Bio-inspired drag reduction surface from sharkskin

Dengke Chen, Yang Liu, Huawei Chen, Deyuan Zhang

School of Mechanical Engineering and Automation, Beihang University, Haidian District, Beijing, People’s Republic of China

Abstract: Nature evolution provides nature surface treasures with special and fascinating surface function to inspire design, such as the drag reduction of sharkskin. In this overview, the morphology and mechanism of the sharkskin explained from different aspects, and various methods of fabricating surfaces with sharkskin morphology are illustrated in details, and then the applications in different fluid engineering are demonstrated in brief. This overview will improve the comprehension of the morphology and mechanisms of sharkskin, and methods of fabricating the surface with morphology, and the recent applications in engineering.

1 Introduction

With the improvement of the micro/nanofabrication, many advanced materials and sophisticated structures with special functions have been manufactured. Natural evolution provides natural surface treasures with a marvellous surface function to inspire innovative design, such as the drag reduction of sharkskin, superhydrophobicity of bird feather [1–3]. Biological samples found in nature with the surface functions can guide us to imitate and produce micro/nanomaterials, processes and micro/nanodevices. A model surface for superhydrophobicity and drag reduction is the leaves of the lotus plant, which have an intrinsic hierarchical structure [4]. Another biological sample of the natural surface is sharkskin with superior drag reduction. As well known, the sharkskin is covered with small individual toothlike scales called dermal denticles, whose ribs are mostly parallel with swimming direction of the water. These typical surface morphologies were demonstrated to play a greater role in the superior drag reduction. However, the sharkskin is complicated with the hierarchical surface pattern. How to large-scale or large-area fabricate bioinspired sharkskin was still the hot topic of micro/nanofabrication research for years. Moreover, the drag reduction mechanism in microscale was also widely investigated and several hypotheses were proposed. Especially apart from the superior drag reduction, the sharkskin was also found to have potential of protection from marine fouling and the defence against adhesion and growth of marine organisms, e.g. bacteria and algae [5–9].

In this review, we will introduce the morphology and mechanisms of the sharkskin and the applications in engineering. Especially, the fabrication methods of sharkskin are illustrated in detail.

2 Sharkskin surface morphology and drag reduction mechanism

2.1 Morphology of the sharkskin

Sharks swim fast at the speed of about 60 km/h to catch the prey in the ocean. The high speed is attributed to their specific hierarchical structure embedded in their skins. Three different micro/nano-hierarchical structures on the sharkskin have been discovered by Reif and Dinkelacker [10], and 2–7% drag reduction rate was demonstrated by compared with simple microgroove riblet in fluid flow. Walsh experimentally proved that the friction on bio-inspired sharkskin ribbed surface decrease at certain flow conditions. Bechert et al. [11, 12] conducted the hydrodynamic experiments and the results show that the drag rate of the bio-inspired sharkskin surface is ~10%. The continuous sharkskin surface fabricated by the microrolling method and drag reduction rate could be >10% compared to the smooth surface [13]. Under the inspiration of sharkskin, the biomimetic drag reduction microgrooves have been applied in a gas pipeline, yacht and achieved drag reduction >8%.

To better understand the mechanism of the sharkskin, the morphology of the sharkskin surface has been obtained as shown in the SEM image (Fig. 1). In general, sharkskin surface morphology was formed by perfectly aligning of placoid scales over the whole body. It can be seen that the size of sharkskin scale range of 0.1–0.2 mm and the height of groove is about 10–20 μm. More interestingly, the morphology is not same on the different sharkskin parts, as shown in Fig. 2.

Within the fastest swimming sharks, the height (~30 μm) and spacing (~40–80 μm) of the riblet is quite consistent, and sharks such as Squalus acanthias and Carcharhinus falciformis can alter the angle of attack of the scales relative to the skin, although the mechanism is unknown. In these shark’s scale pliability may be related to basal plate size reduction and therefore less firm anchoring in the dermis [14–16].

2.2 Drag reduction mechanism of sharkskin surface

Sharkskin has the effect of drag reduction compared to the smooth surface in turbulence, therefore, many scholars and scientists carried out lots of experiments and simulation analysis to explore the mechanism of the sharkskin surface. Although some mechanisms of the sharkskin are still not clear, some important conclusions about superior sharkskin effect have been put forward as follows [17–24]:

(i) ‘Protruding height’ theory. The theory thinks that the tips of microgrooves can stick out the viscous sublayer and the turbulence can be combed by the protruding height with decreasing intensity. In the meanwhile, the principal vortex can be reflected by the tips, and the second vortices are generated, which can lower the turbulence intensity further. With decreasing of turbulence intensity, the viscous force is lowered. The theory of the ‘protruding height’ has been widely accepted now.

(ii) Another important influencing drag reduction factor is the sharkskin scales attack angles. The attack angle of the sharkskin is not fixed and the angles varying from 10° to 40° with the flowing
conditions, and the back-flowing phenomenon can occur on the slope surface, which lead to a decrease of viscous drag. (iii) The sharkskin surface covered with mucus that could reduce the viscous drag in turbulent and laminar flowing conditions, especially in turbulent flowing. The mucus on the sharkskin have lubricating function and raised the depth of viscous sublayer, therefore, the slipping phenomena produced on the fluid and solid interface, which can result in the decrease of velocity gradient and viscous drag. Therefore, the mucus has the effect drag reduction in turbulence flow.

The sizes and shapes are not same in different parts of the shark’s body, and perhaps this is another reason that sharkskin has high drag reduction.

3 Methods of fabrication sharkskin

Sharks’ swimming maximum speed can be over 60 km/h, which attributed to sharkskin surface [25]. To effectively utilised the structure of the sharkskin and widen its applications, scientists developed various methods to fabricate a surface with sharkskin morphology. Generally, the fabrication methods can be divided into two types, i.e. biological surface-based fabrication and conventional process-based fabrication. In this section, eight different kinds of sharkskin fabrication methods are summarised, as shown in Fig. 3.

3.1 Direct bio-replicated method

The direct bio-replicated method is a feasible approach to fabricate the sharkskin textured based on the vivid sharkskin. This method takes direct use of sharkskin as a replica to realise the complicated sharkskin replication. This method has been regarded as an effective path to achieve the transition from ‘appearance imitation’ to ‘sprit imitation’ [26, 27]. The replication accuracy was validated to be over 95% as compared with real sharkskin [28]. The whale sharkskin was chosen as the replica template and the processes of the method are illustrated in Fig. 4. The processes of the direct bio-replicated method generally include the following steps: (i) Pre-treatment of sharkskin. This process is to retain the integrity of biological sharkskin and to improve the mechanical property which includes cleaning, chemical fixation, re-cleaning, dehydration and drying. (ii) Flat sharkskin template preparation after pre-treatment. (iii) Casting polymer materials into the template. (iv) Drying and demoulding.

To obtain highly precision sharkskin by bio-replication. vacuum casting is commonly applied to eliminate air bubbles from the bottom of the sharkskin in the pouring process [23].

3.2 Synthetic fabrication method

Sharkskin has mucus on their surface, which can lubricate and reduce friction in turbulence [29]. The synergetic effect between hierarchical structure and mucus was regarded as the main cause of superior sharkskin effect. Then, if some drag reduction agent is grafted on the surface, the drag reduction can be greatly enhanced as like sharkskin. Synthetic fabrication method was proposed and it can be simultaneously grafted nanolong chains to microgrooves on sharkskin and maintained the simplicity of direct bio-replicated forming [30]. Synthetic fabrication method combined grafting and soft die forming technology together and provided an effective method to manufacture sharkskin surface with high accuracy and excellent drag reduction performance. The processes of manufacture sharkskin surface as shown in Fig. 5, and it includes the following steps: (i) Pre-treatment of the sharkskin, which contains rigidity fixing, cleaning, chemical fixing, rinsing, dehydration, and drying. (ii) Moulding of the flexible female die. (iii) Formation of the synthetic drag reduction sharkskin, in which a graft copolymer of water-based epoxy resin...
and polyacrylamide was used as the substrate of the synthetic drag reduction sharkskin. The synthetic fabrication method perfectly combines the effect of rib structure and agent on the drag reduction. Of course, this process can also be available for the fabrication of vivid sharkskin as shown in Fig. 6.

3.3 Bio/microrolling method

Even though a bio-replication sharkskin can be fabricated by the direct method, which has the good forming precision and drag reduction effect of >12% is obtained [31, 32]. However, bio-replicated and synthetic fabrication methods only produce a small area surface and cannot satisfy needs in engineering application. Therefore, it is necessary to explore a new method to manufacture sharkskin surface with a large area.

To manufacture large area sharkskin, the rolling method was invented and optimum selection. It can be guaranteed the accuracy of the sharkskin morphology and speed of the manufacturer. Bechert utilised the microrolling method to fabricate an adjustable drag reduction surface for different flow conditions. Hirt and Thome explored rolling method in detail to realise large area fabrication of the riblet structure [33, 34]. Luo and Zhang exploited the microrolling method to fabricate continuous vivid sharkskin on a semi-cured epoxy resin coating [35]. In the fabricating process, the flat polymethyl methacrylate (PMMA) plate as a negative template is heated to glass state. The microrolling model and its processes are shown in Fig. 7. The main challenge is the fabrication of roller with complicated microscale surface morphology. In order to transfer the surface morphology from roller as vivid as possible, the UV curable polymer and thermal curable polymer are widely used as the substrate material.

3.4 Large proportional solvent swelling and shrunken method

As well known, the drag reduction of sharkskin is greatly dependent on its surrounding velocity, in which the maximum of drag reduction appears just in its living environment (60 km/h). Drag reduction declines when the application velocity is far away from its conventional swimming speed. In order to widen the potential applications of sharkskin effect in diverse fields, it is very necessary to adjust the sharkskin microstructure according to practical velocity. However, the direct bio-replicated and other methods used vivid sharkskin as replica template just only achieve 1:1 transfer sharkskin morphology [30]. These kinds of fabrication methods are difficult to keep the maximal drag reduction of sharkskin when the application conditions are different from the living conditions of shark. To solve these drawbacks, Pan et al. explored the large-scale equal-proportional amplification bio-replication of sharkskin based on solvent-swelling polydimethylsiloxane (PDMS) [36]. The solvent-swelling method mainly contains the following steps: (i) moulding of PDMS, (ii) swelling of PDMS mould, (iii) formation of amplified sharkskin, as shown in Fig. 8. The control of PDMS mould swelling is the most important for precision bio-scaling formation among the three steps. In the swelling process, n-hexane is chosen as the swelling agent and the swelling ratio is controlled by change of n-hexane concentration and the swelling times. By experiments, it is clear that the sharkskin can be amplified up to 45% in the one-time swelling process and much larger amplification can be realised by multiple amplification processes as shown in Fig. 9 [30, 35, 36]. The maximal drag reduction of amplified sharkskin was validated to be transferred to low-speed region.

In order to extend the potential application to high fluid velocity, the sharkskin should be shrunken in large scale [35]. Chen et al. developed the large-proportional shrunken bio-replication method. This method generally consists of three steps as shown in Fig. 10: (i) moulding of UV-curable material, (ii) shrinking of UV-curable mould and (iii) forming of shrunken sharkskin. By controlling the shrinking of UV-curable mould and utilisation of multiple shrunken methods, high accuracy and large shrunken bio-replication can be achieved. In general, the pre-polymer of UV curable material was bisphenol-A epoxy acrylate in replication process and triethylene glycol diacylate was used as the diluent.

![Fig. 5 Synthetic bio-replication of sharkskin process](image)

**Fig. 5** Synthetic bio-replication of sharkskin process

![Fig. 6 Fabrication samples and its surface morphology](image)

**Fig. 6** Fabrication samples and its surface morphology

- a PDMS sample
- b SEM of synthetic sharkskin

![Fig. 7 Model of rolling sharkskin surface (left is a schematic diagram, right is the roller with sharkskin surface)](image)

**Fig. 7** Model of rolling sharkskin surface (left is a schematic diagram, right is the roller with sharkskin surface)

![Fig. 8 Steps of the large proportional solvent swelling method](image)

**Fig. 8** Steps of the large proportional solvent swelling method

- a Original sharkskin
- b Amplified sharkskin

![Fig. 9 SEM images of original and amplified sharkskin surface](image)

**Fig. 9** SEM images of original and amplified sharkskin surface

- a Original sharkskin
- b Amplified sharkskin
2-Benzyl-2-(dimethylamino)-1-[4-(4-morpholinyl)phenyl]-1-butanone as the photo-initiator. The 621 A-80 and EM223 were mixed at 1:1 (wt/wt) and then their mixture was mixed with 2-benzyl-2-(dimethylamino)-1-[4-(4-morpholinyl)phenyl]-1-butanone at 100:1 (wt/wt) to generate solutions. The shrunken ratio than can be controlled by adjusting the solution volume [23]. SEM images of vivid sharkskin template and large proportion shrunken sharkskin are shown in Fig. 11 [35].

3.5 Direct 3D printing method

With the development of 3D printing technology, lots of 3D models can be printed directly. Luo proposed a direct 3D method to fabricate the sharkskin morphology and the procedures are as follows: (i) accurate scanning of the single biological scale, (ii) data processing and analysing, (iii) building a 3D digital model of a single scale and (iv) finishing the digital model and 3D printing of vivid scales. Different digital models of sharkskin scales can be building with importing the scanned data into the software of Solidworks, as shown in Fig. 12. After building a 3D digital model, the different size sharkskin surfaces can be fabricated by use of 3D printing machine, as shown in Fig. 13 [37]. Wen et al. scanning the sharkskin morphology and created a high-resolution view of sharkskin. Then the detailed model was built through scaled a single denticle and reproduced it thousands of times in a computer model, as shown in Fig. 14. Based on the computer model, 3D printer (Connex 500) was used to print the sharkskin membrane. Two different kinds of materials were applied to manufacture the membrane substrate and denticles in the process of printing, the membranes as shown in Fig. 15 [14].

3.6 UV-curable painting

Microembossing and microimprinting has become more and more popular in engineering application, but they limited to regular 2D microstructure, and difficult demoulding when applied to sharkskin 3D microstructure. In order to transfer vivid sharkskin microstructure to freeform surface, Chen et al. proposed flexible bio-replication coating method for large-area fabrication on a free-form surface based on the mechanism of microembossing as shown Fig. 16. The developed flexible bio-replication coating method is shown in Fig. 17 [38] where a long strip of the soft negative mould with a micromorphology of sharkskin tightly is wrapped on three plastic wheels, and a UV lamp is set inside. The UV curable paint was used as the coating material and was sprayed prior to UV rolling through. The rolling speed is great dependent on the film thickness and parameters of UV source such as height and power of the UV lamp.
3.7 Stretching deformed method

Sharkskin surface has excellent elastic, so the microstructure can be changed by exerting certain tension on the sharkskin surface, and different sizes and shapes sharkskin could be obtained when replication the microstructure was altered. The procedure of based on the mechanism is summarised in Fig. 18, and the main processes are follows: (i) pre-treating biological sharkskin template; (ii) mixing the silicon rubber and curing agent with a mass or molar ratio of 100:1 and pouring the mixture on the biological template; silicon rubber can be cured at room temperature; (iii) turning over biological sample; (iv) stretching and fixing the negative template; (v) filling the resin polymer onto the negative template; (vi) artificial sharkskin can be acquired after the flexibly demoulding to obtain bio-inspired surface with deformed sharkskin morphology [29, 39]. In this process, the mould-release agent is used to ensure the forming effect. Images of different sharkskin with tension are shown in Fig. 19.

3.8 Bio-inspired sharkskin surface

The above methods can realise the replication of vivid sharkskin by direct use of the vivid sharkskin as a template. Although 3D hierarchical sharkskin is fabricated, these methods are also limited to the scarcity of sharkskin resource. In order to resolve the fabrication difficulties of complicated sharkskin, various bio-inspired drag reduction surface structures were proposed under the inspiration of sharkskin microstructure. In the previous study, scientists deemed the real sharkskin microstructure as the simplified microgrooves with three U, V-shaped or even herringbone riblets [17], as shown in Fig. 20. An engineered surface microtopography based on the sharkskin has been designed on a poly(dimethylsiloxane) elastomer (PDMSe) as shown in Fig. 21 [40], and several commercial bio-inspired thin films were put into market such as Sharklet AF™. These kinds of bio-inspired surfaces with various microstructure possess the function of not only a superior drag reduction but also antifouling, which can be widely applied in medical devices, submarine and even gas pipeline.

4 Application of the bio-inspired sharkskin surface

4.1 Superior drag reduction in engineering

Sharkskin has superior drag reduction, which can find applications in diverse field. The first one is the swimsuit to enhance the swimming speed. Owing to the assistance of high-tech all-over bodysuit,
Spitz won seven gold medals in Athens Olympic and Phelps earned 14 gold medals in Beijing Olympic as shown in Fig. 22. This bodysuit was designed under the inspiration of sharkskin effect. To keep the fair in swimming competition, this kind of swimming suit was banned after 2010.

Another important application of sharkskin surface is the navigation and ship. Carman explored the surface effect of drag reduction for a ship with bio-replication sharkskin and found that it has an excellent drag reduction. The boundary layer remains smooth at low Reynolds and called laminar. Laminar boundary layers are fragile and separate from the surface when they encounter an adverse pressure gradient. Based on the theory, the golf ball with the bio-inspired surface was utilised, which is to make it fly farther, as shown in Fig. 23.

Recently, with the demands on the energy consumption and high speed becoming urgent, many other applications are anticipated widely such as racing car, high-speed train, airplane, gas pipelining and so on, as shown in Fig. 24.

4.2 Antifouling effect in engineering

Apart from drag reduction, antifouling is another important function of sharkskin. To compare the antifouling function, Chen et al. tested three type samples (smooth, microgroove, and bio-replicated vivid sharkskin surface) by immersing in the open algae pond. Static and dynamic antifouling tests were carried out by keeping the samples steady or moving in the pond. The antifouling experiments clearly demonstrated that antifouling of the bio-replicated sharkskin is remarkable better than smooth and microgroove surface. The adhesion of diatoms can be reduced about 90% rather than smooth surface. Of course, as the sample keeps moving, the antifouling can be further improved as compared with static state as shown in Figs. 25 and 26.

5 Conclusions

In this overview, the recent research of sharkskin is systemically illustrated and various fabrication methods are introduced in brief. The morphology of the sharkskin surface was made clear until now, but its mechanism of drag reduction is not yet clear. To unveil its mechanism is still the hot topic of research. Superior
drag reduction of sharkskin attributes to its hierarchical surface structure. In order to widen its application to diverse fields, various fabrication methods were developed which consist of bioinspired micromorphology design, et al. 1, as the potential applications antifouling is also anticipated apart from drag reduction. How to large-area and large-scale fabrication of sharkskin is necessary to be explored from now.

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All procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted.

7 References

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