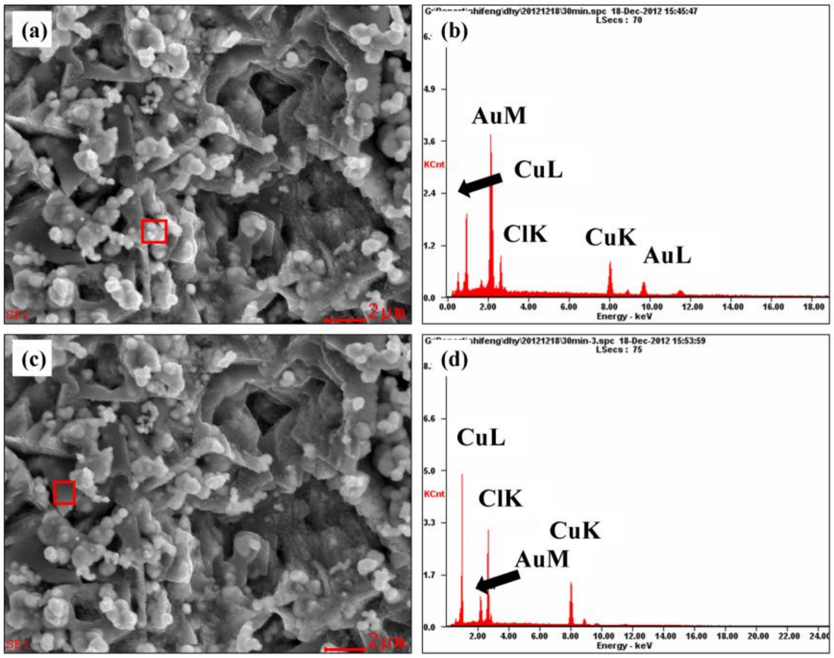
E. S. I. Fig. 1 SEM images for (a) bare copper foil and copper foils deposited in $HAuCl_4$ at a concentration of (b) 1 mg mL^{-1} (c) 2 mg mL^{-1} and (d) 4 mg mL^{-1} for 10 min.

S2. SEM and EDS images for the copper foil deposited in $HAuCl_4$ for 10 min and 30 min.



E. S. I. Fig. 2 SEM images of the copper foil after deposited in $HAuCl_4$ for 10 min together with their related EDS spectra of (b) and (d), corresponding to the selected zone in red squares in (a) and (c), respectively.

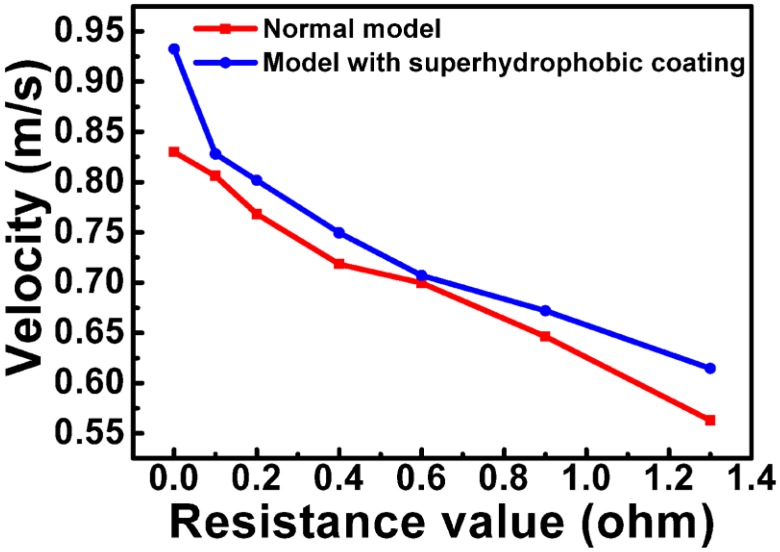
SEM images in E. S. I. Fig. 2a and Fig. 2c present two kinds of surface morphology: rough three dimensional structures and a flat surface covered by a layer of particles. The composite of these two areas was characterized by EDS patterns correspondingly. From the EDS of the selected rough area in E. S. I. Fig. 2a, we can find that after deposited for 10 min, the main composites of the rough structures are CuCl accompanied by gold. The EDS pattern of the selected flat area in E. S. I. Fig. 2c indicates that the weight percentage of gold increase to the amount almost similar to that of copper. These results suggested that CuCl aggregates contribute mainly to the roughness of the surface while the gold particles formed continuous plate beneath the rough structure. When increasing the deposition time to 30 min, the surface exhibits a very rough appearance with porous and aggregated structures in E. S. I. Fig. 3a and Fig. 3c. The related EDS patterns imply that the aggregated particles are mainly gold while the majority of the rough backbones are comprised of CuCl.



E. S. I. Fig. 3 SEM images of the copper foil after deposited in $HAuCl_4$ for 30 min together with their related EDS spectra of (b) and (d), corresponding to the selected zone in red squares in (a) and (c), respectively.

S3. Drag reducing effect when the power of the model ship is 3 V.

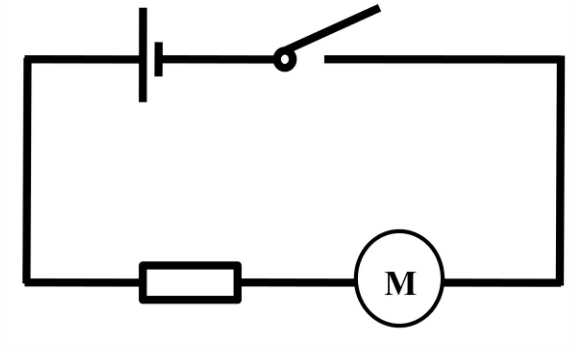
The model ship was powered by an open circuit, whose moving velocity can be adjusted by tuning the power and resistance in the circuit. When increase the power supply to 3 V, the velocity of the model ships with and without superhydrophobic coatings were recorded and calculated. As displayed in E. S. I. Fig. 4, with the increasing resistance value, the velocity of these two kinds of ships decrease, during which the model ship with superhydrophobic coatings always has a higher velocity than the one without the coating under identical conditions.



E. S. I. Fig. 4 Velocity of the model ships with (blue line) and without (red line) a superhydrophobic coating versus the values of the resistance in the circuit within the ship.

S4. Analyses on the nondimensional drag coefficient.

To determine the drag coefficient values of C_x, we carried out analyses on the energy of motion based on the energy conservation law, and calculated the drag coefficient values by the given parameters of electronic devices in the circuit and the measured velocity data of the ships. The model ships are powered by the motor in the circuit (E. S. I. Fig. 5) within the ship. The correlation between the electric energy and energy of motion is established by Equation S1 and Equation S2. According to the law of conservation of energy, the total power of the motor ($P_{total}=UI$) provides output power (P) and the internal resistance (I^2R_0), respectively. When moving for a time of t, the energy applied on the motor (Pt) is shared by the motion of the ships ($mv^2/2$) and the energy dissipation of drag force (W_f), the latter of which is related to a typical drag equation (Equation S3). C_x is the drag coefficient, ρ is the density of the fluid, v is the moving velocity of the fluid, L is the length of the sink, and S is the investigated area, which in our case is the wetting area of the model ship.



E. S. I. Fig. 5 Illustration of the circuit within the model ship.

$$P_{total} = UI = P + I^2 R_0 \qquad (1)$$

$$Pt = \frac{1}{2} mv^2 + W_f \qquad (2)$$

$$W_f = \frac{1}{2} C_x \rho v^2 SL \qquad (3)$$

Given the values of rated current I=0.6 A, the maximum output power P=0.9 W and the resistance R_0=1.2 Ω, the voltage U applied in the motor can be calculated according to Equation 1:

$$U = \frac{(P + I^2 R_0)}{I} = \frac{(0.9 + 0.6^2 \times 1.2)}{0.6} = 2.22\ \text{V}$$

Since the total voltage in the circuit U_T= 3 V supplied by batteries, an extra resistance of R_x is needed to be added in the circuit to ensure the optimized working condition and maximum output power under rated power supply. The value of R_x is calculated as follows:

$$R_x = \frac{(U_T - U)}{I} = \frac{(3.0 - 2.22)}{0.6} = 1.3\,\Omega$$

After adding the extra resistance, the sailing tests of the model ships with and without superhydrophobic coatings model is carried out. The result shows that it took 12 s and 10 s, respectively, for the model ships without and with coating to complete the voyage. Equation S2 and Equation S3 can be correlated as Equation S4 to resolve the value of C_x.

$$Pt = \frac{1}{2} m v^2 + \frac{1}{2} C_x \rho v^2 SL \quad (4)$$

Given t=12 s, the mass of the normal model ship m=0.115 kg, the velocity of fluid, *i. e.* the velocity of the ship v=0.5 m s^{-1}, the fluid density ρ=1000 kg m^{-3}, the wetting area S=0.0136 m^2, and the length of the sink, *i. e.* the voyage L=6 m, we can obtain the C_x value for the normal model ship:

$$C_x = \frac{Pt - \frac{1}{2} m v^2}{\frac{1}{2} \rho v^2 SL} = \frac{0.9 \times 12 - 0.5 \times 0.115 \times 0.5^2}{0.5 \times 1000 \times 0.5^2 \times 0.0136 \times 6} = 1.06$$

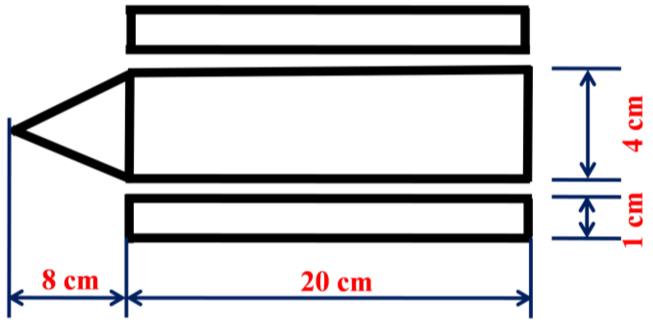
Similarly, due to the differences of t=10 s and v=0.6 m s^{-1}, the C_x value of the model ship with supramolecular coatings is calculated as follows:

$$C_x = \frac{Pt - \frac{1}{2} m v^2}{\frac{1}{2} \rho v^2 SL} = \frac{0.9 \times 10 - 0.5 \times 0.115 \times 0.6^2}{0.5 \times 1000 \times 0.6^2 \times 0.0136 \times 6} = 0.611$$

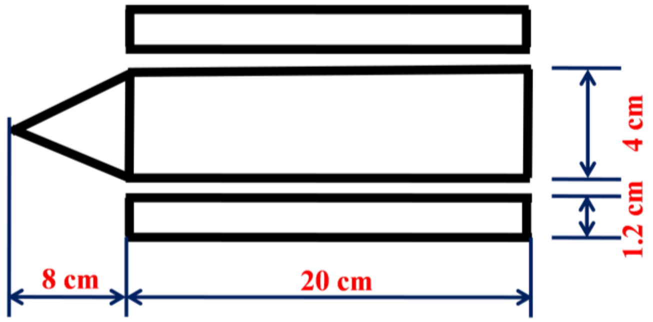
The drag coefficient of a normal model is as twice as that of a superhydrophobic-coated model.

S5. Calculation of the wetting area (S).

Some reports hold the opinion that the objects modified with superhydrophobic coatings show drag reducing effect mainly due to the decrease of the wetting areas compared with the objects without coatings. That may be true especially when the moving object has a small size, for which a little deviation in the wetting area affects a lot on the locomotion. To clarify the role of the wetting area difference in our experiment, we measured the wetting areas of the model ships with and without superhydrophobic coatings are compared by placing these two ships on water surface and recording their waterlines. The sizes for the wetting for both of the ships are plotted as illustrations of plan view in E. S. I. Fig. 6 and E. S. I. Fig. 7, respectively.



E. S. I. Fig. 6 Illustration and sizes for wetting area of the model ship with superhydrophobic coatings.



E. S. I. Fig. 7 Illustration and sizes for wetting area of the normal model ship without superhydrophobic coatings.

The wetting area of model ship with superhydrophobic coating can be calculated as follows:

$$S = 20\times 1\times 2 + 4\times 20 + \frac{1}{2}\times 4\times 8 = 136 cm^2$$

Similarly, the wetting area of normal model ship can be obtained as follows:

$$S = 20\times 1.2\times 2 + 4\times 20 + \frac{1}{2}\times 4\times 8 = 144 cm^2$$

As we can see, the difference of the wetting areas (8 cm^2) of these two kinds of model ships is quite small owing to their large surface area (144 cm^2), which leads to a change of only 5.6% of the original ship. In our experiments, the superhydrophobic surface can effectively reduce the drag force up to 49.1% compared with normal surface. Hence, the decreased wetting area did not make the major contribution to the drag reducing effects.

S6. Illustration for Movie S1.

We placed the model ships with and without modification into one sink and traced their locomotion with a camera. It shows a 38.5% reduction in drag induced by superhydrophobic coatings.

Keywords: *drag reducing property, sailing velocity, superhydrophobic coating, model ship, electroless deposition*