Micron 82 (2016) 9–16

Contents lists available at ScienceDirect

Micron

journal homepage: www.elsevier.com/locate/micron

Water repellent/wetting characteristics of various bio-inspired morphologies and fluid drag reduction testing research

Yuehao Luo[a,*], Wen Song[b], Xudong Wang[b]

[a] School of Engineering and Applied Science, The George Washington University, Washington D.C. 20052, USA
[b] School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an 710072, China

ARTICLE INFO

Article history:
Received 10 September 2015
Received in revised form
17 December 2015
Accepted 17 December 2015
Available online 24 December 2015

Keywords:
Anisotropic wetting
Micro-fabrication
Low resistance surface
Biological surface
Bionics

ABSTRACT

It is well-known that the bio-inspired sharkskin covering the original pattern has the apparent drag reduction function in the turbulent flowing stations, which can be regarded as "sharkskin effect", and it has progressively been put application into the fluid engineering with obtaining great profits. In this paper, the anisotropic wetting phenomena on sharkskin are discovered, the contact angles and rolling angles on different orientations are not the same. In addition, the hydrodynamic experiments on different sharkskin surfaces are conducted, and the experimental results illustrate that the super-hydrophobic and drag-reducing properties on deformed biological surfaces are improved to some extent compared to the original morphology, which has important significance to expand its practical applications.

1. Introduction

In the 21st century, the biological and bio-inspired technology has entered a new era, and so many amazing and shocking achievements are springing up (Bechert et al., 2000; Guo et al., 2014; Zhang et al., 2012a,b; Hu et al., 2014). Continuous efforts have been actively exerted to realize drag reduction and energy saving in the fluid engineering, such as airplane, nature gas pipeline, ship, robotic fish, submarine and other underwater moving objects (Bechert et al., 1997; Luo and Zhang, 2012; Zhang et al., 2011; Luo, 2015). Substantial inspiration has been drawn from observations and investigations on different creatures, mainly including sharkskin, lotus leaf, dolphin skin, gecko feet, dragonfly wing, spider silk and so on (Ren and Li, 2013; Zhao et al., 2012; Martin and Bhushan, 2014; Zheng et al., 2010; Luo et al., 2015a; Xin and Juan, 2011). After experiencing the long time nature selection, shark has evolved into one of the fastest swimming animals in the ocean, and its remarkable ability is not only depending on the perfectly streamline-shaped appearance that can lower down the friction, but also arises from the nano/micro hierarchical structured pattern covering over sharkskin. The fascinating drag reduction/low friction phenomenon has attracted so many attentions throughout the world.

Scientists in different fields have conducted great studies on the structure and pattern of sharkskin for several decades. Han and Wang (2011) fabricated the vivid sharkskin with high forming precision utilizing the direct bio-replicated method, and the experiments in water tunnel showed that the drag reduction rate could surpass 8% compared to the smooth skin. Park explored two different replicating methods to manufacture vivid sharkskin surfaces, and experimental results showed that the precision could be greater than 90% (Park and Kim, 2014). Movable shark scales with different attack angles can act as a passive dynamic factor to control the flow separation, and viscous resistance can be decreased apparently with smooth skin as baseline (Lang et al., 2014). Zhao investigated the hydrophobic property on sharkskin with potential engineering applications, and it was discovered that the wetting property could be affected by the scale arrangement and micro-riblets' structure (Zhao et al., 2014). Bio/micro-rolling method has been exploited to machine the vivid sharkskin surface, and the experimental results told me that the drag-reducing rate could surpass 8% (Luo et al., 2016; Luo and Zhang, 2013) In a word, the bio-inspired drag-reducing technology has huge room to be developed further.

Lots of actual experiments and numerical simulations have validated the superiorities of biological sharkskin compared to the simplified/straight micro-grooved surface in different aspects of drag reduction, anti-wear, self-cleaning and so on (Wang et al., 2013; Lin et al., 2002; Dou et al., 2012; Ge et al., 2014). But at the meanwhile, we should pay enough attention to that biological

* Corresponding author.
E-mail addresses: luoyuehao1985@163.com, luoyuehao@gwu.edu (Y. Luo).

http://dx.doi.org/10.1016/j.micron.2015.12.004

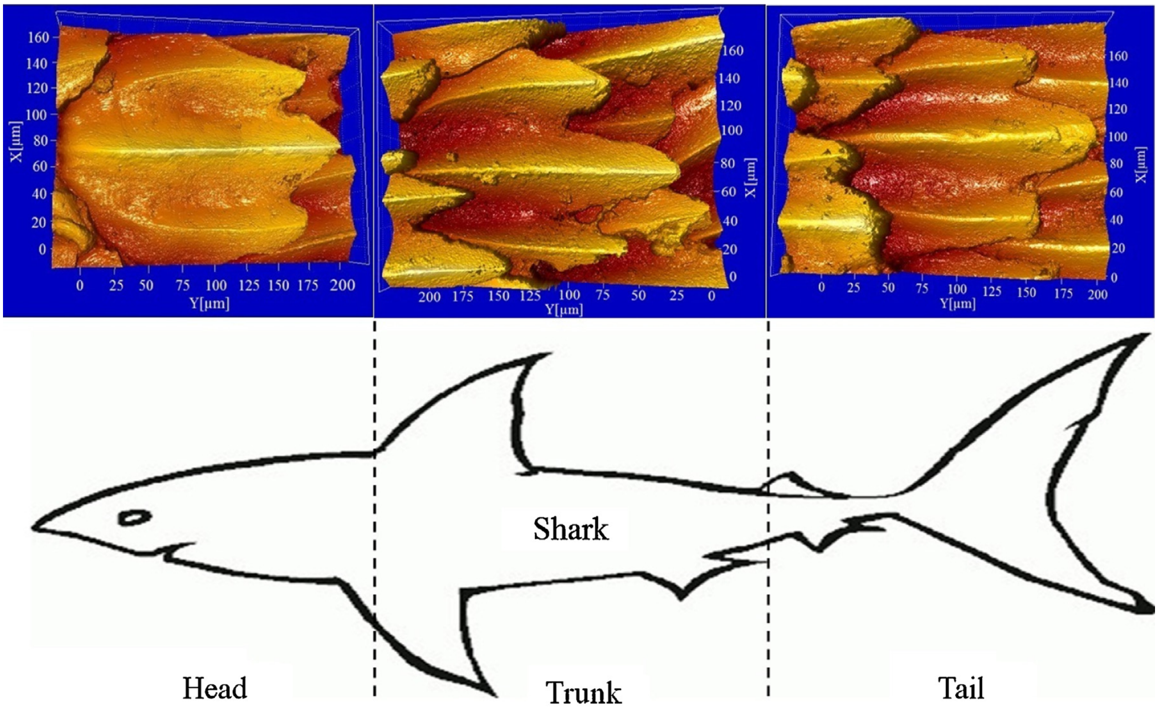

Fig. 1. Three dimensional image of sharkskin scale.

sharkskin pattern can only match its living surroundings perfectly, for purpose of expanding its practical applications in more hydrodynamic conditions, and the biological sharkskin pattern should be deformed further. However, the available methods are difficult to realize the function with high drag reduction effect. In this manuscript, the anisotropic wetting phenomena on sharkskin are investigated and drag-reducing surface with stretched sharkskin pattern is fabricated, and testing results show that it has developed into super-hydrophobic surface and its optimal speed scope with high drag-reducing rate is extended, which will inevitably prolong the biomimetic drag-reducing technologies in fluid engineering.

2. Wetting model on sharkskin

2.1. Sharkskin morphology

To the best of our knowledge, there are several hundred kinds of sharks in the ocean, although they have different appearances and sizes, there are the micro-grooves covering on sharkskin scales, which can protrude out of the viscous sub-layer and comb the turbulence, the consequence of which is that the force friction can be lowered down. The typical three dimensional images of single scales on different parts of shark are illustrated in Fig. 1.

2.2. Anisotropic wetting model on sharkskin

Since the ancient China, there has been the proverb that "Lotus leaf can never be polluted, although it comes from the dirty sludge", which implies that that the nano/micro hierarchical structures on lotus leaf can produce the water-repellent/super-hydrophobic phenomenon (Luo et al., 2015b; Guo et al., 2012, 2011a; Zhang et al., 2015; Wang et al., 2012). In the recent several decades, some experiments and facts have ascertained that sharkskin surface also holds the anti-fouling and super-hydrophobic function. Wetting theories of Young, Cassie and Wenzel have been utilized to investigate the isotopic surfaces for a long time, and the relevant academic and application achievements have been validated from different aspects (Wenzel, 1936; Cassie and Baxter, 1944) However, the recent studies have indicated that the above-mentioned theories cannot be suitable for predicting the contact angle on an anisotropic surface. Actually, a water droplet on the micro-textured surface exhibited both the non-composite and composite simultaneously, depending on the micro-texture orientation/direction.

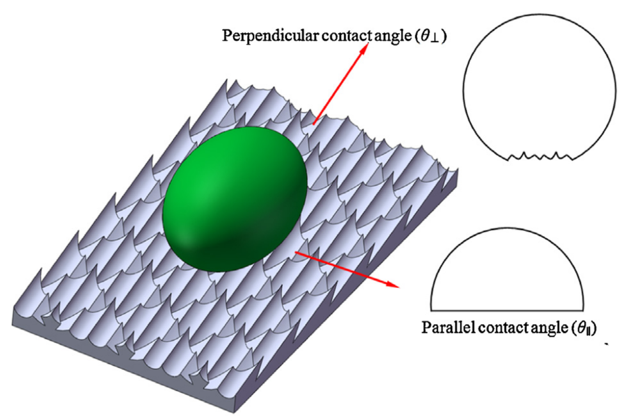

Fig. 2. Schematic drawing of water droplet on sharkskin.

The anisotropic wetting phenomenon on the micro-grooved surface has been investigated and explored by different academic groups. Along the parallel direction with the micro grooves, the water droplet can contact the sides of grooves, and therefore, the parallel contact angle $\theta_\parallel$ can be deduced from the modified Wenzel model. And meanwhile, along the perpendicular orientation, the air can be entrapped at the interface between the droplet and the solid on the micro-grooved texture, and therefore, the perpendicular contact angle $\theta_\perp$ can be induced by the Cassie–Baxter model. Sharkskin can be deemed as a special micro-grooved surface, and also one kind of anisotropic surface. The schematic drawing of water droplet on the sharkskin is illustrated in Fig. 2, and generally speaking, the