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One-step hydrothermal method to fabricate drag reduction superhydrophobic surface on aluminum foil

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ABSTRACT

Superhydrophobic surface, covered by micro or nano textured layer, can trap and retain air pockets and possesses unique excellent properties. Here we propose a novel one-step hydrothermal method to fabricate superhydrophobic surface on aluminum foil. The film of sheet structure is $Al[CF_3(CF_2)_{12}COO]_3$, which can provide micro structures and reduce surface energy. The as-prepared surface with high contact angle and low sliding angle has some interesting characteristics. In the test, the powder dirt can be easily removed from the surface and the formation of ice is inhibited on it. The drag reduction ratio of the superhydrophobic surface is about 20–30% at the velocity of 2–5 m/s. We envision this superhydrophobic surface has a great prospect in industrial applications.

1. Introduction

Inspired from the natural phenomenon that the lotus leaf is not dyed out of the sludge and the water strider can walk on the water, researchers have found the superhydrophobic phenomenon. In recent years, superhydrophobic surface has aroused widespread concern, owing to its excellent properties such as self-cleaning, corrosion resistance, anti-icing and drag reduction [1–4]. Generally, there are two ways to prepare superhydrophobic surface, the first is to create a suitable roughness on the hydrophobic surface, the second is to fabricate superhydrophilic surface with micro-nano structures and then modify the sample with chemical reagent to reduce surface energy [5,6]. The superhydrophobic surface can trap and retain air film underwater to reduce the contact area between solid surface and water. Therefore, this superhydrophobic surface is in Cassie-Baxter wetting state, which is defined as a high contact angle (>150°) and a low contact angle hysteresis [7,8]. So far various technologies have been used to fabricate superhydrophobic surface, such as chemical etching, laser micromachining, electrodeposition method and sol-gel method, etc. [9–12]. Maciej et al. have prepared superhydrophobic surface by laser ablation, replication, and RF plasma treatment, to improve the ability of industrial application [10]. Song et al. have fabricated superhydrophobic surface via electrochemical machining and fluoroalkylsilane modification and proved that rough structures and low surface energy is the crucial factors for superhydrophobicity [12].

In this paper, we present a novel one-step method to fabricate superhydrophobic surface on an aluminum substrate. The surface is evenly distributed with nanosheets, which form microcavities to trap air. The nanosheets are prepared by one-step hydrothermal reaction in a high pressure autoclave. With the increase of the reaction time, the density of the nanosheets becomes larger. When the reaction time is 1 h, the contact angle (CA) is 158° and the sliding angle (SA) is 3°. Compared with other common methods, this one-step method does not require expensive equipment, high voltage, strong acid or alkali. Its process is simple and causes less harm to the operators and environment.

When the as-prepared superhydrophobic surface is tilted in a certain angle, the dust can be easily removed by rolling droplets of water and the superhydrophobicity can inhibit the surface freezing at low temperature. Another interesting property of the as-prepared surface is drag reduction, which is due to the composite surface of air and solid underwater. The air pockets trapped by the micro-structures on the superhydrophobic surface can reduce the liquid-solid contact area, thus reducing the frictional resistance between water and substrate. The drag reduction property of superhydrophobic surface can help to reduce the energy consumption. For the marine ships, more than half of the energy used for propulsion is wasted on overcoming the surface friction [13]. In the pipeline of liquid transport, the energy of pump is mainly used for the wall friction. The application of superhydrophobic surfaces in these industrial fields will save energy and improve national

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economic efficiency. But most of the drag reduction research on superhydrophobic surface is focused on the theory of model simulation and numerical analysis. Koji et al. have investigated the effects of superhydrophobic surface on friction drag through direct numerical simulations of a turbulent channel flow, and found that the superhydrophobic surface inducing a slip length on the order of ten wall units or more is possible to have a large drag reduction [14]. There are a few studies on the experimental test of drag reduction property, and most of them are not directly. Gao et al. have found the drag reduction effect in polydimethylsiloxane microchannels when the flow is pulled by depressurization at the inlet, and drag reduction is expressed by the change of pressure and flow [15]. In our research, we use a self-designed friction resistance testing device to measure the friction drag at solid-liquid interface. The testing device can convert the mechanical signal into an electrical signal and achieve a real-time testing of solid-liquid interface friction drag. Through the test, we find that at the velocity of 2–5 m/s, drag reduction ratio of the superhydrophobic surface is about 20–30%.

2. Experimental

2.1. Materials and reagents

The substrate material is aluminum foil that is industrial grade (99% purity) and the thickness is 0.8 mm. The chemical reagents are aluminum oxide (Al_2O_3), perfluorotetradecanoic acid ($CF_3(CF_2)_{12}COOH$) and ethanol. These regents are utilized without further purification. In addition, deionized water is used throughout the experiment.

2.2. Fabrication of superhydrophobic surface

The aluminum foil is cut into small pieces (50 mm × 30 mm) and then polished by #800, #1700 sandpapers. After cleaning by acetone, ethanol and deionized water, the aluminum piece is vertically put into a high pressure autoclave where contains 0.1 g Al_2O_3 powder, 0.05 g perfluorotetradecanoic acid, 10 ml deionized water and 5 ml ethanol. Hydrothermal reaction takes place at 150 °C for a period, after that a superhydrophobic surface can be obtained. The illustration for the fabrication of the superhydrophobic surface is showed in Fig. 1.

2.3. Surface characterization

A field-emission scanning electron microscope (FE-SEM, TESCAN VEGA) is used to observe the morphology of the as-prepared aluminum samples. Energy dispersive spectroscopy (EDS) and X-ray photoelectron spectroscopy (XPS) are used to characterize the chemical composition of the as-prepared samples. A contact angle meter system (JC2000D2A, Shanghai Zhongchen Digital Technic Apparatus Co., Ltd.) is used to measure CAs and SAs of the superhydrophobic surface under ambient conditions.

3. Results and discussion

3.1. Surface morphology and wettability

After hydrothermal reaction, the sheet-like structures have been formed on the aluminum surface. Fig. 2 shows the SEM images of aluminum samples after hydrothermal reaction for different time. When the reaction time is 20 min, a few sheet structures are randomly distributed on the aluminum surface, and the CA of water is 145° ± 2°. Under this condition, the water droplets cannot slide on the sample, so the as-prepared surface is not superhydrophobic. As the duration of the hydrothermal reaction increases, more of the sheet structures are formed on aluminum surface. When the reaction time reaches to 1 h, the sheet structures are dense and evenly distributed on the aluminum surface. The as-prepared sample exhibits a well superhydrophobic property with the CA of 158° ± 2° and the SA of 3.5° ± 0.5°. As the reaction time continues to lengthen, larger flake structures begin to appear at substrate surface, and the CA of water decreases slightly. In addition, when the growth solution does not contain Al_2O_3 particles, the superhydrophobic surface also can be obtained. The SEM images are shown in Fig. 2e and f, when the reaction time is 1 h, the flaky clusters form flower-like structures and evenly distribute on the surface. When the reaction time is 2 h, the flake is denser and CA reaches to 160°. Compared Fig. 2c with e, the aluminum particles reduce the formation rate of the flake structures and ensure that the microstructures are formed by chemical bonds rather than physical deposition in a short reaction time. The SAs of different samples are in the supplementary materials.

3.2. Composition of superhydrophobic film

The chemical composition of the superhydrophobic surface is characterized by EDS and XPS. Fig. 3 shows the distribution of elements on the substrate after hydrothermal reaction for 1 h. The sheet structures consist of four elements about Al, C, O, and F, and each element is evenly distributed on the substrate. Fig. 4 shows the XPS results of the superhydrophobic surface. There are four signals: Al2p, C1s, O1s and F1s. The Al2p spectrum of the as-prepared sample is divided into two components: the signal

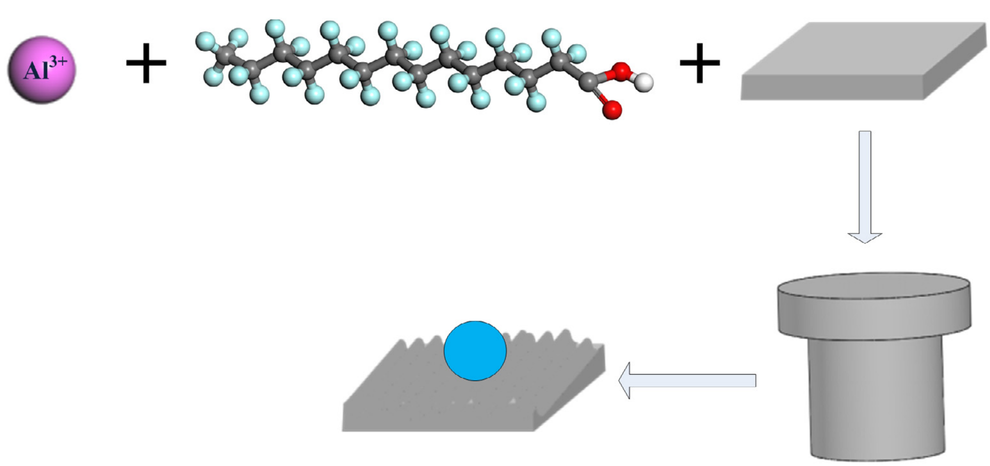

Fig. 1. Illustration for the fabrication of the superhydrophobic surface.

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