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Fabrication of a lotus leaf-like hierarchical structure to induce an air lubricant for drag reduction

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ABSTRACT

In this study, a lotus leaf-like hierarchical structure featuring microscale and nanoscale dimensions was fabricated through chemical deposition. Wetting and tribological experiments showed that the micro–nano hierarchical structure displays superhydrophobic and drag-reducing attributes. Simulation revealed that the structure with a micro–nano feature surface allows ultra-low friction drag reduction when fluid flows through microchannels by trapping air inside surface cavities. Experimental results proved the feasibility of the model in predicting the friction drag reduction performance of the structure. The model was thus used to investigate the effect of the distribution density of micropapillae on friction coefficient. Optimization results indicated that an interval ratio of 0.75 can improve the air fraction of the liquid/solid interface and thus reduce friction drag.
Novelty statement: In this work, a novel hierarchical structure has been successfully fabricated to improve the lubrication properties by its superhydrophobicity. The fabricated surfaces are used to test the effects of hierarchical structure on the values of friction coefficient. Results of wettability and lubrication experiments facilitate understand of reducing frication drag. The volume of fluid simulation method is used to explain the friction drag of the surface is reduced by air lubrication, and help optimization design the distribution density of micro roughness. The results are important because that it can provide feasible approach to have a broad prospect for micro/nano hierarchical structure surfaces for many technological applications.

1. Introduction

Barthlott and Neinhuis [1] discovered the "lotus effect," i.e., water droplets placed on the apex of nanostructures combined with microstructures do not wet the surface because the hierarchical dual-scale roughness of the micro–nano structure provides air cushion [2,3]. Friction drag can be reduced by superhydrophobic surfaces [4]. Studies in the past decade found that slip flow past a superhydrophobic surface reduces drag during fluid flow. To date, several scholars have reported various approaches to create hydrophobic surfaces for friction drag reduction. For example, Haibao et al. [5] reported that hydrophobic surfaces promote trapping of air on their microfeatures, thereby locally providing shear-free boundary conditions under flows. Gao et al. [6] found through numerical simulations that air film formation over periodically patterned substrates results in shear reduction. Martell et al. [7] reported that slip formation and shear reduction occur at the air-–liquid interface between microfeatures. Song et al. [8] found a maximum slip length of 20 μm for the laminar flow of the liquid through microchannels using hydrophobic surfaces. Yu et al. [9] observed that the macroscopic air layers formed on hydrophobic surfaces can cause apparent velocity slip for drag reduction. Fukuda et al. [10] tested the effect of hydrophobic surfaces with an air film by using ship models and obtained a drag reduction up to 80%.Shi et al. [11] revealed that superhydrophobic coating can decrease fluidic drag by introducing a thin layer of air surrounding the surface. Glen [12] demonstrated the importance of gas circulation within all or part of the surface structure. Bhushan et al. [13] studied the static contact angle and droplet evaporation during air pocket formation. Dong et al. [14] found that superhydrophobic coating induces drag reduction. Cheng et al. [15] reported that superhydrophobic coatings on curved surfaces with large areas demonstrated drag-reducing effects. Relative studies [16–18] indicated that surface hydrophobicity significantly influences fluid flow behavior.

The above literature review shows that hydrophobic surfaces can trap air and their microfeature helps to generate the air–liquid interface that replaces the liquid–solid interface [19]. In addition, most previous studies [20–23] focused on the hydrophobic property and observed interesting drag reduction effects through theoretical approach and practical experimentation in some cases. However, the hydrophobic micro–nano structure and flow frictional drag behavior of these

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Table 1
Bath compositions and operating conditions for electroless deposition.

Composition	Concentration (gL^{-1})	Condition
$CuSO_4$ $5H_2O$	10	Temperature: 50–80 °C
$NiSO_4$ $6H_2O$	2	pH: 9
$Na_3C_6H_5O_7$ $2H_2O$	23.5	Time: 20 min
NaH_2PO_2 H_2O	30	No stirring
H_3BO_3	30	
Polyethylene glycol 1W	10–50 ppm	

Table 2
Bath compositions and operating conditions for electrodeposition.

Composition	Concentration (M)	Condition
$NiCl{\cdot}6H_2O$	1	Temperature: 60 °C; pH: 4
H_3BO_3	0.5	Current density: 0.02 A cm^{-2}
Ethylenediamine dihydrochloride	1.5	Time: 5 min

surfaces have yet to be characterized. Hierarchically structured surfaces with hydrophobic properties form an air cushion and cover the entire surface. These surfaces have attracted increasing attention because of their wide range of potential applications, including microfluidic devices and controllable oil delivery. In this paper, we propose the microfabrication method to mimic the lotus-like micro–nano hierarchically structured surface with different distribution densities. Simulation and practical experimentation are also performed to investigate whether surfaces with hierarchical structure and roughness density distribution induce flow frictional drag reduction. The proposed method may contribute to improving the lubrication behavior in some engineering applications. The current work presents a new concept to understand the behavior of ultralow frictional coefficient lubrication generated by a hierarchical structure and proposes an optimization design method for its roughness distribution to improve lubrication.

2. Experimental procedure

2.1. Synthesis of copper micropapillae and nickel nanobranch

In this work, copper micropapillae were electroless plated onto 25 mm × 25 mm × 0.3 mm copper plates (commercial pure 99.5 wt %). First, Cu plates were pretreated by electrochemically degreasing in an alkaline for 1 min, acid-cleaned with 10% H_2SO_4 for 10 s, and then subjected to $PdCl_2$ activation for 1 min. After pretreatment, an orderly micropapillary layer was electroless plated on the substrate in an electrobath. The composition and other parameters of the electrolyte are given in Table 1. Subsequently, various distributions of the copper micropapillae were obtained from polyethylene glycol (PEG) 1 W with different concentrations (10–50 ppm) at 50–80 °C.

To obtain the hierarchal structure, nickel branch-like nanostructures were electrodeposited on the surface. The composition and other parameters of the electrolyte are listed in Table 2. Nickel coating was electrodeposited on the surface of the as-prepared copper microstructure.

At last, the long-chain stearic acid was used to lower the surface energy. The sample coated with the hierarchal coating was immersed in a 0.02 M ethanolic stearic acid solution for 5 min at room temperature. The main experiments for fabricating the superhydrophobic micro–-nano hierarchical surface are illustrated in Fig. 1.

2.2. Wetting and lubrication tests

The surface morphologies of the micro–nano hierarchical structure were observed via field-emission scanning electron microscopy (Nova 400 NanoSEM, FEI, USA). The elemental composition of the surface was investigated by energy dispersive spectroscopy (EDS). The water contact angles (CA) of the as-prepared surfaces were measured with an optical CA meter (CHtesting Co. JGW-360B). The average CA was measured using a water droplet size of 2 μL at five positions for each sample.

The friction drag reduction property of the hierarchical surface was investigated using a pin-disk tribology tester (Bruker, UMT3, USA) under water lubrication conditions (Fig. 2). A 2Cr13 steel pin-disk 20 mm in diameter and 5 mm in thickness was allowed to slide against a rotating plate specimen. The specimen plate was mounted in a basin soaked with water lubricant. Given the depletion of the lubricant present at the specimen surface due to side leakage, an upper insert was selected to ensure that the lubricant flows into the insert from which the lubricant was drained back into the center of the specimen. Lubrication friction tests were conducted at room temperature in laboratory air environment. The clearance gap between two friction surfaces was constantly set at 5 μm. The sensor was positioned properly to drive the shaft atop the disc holder and fix the clearance gap value. The sliding speed was 10 rpm, and no normal loads were used. On the basis of the measurement data, the friction coefficient was calculated in real time every 0.5 s during the sliding test. Each set of test conditions was performed twice to confirm the repeatability and reliability of the results.

3. Results and discussion

3.1. Morphological observation

Fig. 3 demonstrates the typical morphology of the fabricated surfaces before and after electrodeposition. In the upper figures, the Cu micropapillae fabricated by electroless deposition are obtained. The copper deposits are fine, dense, uniform and typically hemisphere shaped as shown in Fig. 3(a). Cu micropapillae are chemically deposited on the copper foil substrate 1.5 μm in height and about 1–1.5 μm in bottom diameter as shown in Fig. 3(b). The low figures are morphologies of dual-scale structured surfaces after the electrodeposition. Nickel nanoscale branch-like structures 200 nm in diameter and approximately 200 nm in height are densely and uniformly plated on the Cu micropapillae. The nanoscale branch-like nickel structures are significantly denser than the copper papillae in the first layer. Thus,

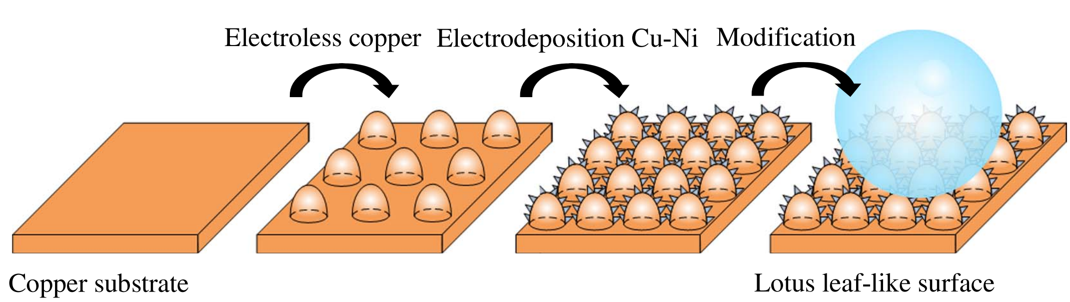

Fig. 1. Schematic of the fabrication of the hierarchically structured surface.