A Study to Compare the Fouling Resistance and Self-cleaning Properties of Two-patterned Surfaces with an Un-patterned Control Surface

F Y M Wong1* and M S Mak1

1School of Computer Science and Engineering, Taylor’s University, Malaysia

* Email: FeliciaYenM.Yan.Wong@taylors.edu.my

Abstract. Biofouling is an unwelcomed phenomenon where unwanted biological matter adheres to surfaces with the presence of water, resulting in alteration to the properties of the surface. This affects many industries, especially the marine industry. Multiple biofouling control studies have been conducted to minimize damage and maintenance cost of these surfaces. With rising concerns on the toxicity of current control methods towards the environment, non-toxic methods shown to be effective are surface modifications such as self-cleaning or biomimetic textured surfaces. One of the biomimetic surfaces, shark’s skin has shown anti-fouling properties due to its surface riblets with low drag properties based on studies done. However, few researches are conducted to implement these biomimetic surface topographies for real anti-fouling applications. Therefore, this project explores the possibilities in implementing biomimetic surface topographies such as shark’s skin in real life applications using computational fluid dynamics (CFD) analysis and also to manufacture these surfaces using 3D printing methods. A computer-aided design (CAD) model of shark skin and un-patterned surface topographies are used to study the behavior of fluid over these surfaces in CFD fluent in ANSYS software. The hydrodynamic variable data such as wall shear stress over the surface topography is represented in a contour and vector plot, these results are then analyzed. According to the hypotheses, the biomimetic shark skin surface topography will show higher wall shear stress, indicating anti-fouling properties. In the next part of this project is the manufacturing of these surface, the goal is to provide a cheaper alternative to current micro-structured surface production methods such as photolithography. Additive manufacturing such as fused deposition modeling (FDM) 3D printing can potentially provide a manufacturing method with a much lower cost and time needed. Thus, 3D printing of the biomimetic shark skin surface topography will be carried out in this project to determine if FDM can provide a manufacturing solution to anti-fouling micro-topography surfaces.

1. Introduction
Biofouling is a colonization of living organisms on a surface held by biofilm formed by micro-organisms and macro-organisms [1-2]. This natural occurring phenomenon is found on artificial surfaces where water is present, this has plagued many industries mainly the marine industry, where ships are highly affected due to the increase in weight from biofouling on ship hulls, resulting in higher fuel consumption as much as 77% [3]. Moreover, increase in maintenance cost and time comes with biofouling due to higher frequency of maintaining the ship hull corrosion in dry-docks [4].

There are two main categories of marine adhesion organisms, firstly are the biofilm organisms involving bacteria and diatoms that exist everywhere where water is present. The second category are
the macrofouling organisms which are primarily barnacles, mussels, polychaeta worms and seaweed [5]. These organisms play an important part in the biofouling process which occurs in three main processes [6]. Biofouling begins with a primary step of conditioning film development from organic materials secreted by the bacteria or microalgae present on the surface, this sticky layer of film allows microorganisms to adhere, which leads to the next step, microorganism colonization. The following step is where settlement of these organisms starts to attract larvae and spores of macro-fouler. Within roughly a week, a diverse biological community is born on this surface.

Biofouling control consists of three ways as suggested by researches, which are firstly manual removal, secondly is the chemical removal and lastly surface engineering for low- or non-adhesive characteristics [7]. The most commonly used and effective method used currently is chemically inhibiting settlements of microorganisms with special paints, which have been banned in recent years due to biocides in the paints having a toxic impact to the environment. Thus, current eco-friendly approaches are anti-fouling surfaces with low drag or self-cleaning surfaces.

Studies on anti-fouling surfaces are looking into nature, where fouling control physically is done by surfaces with low frag, adhesion and wettability [8]. These surfaces can be reverse engineered to be fabricated for anti-fouling surfaces [9]. One example chosen for this study is the biomimetic shark skin surface. As in the marine environment, fouling is usually never seen on a shark’s body. Research shows that the scales of a shark skin possess aerofoil-like characteristics, where the near surface region of a shark skin shows high hydrodynamic changes [10]. However, it is unclear if shark skin topography works better compared to simple geometric shape surface topographies.

With recent attention on non-toxic methods to biofouling, fabrication still remains a big challenge that results in this method being unviable to many [11]. Current fabrication methods with capabilities to produce micro-sized structures on a surface are photolithography and soft lithography which are common in micro-fluidic applications, however, the cost is unrealistically high to be used for mass production of these surfaces. In recent years, FDM 3D printing technology has become financially accessible to the masses, with printers available for as low as RM 400. Thus, this project aims to explore the possibility of using FDM 3D printing fabrication methods to provide a cheaper alternative for mass fabrication of micro-sized surface topographies.

2. Research Methodology

In this project, a surface modification approach was applied to reduce or prevent biofouling. The software used for this project are SolidWorks 2020 and ANSYS Fluent software. The geometry of a sharkskin scale and its fluid domain is generated using SolidWorks and the simulation of the flow over the shark skin surface is run in ANSYS Fluent. Subsection below shows the methods used to obtain the results for the effectiveness of shark skin surface against biofouling. All methods used for this project are numerically obtained.

A sample of a surface topography was printed using fused deposition modeling (FDM) 3D printing method. The settings used in the slicer software Cura are analyzed and tested for obtaining the best print quality of the surface topography sample.

2.1 Geometry Modelling

Biomimetic approach is used to combat biofouling on a surface, where the scale of a shark skin is chosen to be studied in this project. A CAD model of a scale from a skin’s skin is produced according to dimensions reported by Wen, L [10], using SolidWorks 2020 software, shown in Fig. 1. The fluid domain over the surface of a shark’s skin and a non-patterned surface is modelled with dimensions of 4 mm x 12 mm x 12 mm. The domain of the shark skin surface topography and the non-patterned surface topography is as shown in Fig. 2 and 3 respectively.

The shark skin surface topography consists of 5 x 5 scales located 8 mm away from the inlet of the rectangular microchannel as shown in Fig. 2. This space between the inlet and the surface topography
is to allow the flow to fully develop in terms of parabolic-curve flow, as shown in subsection 3.1, Fig. 6.

**Figure 1.** Image of one scale of a shark’s skin.

**Figure 2.** Model of fluid domain of the shark skin surface topography

**Figure 3.** Model of fluid domain of the non-patterned surface topography
2.1.1 Mesh Independence Test

Tetrahedron mesh method with patch conforming method is applied to the shark skin model. Refinement applied around the shark skin topography will produce higher accuracy of results around this region and achieve mesh convergence. A grit independence test is conducted for the shark skin topography domain to obtain a mesh that produces high accuracy in results with minimum computational time. For the non-patterned topography domain, sweep method is applied as no complicated feature exists in the fluid domain. Refinement is applied to the surface to provide better mesh to this area. The growth rate of 1.2 is used for both fluid domains.

Mesh quality was evaluated with focus on the mesh quality around the surface topography before mesh convergence study was carried out. The mesh metric of skewness and the orthogonal quality were used for the evaluation. Tab. 1 and 2 shows the results of the mesh independence study with relative error for each interval calculated.

Table 1. Mesh results for shark skin surface topography domain model

| No. | Statistics | Mesh Metric | Wall Shear (Pa) | Relative Error (%) |
|-----|------------|-------------|----------------|--------------------|
|     | Nodes      | Element     | Orthogonal Quality | Skewness       |                       |
|     |            |             | Min | Max | Avg | Min | Max | Avg |                       |
| 1   | 349595     | 1263520     | 2.03E-02 | 0.99504 | 0.69744 | 7.67E-05 | 0.97967 | 0.30139 | 2.96031 | 11.38 |
| 2   | 600129     | 3188291     | 1.29E-03 | 0.99322 | 0.69596 | 2.95E-04 | 0.99871 | 0.30183 | 2.6578 | 25.65 |
| 3   | 894845     | 4768184     | 4.72E-04 | 0.99464 | 0.69972 | 1.33E-04 | 0.99953 | 0.29804 | 3.57499 | 5.90 |
| 4   | 1187159    | 6334744     | 4.67E-03 | 0.9967 | 0.73064 | 2.19E-04 | 0.99533 | 0.26796 | 3.37414 | 27.32 |
| 5   | 1401738    | 7484409     | 4.04E-04 | 0.9958 | 0.7317 | 2.65E-04 | 0.9996 | 0.2669 | 4.64273 | 0 |

Table 2. Mesh results for non-patterned surface topography domain model

| No. | Statistics | Mesh Metric | Wall Shear (Pa) | Relative Error (%) |
|-----|------------|-------------|----------------|--------------------|
|     | Nodes      | Element     | Orthogonal Quality | Skewness       |                       |
|     |            |             | Min | Max | Avg | Min | Max | Avg |                       |
| 1   | 3223       | 11342       | 5.15E-03 | 0.97173 | 0.41206 | 1.61E-02 | 0.99485 | 0.58709 | 7.44E-03 | 6.53 |
| 2   | 7518       | 36432       | 4.05E-02 | 0.98433 | 0.73896 | 1.70E-03 | 0.95952 | 0.25948 | 7.96E-03 | 2.69 |
| 3   | 13345      | 66263       | 1.84E-02 | 0.99386 | 0.73927 | 1.56E-03 | 0.98156 | 0.25929 | 8.18E-03 | 11.76 |
| 4   | 16917      | 84512       | 3.68E-02 | 0.98417 | 0.74412 | 1.97E-03 | 0.9632 | 0.25432 | 9.27E-03 | 2.22 |
| 5   | 44164      | 155426      | 1.69E-04 | 0.96221 | 0.31317 | 5.49E-03 | 0.99983 | 0.68567 | 9.48E-03 | 0 |

From the results of mesh metrics obtained, orthogonal quality and skewness around the surface topography region is in the desirable range for both shark skin topography and non-patterned surface fluid domains. The results shown that wall shear increases with no element of the mesh. Convergence is acceptable when refinement shows relative error between mesh of the model is low. From the results,
mesh no. 3 and mesh no. 2 are chosen for the shark skin surface domain and the non-patterned surface domain respectively.

2.2 Numerical Setup (Pre-Processing)

2.2.1 Governing Equations

The software used is the ANSYS Fluent to conduct this flow simulation. Equations used to solve the hydrodynamic variables, such as pressure and velocity, are the continuity and the Navier-Stokes equations. The fluid model is set as a steady state incompressible fluid. The governing equations are simplified and shown in equation (1) and (2).

\[ \nabla \cdot \vec{V} = 0 \]  
\[ \rho \frac{\partial \vec{V}}{\partial t} = -\nabla P + \rho \vec{g} + \mu \nabla^2 \vec{V} \]  

Velocity vectors, \( \vec{V} \) is simplified as shown in equation (3):

\[ \vec{V} = u \hat{i} + v \hat{j} + w \hat{k} \]  

The velocity components are represented in vector form as \( u, v \) and \( w \) for \( x, y \) and \( z \)-direction respectively.

2.2.2 Initial and Boundary Conditions

The fluid domain in this simulation is a steady-state laminar flow model, with fluid material as water-liquid with dynamic viscosity of \( 1.0 \times 10^{-6} \) kg/m-s, density of 998.2 kg/m\(^3\). The surface topography and the wall surrounding are set as no-slip conditions. The inlet velocity is set as 0.1 m/s, relative pressure at the outlet is as zero, with mass flow rate of 0.001 kg/s.

2.3 Data Acquisition (Post-Processing)

The main hydrodynamic variables to be analyzed in this flow simulation are the velocity and the wall shear stress, as these variables interfere with the biofouling process, thus giving the surface anti-fouling properties. The wall shear stress of the surface topography is studied from the contour plot. Readings of wall shear stress is obtained about a point, as shown in Fig. 4, this reading is used to conduct mesh quality analysis and comparison between the two fluid domains.

Fig. 5 shows lines across the shark skin topography in different depth, all 3 lines used for data collection are parallel to the direction of the flow in the micro-channel, with depth evenly spaced between scales of shark skin on the surface topography. Readings of wall shear stress are obtained from these lines to study the wall shear across different depths across the surface topography.
2.4. Fabrication

In the second part of this study, a sample of a surface topography is fabricated using the FDM 3D printing method. The settings of fabrication are analysed to achieve the best print quality of the surface topography. A FDM 3D printer, model Creality Ender 3 pro, with regular polylactic (PLA) filament in white is used for this part of the project. The standard 0.4 mm nozzle is switched to a 0.2 mm nozzle for the printing of the model. The slicing program used for all models for printing to generate the G codes for the printer is the Ultimaker Cura 4.8.0 software.

To determine the limit of 3D printing on how small it could print, a test model consisting of cubes of sizes of 200 μm, 400 μm, 800 μm and 1000 μm, is produced using SolidWorks software, as shown in Fig. 6. Dimensions of the model are modified until the printed part shows details of the geometry to obtain the smallest possible print on from 3D printing. The starting printing parameter for this standard white filament by creality are printing temperature of 180 °C, bed temperature of 69°C, at printing speed of 40 mm/s with retraction of 3 mm is enabled. The printing layer height is set for high quality of 0.08 mm layer height.
3. Results and Discussions

3.1 Fully Developed Flow

The fluid flow is ensured to be fully developed before moving across the surface topography. A fully developed flow is important to avoid interruption of flow from other directions and ensure velocity is constant only in one direction.

As shown in Fig. 7, a fully developed flow is shown on this plane located in front of the surface topography, this is represented by the velocity contour on this plane. The velocity of the flow increases when it’s approaching the middle region of the fluid domain.

Fig. 8 shows the velocity profile for the full depth of the fluid domain located before the surface topography. The graph shows a parabolic-curve profile with maximum velocity located in the centre region of the flow, indicating a fully formed flow.

Figure 6. Isometric view of the test model geometry for 3D printing

Figure 7. Fully developed flow in the fluid domain located before the surface topography
3.2 Wall Shear Stress

For effective antifouling properties of a surface topography, fluid region over the surface topography should display high wall shear stress. High shear stress over the surface topography is shown to disturb the settlement of biofouling organisms, preventing biofouling from occurring on the surface [12]. This part shows the wall shear stress developed over the shark skin surface topography and comparisons with the non-patterned controlled surface topography.

The wall shear stress at the highest point of the sharkskin scale topography is 3.57 Pa and no wall shear exists on the surface of non-patterned surface topography. Thus, the non-patterned surface topography will not show any anti-fouling properties and will promote the colonization of fouling organisms [13].

The wall shear for both models is plotted into a chart using ANSYS Fluent as shown in Fig. 9. Based on the wall shear chart, the highest peak of wall shear is located at the top surface on the shark skin surface topography, followed by the middle and the bottom. The bottom region shows the lowest in wall shear compared to the top, middle and non-patterned region of the surface topography. This indicates that the gaps between the shark scales are the most vulnerable to biofouling. This may be improved with rearranging the layout of the scales of the shark’s skin, removing or minimizing the gaps between each scale.
Figure 9. Wall Shear Chart of shark skin surface domain over various locations

From the wall shear stress contour plot in Fig. 8, the scale of a shark shows fluctuation of wall shear stress over the surface topography. This indicates anti-fouling properties of this surface as constant hydrodynamic fluctuation across a surface can prevent microorganism to station itself on the surface and start the biofouling process. The ascending peak of the air-foil-like shark skin scale region shows highest in wall shear stress as shown in red and yellow in Fig. 10.

Figure 10. Contour plot of wall shear over the shark skin surface topography
3.3 Fabrication

Firstly, the 3D printing process of the test sample with cubic topography size of 200, 400, 800 and 1000 μm is printed out, the layer height of this print is at 0.08 mm, with printing temperature of 180 °C and build plate temperature at 69 °C, also the print speed is at 40 mm/s. The results are shown in Fig. 11 on most samples. According to the results, 200 microns was unable to be detected in the slicing process in Ultimaker Cura software, this may be due to dimensions of features on the surface topography is smaller than the nozzle size used, which is 200 microns, thus feature such as edges of the cube could not be made. The cube of sizes above 200 microns were able to be printed out, however, the geometry was deformed due to the limitation of the nozzle’s size of 200 microns. Smaller nozzle size could be used for further printing, however, a brass nozzle of 100 microns is not available commercially for purchase, custom order was required.

The next sample printed out was the same model but scaled up to 1.5 times the original size of the test print model. Thus, the cube sizes were 300, 600, 1200 and 1500 μm. The settings were the same as the first sample. However, all the geometry of the surface topography was not able to be captured, blobs were formed on cube size of 1200 microns, as shown in Fig. 11 second model. This is due to small movement that was not able to be captured accurately, thus the nozzle only moved close to the same point resulting in vibration. This causes a build-up of filament which is then dragged to the next point. In this model, no dimensions of the cube showed signs of geometrical accuracy.

The next print is a reattempt for another print with scaling of 2 times the original print, with cubic sizes of 400, 800, 1000 and 2000 microns. As shown in Fig. 11 bottom model, blobs were formed on a cube

![Figure 11. Samples of 3D printed cube surface topography](image)
size of 800 microns. The cube where geometry was reflected on the print is a cube of 2000 microns, as shown in Fig. 11’s red box marking. The settings used for this print were at layer height of 0.12 mm, printing temperature of 180 °C, build plate temperature at 69 °C and printing speed at 30 mm/s.

From the comparison of the printed models, it shows that 200 microns geometry size is unable to be fabricate using 3D printing with nozzle of size 200 microns, which is the smallest size commercially available. Results shows that the minimum size capable of printing with minimum distortion to its geometry is about 2000 microns in size.

4. Conclusion

This study aims to provide a surface topography design with anti-fouling properties with new fabrication methods to be applied for mass production for large surfaces. This study for anti-fouling properties of a surface topography is fully numerical based using ANSYS Fluent with laminar flow. Simulation results shows that shark skin surface topography is effective against biofouling as hydrodynamic stress is present over the surface topography, with high wall shear present at the highest area on the scale of the shark skin. Thus, the airfoil-like design of the shark scale is able to develop high shear stress regions for anti-fouling properties. However, the indentation region of the scale and the gaps bottom of the scales shows lower in shear stress which may promote biofouling.

Based on the results from the fabrication of the surface topography using 3D printing method with Creality Ender 3 pro printer, 200 microns nozzle size and standard PLA filament, the minimum dimensions can be printed accurately is dimensions of 2000 microns. This shows that current commercially available 3D printing equipment are not able to print anti-fouling surfaces, where dimensions shown to be effective against biofouling are in the range of 1-1000 microns.

The limitation to this project is the lack of real-life marine conditions, thus results presented here may not tally with results from real-life experiments. However, these numerical results provide fundamental knowledge on types and key geometrical features on a surface topography that can be used to prevent biofouling.

In conclusion, future studies could possibly explore the optimum layout of shark skin scales for minimum frictional drag on the surface and the possibility of a 3D printing fabrication method using nozzles smaller than 200 microns. All in all, the design of a scale on shark skin shows promising anti-fouling properties numerically.

5. References

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