Coating Resistance to Biofouling Inception for Freshwater Vehicles

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ABSTRACT

Preventing biofouling in natural bodies of freshwater is important for a wide variety of applications. The relationship between surface properties and antifouling has been the subject of many recent studies, with primary focus on long-term exposure across weeks and months. Current hull biofouling solutions, namely antifouling coatings, focus on reducing the formation of biofilms in long-term scenarios. The current study focuses on short-term exposure and the inception of biofouling, with specific focus on the extension of laminar flow across low-speed freshwater vehicles as a mechanism to reduce drag. Eliminating adherence prevents turbulent wake regions from forming behind particles and provides an extension of effective laminar flow. The current study's novelty is the focus on short-term biofouling elements as opposed to matured biofilms and long-term macrofouling, with an indication that a 99% decrease in adherences greater than 5 μm in height is achievable over traditional coatings.

Keywords: biofouling, hydrophobic, contact angle, laminar flow, transitional flow

1 INTRODUCTION

1.1 Rationale for Low Roughness

The reduction of laminar flow disruption in low-speed freshwater vehicles has the potential to significantly reduce frictional skin drag. The critical height for laminar flow disruption in small, low speed vehicles can be as low as 5 μm. Smoother surfaces have less skin friction and an extension of laminar flow to higher Reynold's numbers. The Reynold's number (Re) is a dimensionless number that gives a ratio of inertial forces (density, velocity, length) to viscous forces (dynamic viscosity), which largely defines the characteristics of a flow; higher Re values generally coorespond to turbulent flows. For small watercraft, the Re is typically on the order of ~ 10^7:

$$Re = 10^7 = \frac{\rho v l}{\mu} = \frac{1000\frac{kg}{m^3} * 4\frac{m}{s} * l}{0.001\, pa * s}$$

This study uses a flow speed of 4 m/s. Laminar flow can be extended up to l = 2.5 m from the leading edge under these flow conditions. The requisite relative roughness for this condition can be found using a flat plate drag coefficient relation, where $\varepsilon / l \sim 2 * 10^{-6}$.

This gives a final **ε** value of ~5 μm, the assumed critical height for laminar flow disruption. Biofouling above this critical value can potentially induce an earlier transition to turbulence and an accompanying increase in skin drag. At $Re=10^7$, assuming low surface roughness, there is an 80% reduction in drag coefficient over a similar, but turbulent flow.

These principles extend to larger boats and ships as well. Larger craft exhibit Re values of roughly 10^8. An ideally smooth surface at this number has a potential 35% reduction in drag coefficient over a rougher surface. As length increases, the requisite critical surface roughness also increases; a 25m boat might have a final **ε** value of ~50 μm.

1.2 Previous Studies on Biofouling

The inception of biofouling consists of bacteria and microalgae producing extracellular polymeric substances (EPS) upon adhering to a surface, which form the base conditions for future adhesions [1]. The current study seeks to examine their relative heights and densities over time intervals and water velocities. It is worth noting that the principle's behind the current study coorelate closely with airfoil studies; insect resides on a wing's leading edge act to cause similar turbulent trips and increases in drag [2].

In the shipping industry, traditional antifouling solutions carry ecological ramifications. Many products operate using toxin-release systems designed to kill attached organisms as opposed to preventing adhesions. However, since the implementation of the International Maritime Organization Treaty on biocides in 2008, there has been rapid growth in studies for new, environmentally benign solutions [3]. Biomimetic solutions are of particular interest, i.e. studies of antifouling mechanisms found in the natural world. Natural material properties such as superhydrophobicity, self-cleanability, and drag reduction are extremely desirable for the creation of antifouling materials [4]. These mechanisms vary from antibacteria nanopatterns on a cicada wing to secretion from skin pores on whale skin [5]

[6]. Indeed, both physical and chemical surface properties affect adherances. Significant successes in biomimicry have been shown, including the use of liquid-infused surfaces as a prevention method for many bacterial adherences [7]. Interestingly, it has been seen that introducing a bacterial microbiofilm can, in the case of certain species, prevent future macrofouling [8]. However, these solutions lack universal applicability and there is no consensus for an inexpensive and effective solution.

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1.3 Objectives

The current study focuses on quantifying short-term biofouling on traditional hull coatings. Additionally, it contrasts biofouling on traditional surfaces with other potential solutions. The alternate surfaces used represent relatively inexpensive and available coatings. Polytetrafluoroethylene (Teflon) was chosen for comparison to traditional polyurethane coatings for its hydrophobic properties based on static contact angle. The study attempts to keep surface roughness (R_a) consistent and below 1 μm for each solution. The R_a is the arithmetical mean roughness of a surface, i.e. the average height of surface features.

A superhydrophobic solution developed at the University of Virginia Department of Mechanical and Aerospace Engineering was examined to contrast the above coatings. Its inclusion represents a possible novel solution, but, as it is still in-development, carries certain limitations and instabilities as outlined in the results.

2 METHODS

2.1 Surface Preparation

Two roughly one-inch by two-inch samples for polyurethane, Teflon, and the superhydrophobic surface were prepared. One of each was prepared for a) static testing and b) dynamic testing.

The preparation for the polyurethane samples consisted of applying a glass slide with a polyurethane coating and polishing the sample to reduce the surface roughness. The Teflon samples were sanded with 1000-grit sandpaper prior to polishing as this provided the lowest surface roughness. The superhydrophobic surface was not polished or sanded because its superhydrophobic properties are derived from its surface finish. Table 1 illustrates contact angle properties of the polyurethane and Teflon samples.

	Static Contact Angle	Roll-off Angle
Teflon	110°	25°
Polyurethane	77°	48°

Table 1: Water angle measurements on surfaces

Following their preparation, the samples were examined for surface roughness measurements. The goal prior to measurement was to have the surfaces exhibit similar R_a measurements well below the critical height for laminar flow disruption (~5 μm).

Surface profilometry found the polyurethane samples exhibiting R_a values of 0.05 μm. The Teflon samples exhibited R_a values of 0.36 μm.

The samples were then imaged on a Hirox 3D digital microscope. These pre-testing images are shown for polyurethane (figure 1a) and Teflon (figure 1b) as a baseline for comparisons with post-test images. Note the image field of view is 1mm x 1mm.

2.2 Tests in Static and Moving Freshwater

Static testing seeks to examine biofouling over the course of five days in a non-moving freshwater environment. This was achieved by transporting roughly 0.5L of reservoir water to an open container in lab. The three samples (polyurethane, Teflon, superhydrophobic) were then immersed in the container for a period of 5 days. Following this period, the samples were lightly rinsed with clean water prior to being imaged under the 3D digital microscope for fouling height and population density analysis. Note that the static tests were used as a proof of concept prior to the more complex dynamic testing.

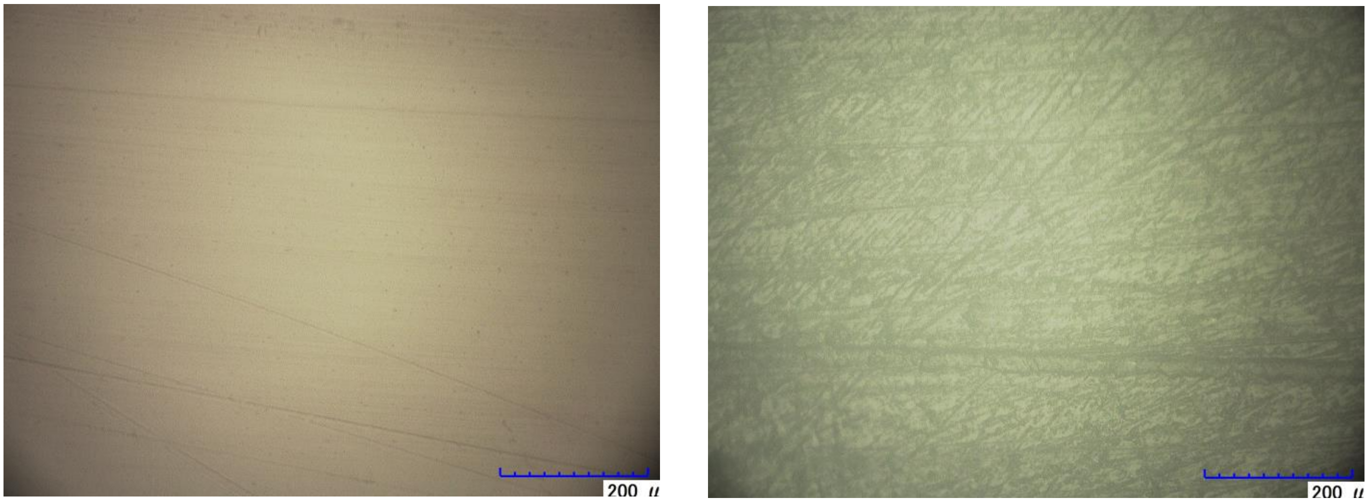
Dynamic testing observes the samples in a very short-term, moving water environment. These tests seek to understand the degree of fouling that can occur in a moving freshwater environment. Samples were attached to a vessel 15 cm below the waterline and 1 m from the leading edge. 3D digital microscopy followed a 45 minute dynamic freshwater environment at 4 m/s for fouling analysis. This test focuses on the inception of biofouling and examines its presence at very early stages.

3 RESULTS

3.1 Static Tests

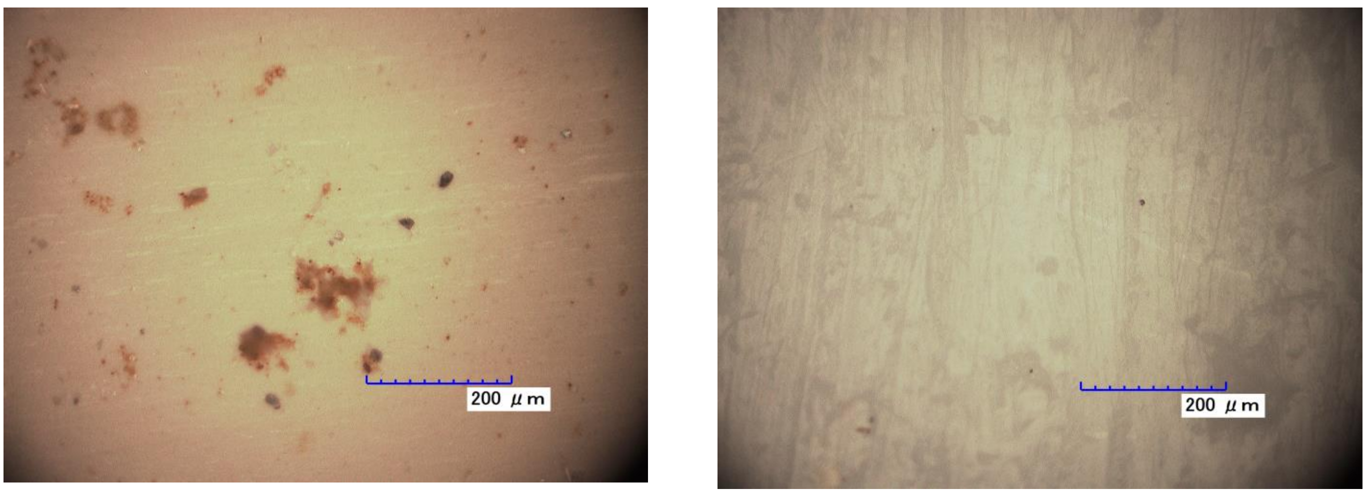
The static test on the polyurethane coating indicated the beginnings of a biofilm. Over several observed sections, it was found that close to 10% of the sample had been covered by fouling specimens. Figure 2a is a representative 1 mm x 1mm image of the polyurethane sample as a whole. Figure 2b is a representative 1 mm x 1mm image of the Teflon sample in the same static test. Note differences between figures 1 and 2.

Teflon easily outperformed polyurethane in the static experiment. The polyurethane sample developed the early stages of a biofilm while the Teflon remained virtually clean. The superhydrophobic surface was also tested during the 5 day interval and was never saturated. That is, the surface was able to maintain an air boundary layer and no biofouling was observed.



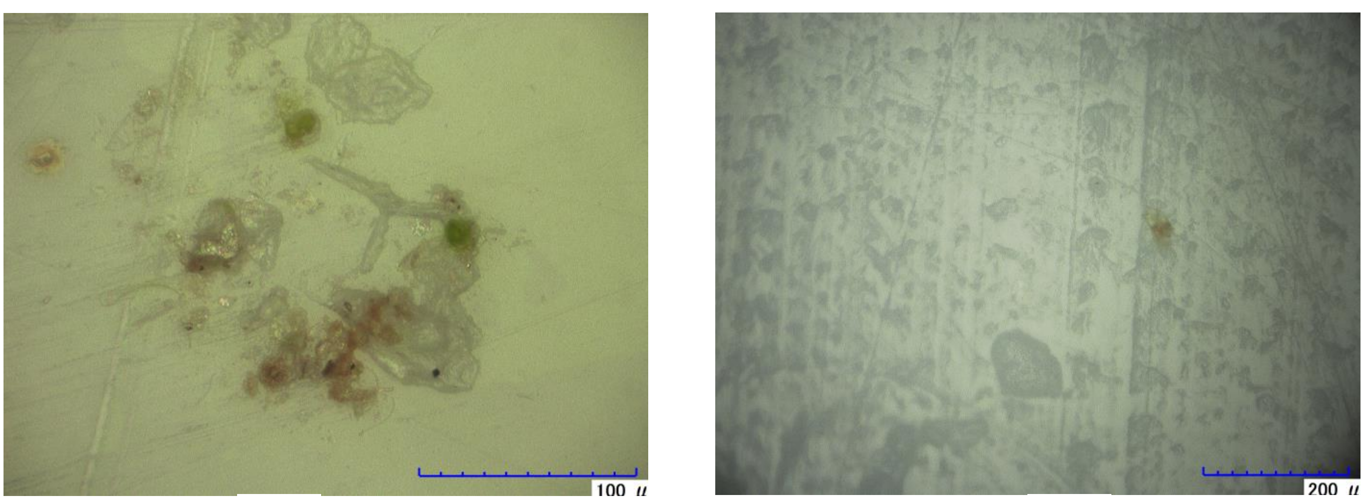
1a 1b

Figure 1: Pre testing images at a 1 mm x 1mmfield of view for: a) polyurethane, b) Teflon



2a 2b

Figure 1: Post static testing images at a 1 mm x 1 mmfield of view for: a) polyurethane, b) Teflon



3a

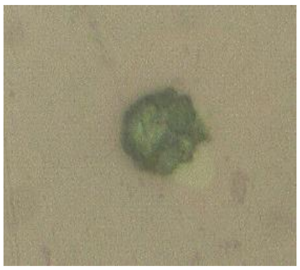
3.2 Dynamic Tests

3b

Figure 3: Post dynamic testing images at a 1 mm x 1 mmfield of view for: a) polyurethane, b) Teflon

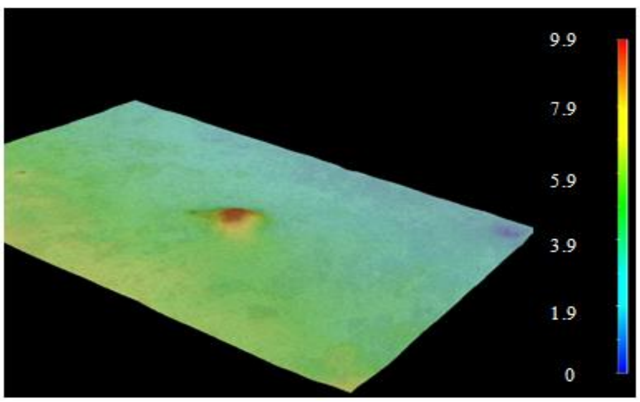
The dynamic tests yielded similar results to the static tests. The polyurethane sample had greater fouling over the 45-minute time period than the Teflon sample. The overall area fouled in the polyurethane sample was smaller than the static test, as to be expected with the shorter exposure time.

The largest specimen found on the dynamic polyurethane test was over 50 μm in height and there were several specimens over 20 μm in height. These were not algae or bacterial fouling specimens, but small insect legs or plant parts. The movement of water past the sample gave these samples a larger exposure to particles within the reservoir water. Still, the main specimens were algaes of roughly 5 μm in height. The following images illustrate the common adherences and the associated imaging process.



a

b



c

Figure 4: Common polyurethane adherences, magnified at 50 μm x 50 μm field of view: a) chlorophytes, b) algae, with c) 3D digital imaging of figure 4b.

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The superhydrophobic surface was tested in the same manner as the polyurethane and Teflon. However, it lost its superhydrophobicity over the 45-minute time period. This is likely due to the increased saturation pressure associated with water flow. Additionally, 3D analysis showed surface structures dwarfing any fouling specimen.

The bar graph comparison was formed by taking several 1 mm x 1mm overhead shots of both the Teflon and polyurethane samples. These representative sample shots were then extrapolated to represent total adherences over a 1cm x 1 cm area. This size was chosen to account for several very large, relatively rare specimens in the polyurethane sample.

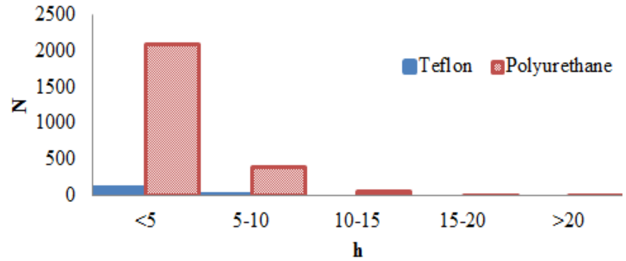

Figure 5: Height distribution, where h= height (μm) of an element and N= # of elements over 1cm x 1 cm area.

The Teflon sample exhibited a 96% decrease in overall adhesions compared to the polyurethane sample and a 99% decrease in adhesions for n>5 μm.

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