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Investigation on fabricating continuous vivid sharkskin surface by bio-replicated rolling method

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ABSTRACT

Vivid sharkskin has been fabricated by a direct bio-replicated micro-imprinting method in previous studies, and the good drag-reducing effect has been validated in water tunnel. However, for surface of fluid is larger than the whole skin of shark, splicing and affixing steps are absolutely necessary. One hand, the complexity of process will be increased significantly, the other hand, the stress concentration produced by external flow will be produced on jointing seams, especially for those which are perpendicular to the flowing direction, the jointing surface will be destroyed at a high speed of flowing, and perhaps, the drag-reducing efficiency can be decreased. Therefore, how to manufacture continuous vivid sharkskin in a large area has become an urgent problem to be resolved. In this paper, for eliminating the influence of wedge angle on scale's back, the sputtering and photo lithography processes are put into application and the continuous vivid sharkskin surface with good forming effect is fabricated by rolling process at last.

1. Introduction

Shark is one of the most swimming fastest animals in the ocean, and there are many small grooves on the surface of scales, which can stick out of the viscous sublayer and has the effect of inhibiting the turbulence and reducing wall resistance. Therefore, many kinds of simplified straight micro-grooves imitating sharkskin surface have been manufactured and applied into fluid engineering, the machining process, forming quality and testing results in fluid are all advanced and satisfactory. Walsh discovered the drag reduction performance of V-groove riblet was a function of the non-dimension groove height h^+ and spacing s^+, and the maximum of drag reduction was about 8% [1]. Liu et al. carried out the experiments of 25.4 mm and 50.8 mm diameter pipes lined with a film of micro-grooved equilateral triangles of base 0.11 mm, and the drag-reducing efficiency could reach 5–7% in fully developed turbulent flow of water [2]. Bechert et al. manufactured the grooved surfaces with different sizes and shapes, and then carried out the experiments in water tunnel, and the maximum of drag-reducing efficiency was 9.9% [3,4]. Koeltzsch et al. investigated the velocity field over convergent and divergent riblet patterns by hot-wire measurements in turbulent pipe flow. Significant changes in the near wall velocity field were found, and drag reductions up to about 10% were measured [5]. Viswanath told us that riblets with symmetric V-grooves (height equal to spacing) with adhesive backed film manufactured by the 3M company in United States had been widely investigated and the results had revealed enormous consistency with regard to the degree of drag reduction as well as certain aspects of flow structure, and the maximum of viscous drag reduction in the range of 4–8% had been measured on a variety of two-dimensional flows with zero or mild pressure gradients [6]. Nakao performed the experiments of pipes with V shape riblets were tested at Reynolds numbers between 5×10^3 and 4×10^4, and all riblet pipes indicated some drag reduction at different degrees [7]. Choi et al. adopted the direct numerical simulation method to explore the drag-reducing mechanism on straight grooved surface comprehensively, and the conclusion of that the drag-reducing efficiency could exceed 8% was received [8]. Li et al. fabricated drag-reducing surface by ultrasonic elliptical vibration cutting (UEVC) technology efficiently, and the drag reduction skin can be applied in different velocities [9]. Klocke et al. produced a defined straight riblet structure by the incremental rolling process on Ti–6Al–4V, and the test body with this geometry would be analyzed for reduction in friction under real flow conditions [10]. Luo and Zhang have applied the biomimetic micro-grooved drag reduction technology into nature gas pipelining, and the testing results in filed showed that the pressure loss at the same circumstance can be decreased more than 8% [11]. Denkena et al. grinded the micro-structured functional surfaces called riblets, and the purpose of which was to grind special designed riblets (microgrooves with a width of 40 μm and depth of 20 μm) on the surfaces of compressor blades with the purpose of drag reduction in turbulent flow [12].

Biology has been imitated but unsurpassed so far, as far as the real sharkskin is concerned, its drag-reducing efficiency can reach

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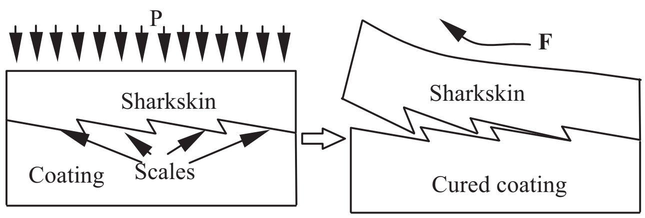

Fig. 1. Elastic demoulding of sharkskin.

more than 12%, which is superior to that of simplified straight micro-grooves. Many researchers have explored the manufacturing processes and investigated the drag reduction mechanism of real sharkskin. Zhang et al. adopted the direct bio-replicated method to fabricate vivid sharkskin, and the testing results in water tunnel indicated that the wall resistance was decreased about 12% than that of smooth surface on some certain circumstances [13]. Lang et al. explored the influence of bristled sharkskin on boundary layer control, and it was concluded that the scales of some fast-swimming sharks were pliable and might erect passively, which could affect the drag reduction effect [14,15]. Zhang et al. analyzed the micro flow field on the real sharkskin surface by numerical simulation comprehensively, and the drag-reducing efficiency in theory could reach more than 12% [16]. Oeffner and Lauder studied the self-propelled swimming speed of different surfaces, and it was concluded that flexible sharkskin foils actually showed a substantial improvement in swimming performance of an average of 12.3% (with a maximal improvement of almost 20%) as compared with the same foils with the surface denticles sanded off, and they stick to the opinion that the sharkskin denticles might thus enhance thrust, as well as reduce drag [17]. Luo et al. machined the vivid trans-scale enlarged sharkskin scales by 3D imprinting method, the visual impression could be exposed to people easily, and the conclusion was received that the "back flowing" phenomenon was one of the most important factors to produce higher drag-reducing efficiency than simplified straight grooved surface by numerical simulation [18]. Therefore, the sharkskin is more advanced than simplified straight micro-grooved surface in drag reduction effect, and it is very necessary to manufacture the continuous vivid sharkskin surface in a large area.

2. Experimental

2.1. Materials and methods

In previous studies, due to the complexity of biological sharkskin, the direct bio-replicated imprinting method has been put into application, and the good forming quality and drag-reducing effect of more than 12% is obtained [19,20]. In the fabricating process, the flat polymethyl methacrylate (PMMA) plate using as negative template is heated to glass state, and the biological sharkskin template is stacked on it with its scale side adown, and then, the isostatic pressure is applied on the template until the coating is cured completely, the sharkskin negative template can be received after the elastic demoulding, as shown in Fig. 1, the vivid sharkskin of silicon rubber can be produced after turnover. However, the area of single sharkskin is limited, the new method to fabricate biomimetic drag-reducing surface in a large area should be investigated and explored.

The rolling method is the best way to manufacture continuous sharkskin in a large area, and the model is shown in Fig. 2. As far as the sharkskin scale is concerned, its size is about 0.1 mm × 0.1 mm, and it is so tiny to the diameter of sharkskin roller and can be seemed as vertical demoulding in rolling, but the coating is semi-cured and not shaped completely, if the vertical demoulding is performed, the coating will be destroyed by the wedge angle on the back of scale, which can lead to the failure of rolling process, therefore, it is urgently needed for us to search out a new way in this regard.

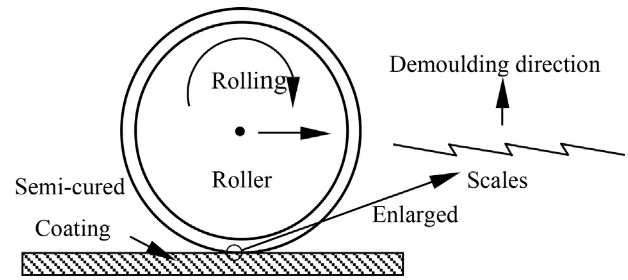

Fig. 2. Model of rolling sharkskin surface.

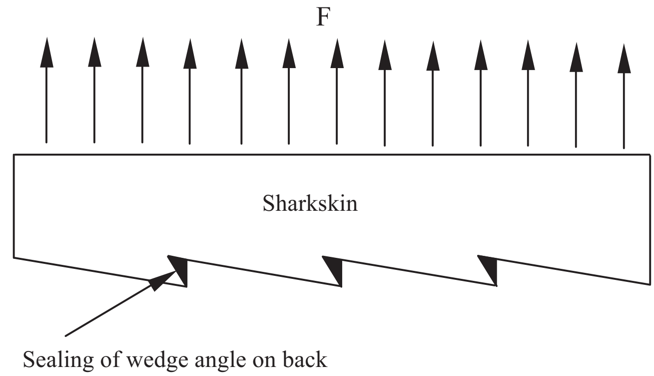

Fig. 3. Model of sharkskin with wedge angle sealed.

As illustrated in Fig. 3, if the wedge angle on the back of scale is sealed, the rolling process can be carried out with the semi-cured coating not being destroyed successfully. Therefore, how to avoid the influence of the wedge angle on scale's back has developed into a crucial problem in rolling process. Fortunately, the photo lithography process can make this function accessible. In which, the positive photoresist can be cured by baking, and then it can be decomposed into some substance by UV light with the given wavelength, which can be rinsed by developing solution and deionized water. But the sharkskin scales are transparent, as shown in Fig. 4, if the photo lithography process is carried out without other measures, the cured photoresist under the scale will also be decomposed, and therefore, the sputtering step should be adopted to ensure the scale lightproof.

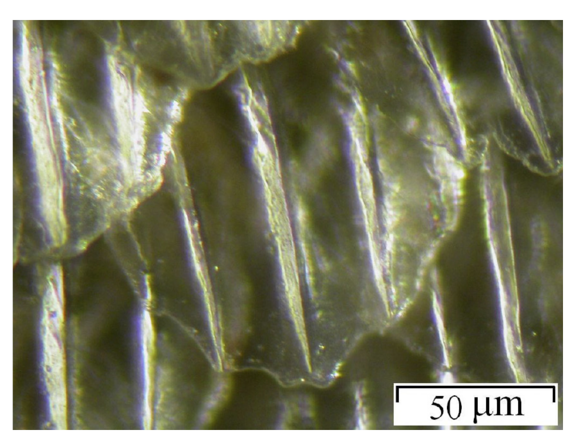

Fig. 4. Surface of biological sharkskin.