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Long-term durability of superhydrophobic properties of butterfly wing scales after continuous contact with water

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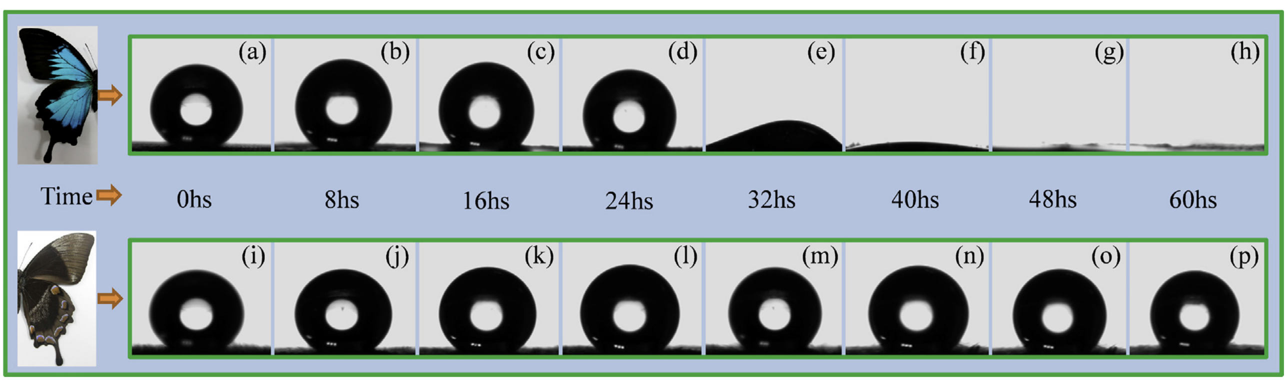
GRAPHICAL ABSTRACT



HIGHLIGHTS

- It was interestingly found that the back side of butterfly *Papilio ulysses* wings exhibits better long-term durability of superhydrophobic properties under water than the front side of the wing.
- It was found that there are so much little hairs on and between the scales on the back side, which don't exist on the front side of the wings.
- The underwater superhydrophobic mechanism of the back side of butterfly wing scales was studied.
- The hairs between the scales on back side of butterfly wings could prevent the liquid from moving down rapidly underwater.

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ABSTRACT

Nature has always provided a lot of inspirations for engineers and scientists. The butterfly wing is a kind of typical surface that performs excellent properties of superhydrophobicity especially for the front side of the wings. However, in this work, it was interestingly found that the back side of butterfly *Papilio ulysses* wings exhibits a better long-term durability of superhydrophobic properties under water than the front side of the wing. In the process of the experiment, both sides of butterfly wings were soaked under the deionized water within 60 h and measured the changes of the contact angle (CA) at regular intervals. It was discovered that the back side of butterfly *Papilio ulysses* wings shows stronger hydrophobicity under continuous contact with water. In contrast, the front side of the wings was obviously somewhat "poorly" in the aspect of superhydrophobicity after a long soak underwater. Then, the optimized 3D configurations of the coupling structures were determined by using the Field Emission Scanning Electron Microscope (*FESEM*). It was found that there are so much little hairs on and between

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the scales on the back side, which don't existed on the front side of the wings. At last, the underwater superhydrophobic mechanism of the back side of butterfly wing scales was revealed. In fact, the strong superhydrophobicity underwater of the back side of butterfly wings should be owing to its special surface structures. The hairs between scales on back side of butterfly wings could prevent the liquid from moving down rapidly underwater. When it reached the new balance, the forces will form the second balance and the liquid level advanced slowly very much. So, the back side of butterfly wing exhibits a better long-term durability of superhydrophobic properties under water than the front side of the wings. If this functional "biomimetic structure" could be applied on metal surface, it would be potential not only to the passive drag reduction but also to preventing bacteria from adhesion to the ships or other aquatic vessels.

1. Introduction

After billions of years of evolutionary development, various species behave survival of the fittest. They have gradually showed their best features to the world [1]. All kinds of living creatures form a magical treasure house-nature. Learning from nature is always the source of the creation for human beings [2]. Among many excellent properties of the organisms, the research on the superhydrophobicity is one of the most hot spots and has attracted great interest of many engineers and researchers [3–5]. Many scientists have studied the superhydrophobic properties of specific surfaces from various aspects [6–12]. The biological community provides us with a lot of superhydrophobic models such as lotus leaf [13,14], peanut leaf [2], rose petal [15], butterfly wings and so on. It was found that the microstructure of surface plays a very important role in the superhydrophobic property. There are two typical superhydrophobic models. One type is that there is a layer of air pocket between the water droplet and the solid interface and the special three-phase contact line will be formed. The other one is that the water drop infiltrates into the microstructure of the surface and it will form two-phase interface of liquid-solid. The two models mentioned above are the famous models named Cassie and Wenzel model [16,17] respectively [18–20].

However, when some researchers have drawn their attention on the lotus leaf, it was gained that the liquid will completely wet the surface of the lotus leaf when the hydraulic pressure is 13.5 kPa [21–25]. There has been little attention to the properties of air-retaining under water relatively so far [26]. In fact, the superhydrophobic surfaces underwater can hold a layer of air between the liquid and the solid surfaces so that the vessel will reduce resistance during the voyage and can be prevented from bacteria adhesion. The use of drag reducing of superhydrophobic surfaces especially in microfluidic systems research has been in vogue [27]. So, it is very meaningful to study the ability to sustain the superhydrophobic property underwater for a long time. However, the key is that the air layer is not very stable under water. When we put the superhydrophobic surface in the water for a long time, the hydrophobic surface will be changed into the hydrophilic. The major factors that lead to the failure of the superhydrophobicity is the increasing hydraulic pressure or the damage of the microstructure [21,28]. To maintain the ability of superhydrophobicity under water is significant to reduce drag of some vehicles for sailing on the sea because the specific surfaces can hold a lubricating gas film between the surface and the liquid. Superhydrophobicity under water mainly depends on the existence of air layer and the air layer is not stable [29]. The two factors that effect the superhydrophobicity under water are hydraulic pressure and the time contacting the liquid. Although some scholars have done some exploratory work in this respect, the performance is not ideal. The theory is strictly limited to laboratory conditions [30,31].This is not only a difficult but also a hot spot.

Recently, the long-term durability of superhydrophobicity under water gradually has drawn our attention because of its special property especially in the field of navigation in a long distance. As a typical hotspot of the bionics field recently, buttery wings are endowed with a diversity of excellent properties [32–35], such as structural color [36–43], light trapping effect [44], water repellency at low temperature [45], observable optical response to temperature [46], highly selective vapour response [47], directional adhesion for fluidic control [48], which have inspired the interest of many researchers. When contacting with water, *Morpho* butterfly wings would present excellent superhydrophobic properties. The butterfly wing is one typical surface that performs excellent properties of superhydrophobicity especially for the front side of the wings. However, in this work, it was interestingly found that the back side of butterfly *Papilio ulysses* wings exhibits a better long-term durability of superhydrophobic properties under water than the front side of the wing. Firstly, both sides of butterfly wings were soaked under the deionized water and the changes of the contact angle (CA) was measured at regular intervals. It was discovered that the back side of butterfly *Papilio ulysses* wings shows stronger hydrophobicity under continuous contact with water. In contrast, the front side of the wings was obviously somewhat "poorly" in the aspect of superhydrophobicity after a long soak underwater. Then, the optimized 3D configurations of the coupling structure was determined. It was found that there are so much little hairs on and between the scales on the back side, which don't existed on the front side of the wings. At last, the underwater superhydrophobic mechanism of the back side of butterfly wing scales was studied. It was confirmed that the back side of butterfly wing exhibits better long-term durability of superhydrophobic properties under water than the front side of the wing. This work can be used as a reference for designing bionic drag reduction surfaces with underwater superhydrophobic properties and the fabrication of highly efficient gas-membrane drag-reduction devices such freighter, steamship, submarine and so forth.

2. Materials and methods

2.1. Preparation of the materials

The scientific type of the butterfly is *Papilio ulysses* (*Linnaeus, 1758*). There are two typical zones on both front and back surfaces of this butterfly wings. They are triangular and rhombus respectively. The samples with uniform rectangular size of 10 mm in length and 8 mm in width were cut off from not only triangular zones but also rhombus ones.