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Tribological Performance of Bio-Inspired Surface Textures Fabricated by SLA 3D Printing

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Abstract

Tribological performance, particularly friction and wear, is one of the key factors determining the service life of engineering components. Although stereolithography (SLA) 3D printing has been increasingly adopted for various functional applications, studies on the tribological performance of SLA-printed surfaces remain limited. Surface texturing inspired by biological systems offers a promising approach to improve surface functionality. This study investigates the friction and wear behaviour of bio-inspired surface textures fabricated using SLA 3D printing. Five texture geometries were evaluated, namely original snake dorsal, simplified snake dorsal, snake ventral, shark micro-riblet, and giant salvinia leaf textures. Tribological tests were performed using a pin-on-disc tribometer under a normal load of 10 N and a rotational speed of 200 RPM. The results show that surface texture significantly influences tribological behaviour. The original snake dorsal texture exhibited the lowest wear of 0.0025 g, indicating superior wear resistance, while the snake ventral texture produced the lowest friction force of 2.82 N. In contrast, the shark micro-riblet texture generated the highest friction of 3.58 N. These results demonstrate that different bio-inspired geometries produce distinct tribological responses and confirm the potential of SLA 3D printing for the fabrication of functional textured surfaces.

Keywords: *bio-inspired surface; friction; stereolithography; surface texture; wear*

Abstrak

Kinerja tribologi, khususnya gesekan dan keausan, merupakan salah satu faktor penting yang menentukan umur pakai komponen teknik. Meskipun teknologi pencetakan tiga dimensi stereolithography (SLA) semakin banyak digunakan pada berbagai aplikasi fungsional, penelitian mengenai kinerja tribologi permukaan hasil cetak SLA masih relatif terbatas. Tekstur permukaan yang terinspirasi dari sistem biologis (*bio-inspired surface texture*) menawarkan pendekatan yang menjanjikan untuk meningkatkan fungsionalitas permukaan. Penelitian ini bertujuan untuk menginvestigasi perilaku gesekan dan keausan pada tekstur permukaan bio-inspired yang difabrikasi menggunakan teknologi SLA. Lima geometri tekstur dievaluasi, yaitu *original snake dorsal*, *simplified snake dorsal*, *snake ventral*, *shark micro-riblet*, dan *giant salvinia leaf*. Pengujian tribologi dilakukan menggunakan tribometer pin-on-disc dengan beban normal 10 N dan kecepatan putar 200 RPM. Hasil penelitian menunjukkan bahwa tekstur permukaan memberikan pengaruh yang signifikan terhadap perilaku tribologi. Tekstur *original snake dorsal* menghasilkan keausan paling rendah yang menunjukkan ketahanan aus terbaik sebesar 0,0025 gr, sedangkan tekstur *snake ventral* menghasilkan gaya gesek paling rendah sebesar 2,82 N. Sebaliknya, tekstur *shark micro-riblet* menghasilkan gaya gesek tertinggi sebesar 3,58 N. Hasil ini menunjukkan bahwa setiap geometri bio-inspired memberikan respons tribologi yang berbeda serta mengonfirmasi potensi teknologi SLA untuk fabrikasi permukaan bertekstur fungsional.

Kata kunci: *bio-inspired surface*; gesekan; keausan; *stereolithography*; tekstur permukaan

1. Introduction

Surface condition plays an important role in determining friction and wear performance in engineering applications. Surface texturing has been widely used as an effective approach to control tribological behaviour, particularly by modifying contact mechanics and lubrication conditions. In recent years, bio-inspired surface textures that are derived from natural systems have attracted significant attention due to their ability to provide optimized functional performance. Examples include shark denticles for drag reduction [1,2], snake scales for friction control wear resistance [3,4], gecko-inspired surfaces for adhesion [5], and plant-inspired textures such as lotus leaf for super hydrophobicity [6].

Various fabrication methods have been developed to reproduce these bio-inspired textures. Conventional techniques include laser surface texturing, lithography, embossing, and advanced coating or synthesis methods. For example, shark denticle structures have been fabricated using UV-LiGa processes and roller embossing on polymer films [7], while laser surface texturing has been applied to replicate fish scales and snake scales on titanium alloys [8]. In addition, additive manufacturing approaches such as laser-powder bed fusion have been used to create micro-textured metallic surfaces [9], and direct laser lithography has been employed to produce plant-inspired hydrophilic structures [10]. Although these methods can achieve high geometric accuracy, they are often complex, time-consuming, and limited to specific materials or scales.

Stereolithography (SLA) 3D printing has recently emerged as a promising alternative for fabricating complex surface textures with relatively high resolution and design flexibility. Although the SLA technology was initially used for prototyping, the SLA-printed products have increasingly been utilized for functional applications, including robotic components [11], medical devices such as microneedles [12], and drug delivery systems [13]. However, challenges remain in both mechanical properties and tribological performance.

Several studies have focused on improving the mechanical properties of SLA-printed materials through material modification [14–16], optimization of printing parameters [17–19], and post-processing techniques [20,21]. These efforts have contributed to enhancing the structural performance of SLA products and expanding their potential for practical use. However, most existing studies mainly address mechanical behaviours, while investigations on tribological performance, particularly friction and wear, are still very limited.

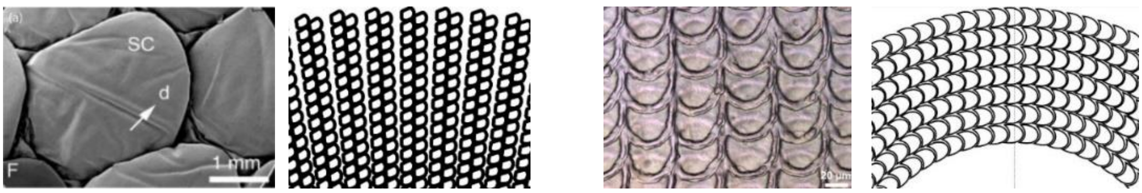
Although several studies have investigated bio-inspired surface textures or SLA-printed components, comparative tribological studies on different bio-inspired texture geometries fabricated using SLA are still limited. Most previous studies focus on a single texture design or emphasize fabrication and mechanical performance rather than tribological behaviour. As a result, the influence of different bio-inspired geometries on friction and wear under identical manufacturing and testing conditions has not been clearly understood. A comparison is therefore needed to identify the advantages and limitations of each texture design and to assess the feasibility of SLA for manufacturing functional tribological surfaces.

This study aims to investigate the tribological behaviour of bio-inspired surface textures fabricated using SLA 3D printing. Friction and wear performance are systematically compared under identical testing conditions to clarify the influence of texture geometry. The findings provide a better understanding of the suitability of different bio-inspired textures for tribological applications and further demonstrate the potential of SLA as a practical manufacturing method for functional textured surfaces.

2. Material and Method

2.1. Surface Texture Design

Five types of bio-inspired surface textures were investigated in this study, namely original snake dorsal (SD1), simplified snake dorsal (SD2), snake ventral (SV), shark micro-riblet (SMR), and giant salvinia leaf (GSL). The geometries were adopted from previous studies and adjusted to match the limitations of the design software and fabrication process. The texture designs are depicted in Figure 1.



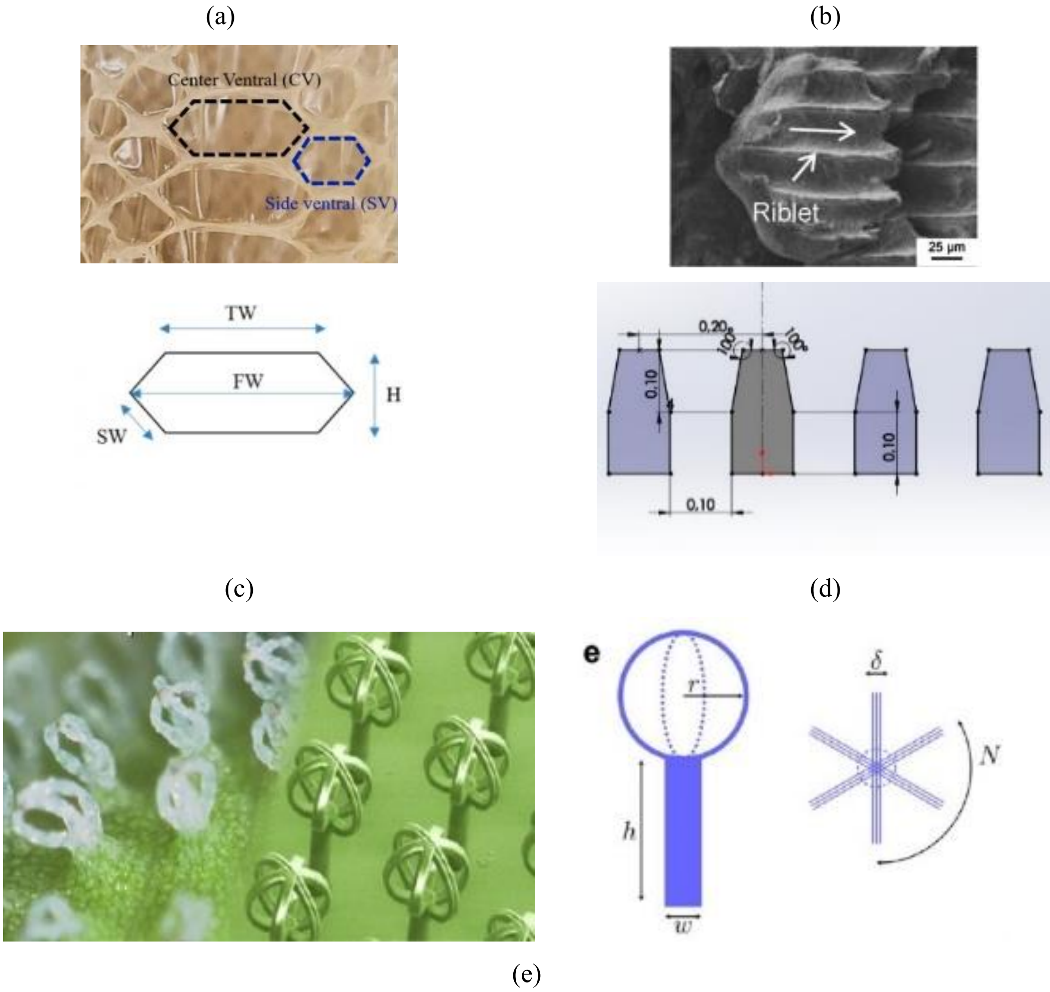


Figure 1. Bio-inspired designs: (a) original snake dorsal **[22]**, (b) simplified snake dorsal **[22]**, (c) snake ventral **[9]**, (d) shark micro-riblet, and (e) giant salvinia leaf **[10]**.

The SD1 texture follows the original geometry of snake dorsal scales, while SD2 represents a simplified version. The SV texture was derived from snake ventral scales. The SMR texture was based on shark denticle riblets, and the GSL texture was inspired by the surface structure of giant salvinia leaves. Due to fabrication constraints, scaling adjustments were applied to all textures while maintaining their characteristic features. All specimens were designed with a uniform base geometry to ensure consistent testing conditions.

Due to fabrication limitations, the original bio-inspired geometries were scaled while preserving their characteristic features. The original snake dorsal (SD1) texture was reduced to approximately 25% of the original scale, resulting in a characteristic scale size of about 0.75 mm. The snake ventral (SV) texture was reduced to approximately 20% of its original dimensions, with feature heights ranging from 0.62 to 0.84 mm. The shark micro-riblet (SMR) texture was enlarged by a factor of two from the reference geometry, whereas the giant salvinia leaf (GSL) texture was enlarged by a factor of 250 from the artificial hair geometry reported in the literature.

2.2. Specimen fabrication

The specimens were fabricated using a resin-based stereolithography (SLA) 3D printer (Anycubic Photon Mono X) with eSun standard resin material. The printing parameters included a layer thickness of 0.05 mm, normal exposure time of 3 s, and bottom exposure time of 40 s. All specimens were printed in a horizontal orientation to ensure identical manufacturing conditions for all surface textures. Post-processing consisted of washing the specimens for 20 minutes using Formlabs Form Wash, followed by curing at 60°C for 20 minutes using Formlabs Form Cure. Each surface texture type was fabricated in three specimens.

2.3. Tribological Testing

Tribological tests were conducted using a pin-on-disc tribometer (DUCOM TR-20 NEO series). A 10 mm diameter AISI 52100 steel ball was used as the counterface. The tests were performed under a normal load of 10 N, a rotational speed of 200 RPM, and a wear track diameter of 70 mm. The tests were stopped after the coefficient of friction reaches a steady state phase. The schematic of pin-on-disc tribometer test is depicted in Figure 2.

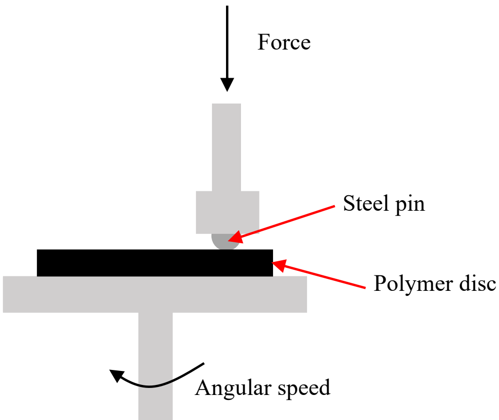


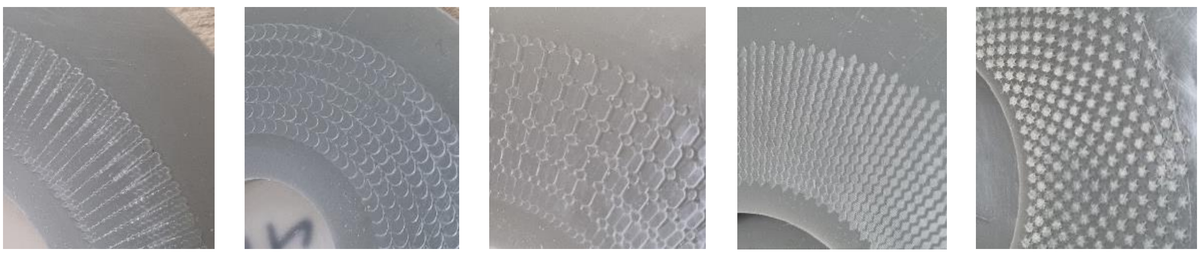
Figure 2. Pin-on-disc tribometer, schematically.

Friction data were recorded continuously during testing, while wear was evaluated by measuring the mass loss of the specimens before and after the test. Each test was repeated three times, and the average values and standard deviations were calculated for analysis.

3. Results and Discussion

3.1. Fabrication Result

All designed bio-inspired surface textures were successfully fabricated using SLA 3D printing, see Figure 3. Each texture type was produced in three specimens, resulting in a total of 15 samples. The printed specimens show that the overall geometry of the textures can be reproduced well, although slight surface imperfections are still visible, which is typical for resin-based additive manufacturing.



(a) (b) (c) (d) (e)

Figure 3. The printed specimens of all textures: (a) original snake dorsal, (b) simplified snake dorsal, (c) snake ventral, (d) shark micro-riblet, and (e) giant salvinia leaf.

3.2. Friction Behaviour

The friction behaviour of all specimens was obtained from pin-on-disc testing and analysed under steady-state conditions. Figure 4 shows that the friction curves generally show two distinct regions: the running-in stage and the steady-state stage. The running-in stage is characterized by fluctuating friction due to initial surface roughness and debris formation. After this stage, the friction becomes more stable, indicating steady-state conditions. The tests were terminated at this stage because the objective of the study was to compare the steady-state friction behaviour of different surface textures. Under the present test conditions, the steady-state condition was typically reached after approximately 90 s. The average friction force during the steady-state stage was used for subsequent analysis.

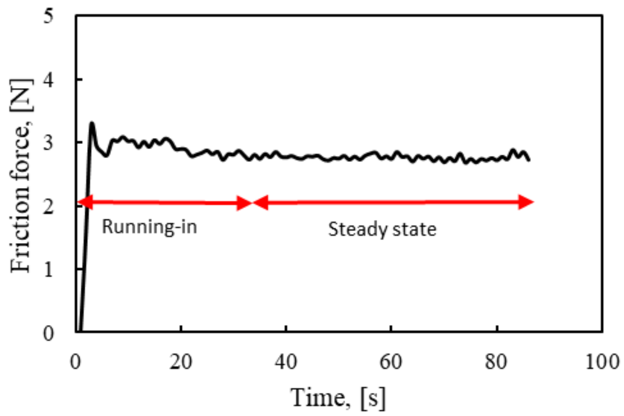


Figure 4. Friction force as a function of time.

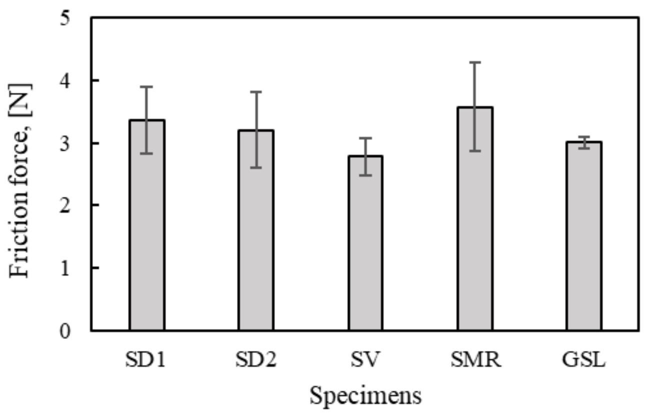


Figure 5. The average friction force at a steady state stage for all specimens, each result was obtained from three independent measurements (n = 3).

The average friction force for each texture shows clear differences among the specimens as can be seen in Figure 5. The snake ventral texture (SV) exhibits the lowest friction value that can be associated with reduced real contact area smoother sliding interaction. In contrast, the shark micro-riblet texture (SMR) shows the highest friction, suggesting stronger interaction between contact surfaces. Similar behaviour has been reported in riblet structures, where certain geometries can increase friction depending on orientation and scale [23]. A comparable trend was also reported by Yuan et al. [24], who demonstrated that the frictional performance of micro-grooved surfaces strongly depends on groove orientation and operating conditions. Consequently, the magnitude of friction reduction may vary with material properties and testing conditions. The SD1, SD2, and GSL textures exhibit intermediate values, with GSL showing relatively stable behaviour with low variation.

3.3. Wear Behaviour

Wear performance was evaluated based on mass loss measurements before and after testing. The results indicate that surface texture significantly influences wear behaviour. Among all specimens, the original snake dorsal texture (SD1) exhibits the lowest wear, indicating the best wear resistance. This is followed by the shark micro-riblet (SMR), while the giant salvinia leaf (GSL) and simplified snake dorsal texture (SD2) textures show moderate wear values. The snake ventral (SV) texture demonstrates the highest wear among all specimens. The superior wear resistance of SD1 can be attributed to its geometry, which may promote more uniform load distribution and reduce localized stress concentration during sliding contact. Similar observations have been reported in previous studies, where appropriate surface texturing can improve wear resistance by modifying contact mechanics and reducing direct asperity interaction [25]. In contrast, the higher wear observed in SV suggests that its surface geometry is less effective in supporting contact loads under dry sliding conditions. This may lead to increased material removal due to higher local stress and unstable contact conditions.

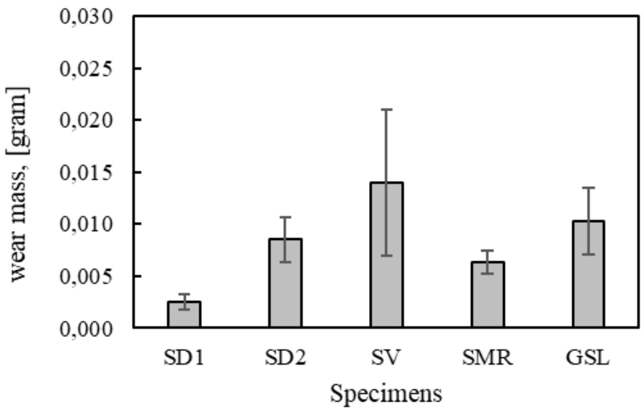


Figure 6. Wear mass of all specimens, each result was obtained from three independent measurements (n = 3).

3.4. Discussion of Texture Performance

The results clearly demonstrate that different bio-inspired surface textures produce distinct tribological responses. A trade-off between friction and wear is observed depending on the texture geometry. The snake ventral texture (SV) provides the lowest friction, indicating its effectiveness in reducing sliding resistance. However, it does not exhibit the best wear resistance. The SV texture reduces friction by lowering the real contact area and facilitating smoother sliding. However, the same texture provides limited load-bearing capability, resulting in higher local contact stress and increased material removal. On the other hand, the snake dorsal texture (SD1) shows the lowest wear, suggesting better durability under repeated contact. The shark micro-riblet texture (SMR) produces the highest friction, which may be beneficial for applications requiring higher grip or traction. The frictional performance of riblet surfaces is highly dependent on their geometry, orientation, and the specific application. For instance, optimal riblet spacing and alignment can minimize friction, while improper configurations may lead to increased surface tensions and higher friction coefficients [26].

These results indicate that surface geometry plays a dominant role in determining tribological performance under identical material and testing conditions. Therefore, the selection of surface texture should be tailored to the intended application. Textures with low friction are suitable for sliding components, while textures with high wear resistance are preferable for improving durability.

4. Conclusion

This study investigated the tribological performance of bio-inspired surface textures fabricated using SLA 3D printing. The results show that surface texture influences both friction and wear behaviour. The snake ventral texture (SV) provides the lowest friction, while the snake dorsal texture (SD1) exhibits the best wear resistance. In contrast, the shark micro-riblet texture (SMR) produces the highest friction, which may be useful for applications requiring higher grip. These findings indicate a trade-off between friction and wear depending on texture geometry. Therefore, the selection of surface texture should be tailored to the intended application. Overall, this study demonstrates the potential of SLA 3D printing for producing functional bio-inspired surfaces.

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