Durable Superhydrophobic Aluminum Surfaces against Immersion and Hot Steam Impact: A Comparative Evaluation of Different Hydrophobization Methods and Coatings

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Abstract: Controlling the wettability properties of metallic materials and surfaces can enhance their applicability and improve their performance and durability in several fields, such as corrosion protection, heat transfer applications, self-cleaning, and friction reduction. Here, we present and compare some versatile fabrication methods that can provide aluminum surfaces with durable superhydrophobic performance which are suitable for heat transfer applications. To probe their stability in heat transfer applications, two evaluation protocols are designed, one which suggests immersion in hot water for several hours, and a second testing against the harsh conditions of hot steam impact. The superhydrophobic aluminum surfaces are fabricated by first creating micro or micro-nano roughness on an initially flat surface, followed by the minimization of its surface energy through two hydrophobization methods, one wet and one dry, thus creating a series of different coating materials. Surfaces are then evaluated by immersing them in hot water and exposing them to steam impact. It is demonstrated that despite the fact that all hydrophobization methods tested resulted in surfaces exhibiting superhydrophobic properties, only the ultra-thin Teflon-like coating, obtained after plasma deposition using C4F8 plasma, exhibited robust superhydrophobicity with hysteresis lower than 8° when immersed in water at 90 °C for 10 h. This surface also showed minimal wettability changes and was the only one to retain its hysteresis below 6° after 4 h of exposure to hot steam.

Keywords: superhydrophobic aluminum; hydrophobic coatings; hot steam impact; hot water immersion; plasma deposition

1. Introduction

Controlling the wettability of solid surfaces has attracted the interest of scientific research, as it is essential for a plethora of practical applications [1]. For example, superhydrophobic metals can be used in heat exchangers to achieve dropwise condensation; for the motion of drops with low friction on surfaces [2]; frictionless motion of ships or liquids inside tubes [3,4]; anti-icing properties [5] for space technologies; and the corrosion protection of metals [6].

The realization of superhydrophobic aluminum surfaces has been extensively studied in the past two decades due to the usability of aluminum in a plethora of industrial applications. As a result, many approaches for superhydrophobic aluminum fabrication, which combine texturing and lowering of the surface energy, have been introduced. For example, Parin et al. [7] fabricated superhydrophobic aluminum through etching with FeCl3 and CuCl2 and spin coating with an FOTS in hexane solution. Chen et al. [8] introduced a facile method of fabrication of superhydrophobic aluminum by immersing the surface...
in a mixture of hydrochloric and stearic acid, whereas Liu et al. [9] created a hierarchical aluminum surface by immersion in an aqueous solution of AlCl₃ and triethanolamine in an autoclave. Besides the texturing of aluminum through chemical etching, many studies involve the fabrication of micro-nanostructures through laser etching [10–14] or anodic oxidation [15–19]. For example, Liu et al. [20] fabricated anticorrosive superhydrophobic surfaces that can efficiently repel a low-surface tension ethylene-glycol mixture by applying laser etching and three different hydrophobic coatings, while Choi et al. [21] fabricated superhydrophobic aluminum using anodic oxidation with great anti-frosting properties. All of the above methods achieve superhydrophobicity after lowering the surface energy of an initially textured aluminum; however, many researchers follow a different approach in which aluminum surfaces are coated (i.e., using spray coating) with a thick hydrophobic layer (>1–2 µm) which is then textured to obtain superhydrophobicity. An example of this approach is the work by Peng et al. where a superamphiphobic surface is fabricated by spray coating hollow glass microspheres with fluorinated nano-silica particles, exhibiting great anti-wetting properties against wax oils and chemical and mechanical durability [22]. Liu et al., from the same group, fabricated mechanical and chemical durable superhydrophobic and superoleophobic surfaces with anticorrosion properties by spray coating several combinations of nanoparticles on aluminum substrates [23–25].

Youfa Zhang et al. [26], prepared durable superhydrophobic aluminum by spray coating with an alcohol solution consisting of hydrophobic silica nanoparticles and methyl silicate precursor on an etched aluminum alloy with pitted morphology. Wang et al. [27] used a similar method in order to improve heat transfer in superhydrophobic surfaces, while Wang and Xiong [28] fabricated superhydrophobic membranes using a sol–gel technique on steel surfaces in order to protect them from corrosion. Lakshmi et al. also used the sol–gel method for the fabrication of a superhydrophobic layer on top of several substrates, such as glass, metals and composites [29].

Despite such an abundance of work, most of the methods reported were not evaluated for long-term durability and may exhibit performance degradation over time, particularly under specific stresses such as exposure to hot steam or high temperatures. In addition, for heat exchange applications, the superhydrophobic polymeric coating should be ultra-thin in order not to affect the heat transfer coefficient. On top of that, most of the methods presented are not generic and can only be applied on specific surfaces and materials. This article comes to fill this “gap” in the literature by presenting a scalable, versatile and simultaneously generic approach for the fabrication of durable superhydrophobic aluminum, which, with small adaptions, can also be applied to other metal substrates. In particular, we propose microtexturing or micro-nanotexturing of aluminum through etching with hydrochloric acid followed by the boehmite process, and then coating with a thin hydrophobic layer through drop casting or spin coating of liquid PTFE (drop casting of 2.5% PTFE aqueous solution (A1), spin coating of 50% PTFE aqueous solution (A2) and spin coating of 1% Teflon AF 1600 (A3)) or plasma deposition (using CHF₃ and C₄F₈ (B1 and B2, respectively)). In all cases, the resulting hydrophobic, polymeric film is thin, making the surfaces ideal for applications such as condensers or industrial distillers. In order to also address the durability requirement against harsh conditions (i.e., thermal stress), we have designed two evaluation protocols: (a) immersion in hot water of 90 °C for 10 h, and (b) exposure to hot steam at atmospheric pressure (T = 100 °C, higher than typical conditions used in condensers [30,31]). Although the immersion test is useful for a preliminary evaluation of the surfaces’ durability under hydrolytic stresses, the existence of plastron in superhydrophobic surfaces protects the coating in the interspace region between structures. In contrast, during the steam impact test, condensation also occurs if there is a temperature difference between the vapor and the surface. Thus, the exposure of the surface to steam flow evaluates the coating’s durability in the space between the micro and nanostructures, as the first droplets, with radii in the order of tens of nanometers, nucleate between the inter-structural regions, and the coating is evaluated without the plastron’s protection. In this way, these two tests probe the coating’s durability both macroscopically (immersion
in hot water) and microscopically (steam impact). The results of these two evaluation protocols exhibited the superior durability performance of the micro/nanotextured surface coating achieved using C$_4$F$_8$ plasma deposition, as its hysteresis slightly increased from 1° to 7° after immersion for 10 h in hot water, and from 1° to 6° after 4 h of hot steam impact at 100 °C. Of the surfaces coated with PTFE solutions, the commercial Teflon (AF 1600), which was spin coated onto the surface, exhibited the highest durability against hot steam impact and immersion in hot water, as its hysteresis remained lower than 10° after 4 h of steam impact, and increased up to ~12° after the immersion test for 10 h in hot water.

2. Materials and Methods

2.1. Materials

Pristine 1.5 mm thick aluminum substrate (99.5%) was cut in 20 mm × 20 mm and 20 mm × 50 mm samples. The samples were cleaned using isopropyl alcohol (IPA), acetone and deionized (DI) water. Samples were immersed in 0.1 mol/L aqueous solution of NaOH for 20 min in order to remove the native aluminum oxide. Aqueous solutions containing different concentrations of PTFE particles were purchased from Dupont (DuPont de Nemours, Inc., Wilmington, DE, USA). Teflon AF1600 dissolved in fluorinated solvent (FC770) and the hydrochloric acid (37%) used for aluminum etching were purchased from Sigma-Aldrich (MilliporeSigma, Burlington, MA, USA).

2.2. Aluminum Micro-Nanotexturing

For micro-texturing, aluminum samples were immersed in 2:1 aqueous solution of hydrochloric acid (9.25% v/v HCl) for 10 min. Immersion of aluminum samples for longer than 7 min in such a solution results in the formation of suitable structures for achieving superhydrophobicity [32]. Shorter durations result in non-uniform structures on the surface, while longer durations lead to a reduction in sample thickness and create large topography structures which are not suitable for superhydrophobicity since the spacing and height of the topography become extremely high.

Nanotexturing was performed through the boehmite process [9,33]. Micro-textured aluminum surfaces were immersed in boiling water for 5 min. The developed boehmite layer on the microstructures had a thickness of ~250 nm.

2.3. Hydrophobization

Surface A1 (chemical micro-texturing + 2.5% aqueous solution LMw PTFE): after micro-texturing, surface A1 was drop cast with 2.5% aqueous solution of low molecular weight PTFE. The PTFE used was in the form of spherical particles with diameters of 150–200 nm. After drop casting, the surface was heated to 100 °C for aqueous solvent removal, followed by thermal annealing at 370 °C for one hour, in order to melt the PTFE particles and form a uniform film of about 1 µm.

Surface A2 (chemical micro/nanotexturing + 50% aqueous solution HMw PTFE): 50% aqueous solution of high molecular weight PTFE was spin coated at 3000 rpm on microtextured aluminum surface. This PTFE was also in the form of spherical particles with diameters of 150–200 nm. Spin coating was followed by heating at 100 °C with subsequent annealing at 370 °C for one hour and cooling at room temperature with a cooling rate of 1.4 °C/min.

Surface A3 (chemical micro/nanotexturing + 1% w/v Teflon AF 1600 spin coating): 1% w/v liquid solution of Teflon AF 1600 with fluorinated solvent (FC770) was spin coated onto the micro-nanotextured aluminum surface at 6000 rpm, creating a film of 100 nm on top of the topography. Teflon AF1600/FC770 is a homogenous solution (i.e., contains no particles), which was spin-coated and heated up to 110 °C to evaporate the remaining FC770 solvent.

Surface B1 (chemical micro/nanotexturing + CHF$_3$ plasma deposition): CHF$_3$ plasma deposition was conducted in a reactive-ion etching plasma reactor under the following conditions: duration 5 min, plasma power 50 W, pressure 100 mTorr, CHF$_3$ flow rate
50 sccm and sample temperature 25 °C. The layer created after CHF₃ plasma deposition under the above conditions had a thickness of 60 nm.

Surface B2 (chemical micro/nanotexturing + C₄F₈ plasma deposition): the C₄F₈ plasma deposition of the hierarchical structured aluminum surfaces was conducted in an induction coupled plasma reactor with the following conditions: duration 2 min, plasma power 900 W, pressure 40 mTorr, C₄F₈ flow rate 25 sccm and sample temperature 0 °C. C₄F₈ plasma deposition in these conditions creates a layer of 27 nm thickness on a flat silicon surface.

2.4. Superhydrophobic Surface Characterization

Wetting properties characterization: static and dynamic contact angle measurements were conducted with a KRÜSS DSA 30 contact angle instrument (KRÜSS GmbH, Hamburg, Germany) using 5 µL water droplets. Surface energy measurement was conducted on the same instrument by using droplets of diiodomethane and DI water of 5 µL. For the calculation of surface energy, the OWRK model was used [34].

The durability of the surfaces during immersion in hot water was evaluated by immersing the surfaces simultaneously in a beaker containing water at the steady temperature of 90 °C, and their wetting properties were measured every hour of immersion. The temperature of water was set at 90 °C because at this temperature the imperfections occurring from the collapse of the bubbles created during the phase transition of the water are eliminated.

The durability of the developed coatings against hot steam impact was evaluated by a simple setup comprising a beaker with DI boiling water and a mount that supports the surfaces to be tested. The beaker with boiling water was placed below the sample at a distance of 2 cm (Figure 1). The produced saturated steam of 100 °C impacted the surface vertically at a speed of 13.9 mm/s. Surfaces were exposed to hot saturated steam from 1 to 4 h, and the contact angle and hysteresis were measured versus exposure time. If small or no change was observed, the coatings were considered durable.

![Figure 1. Illustration of the setup used for the evaluation of surface durability under hot steam impact.](image)

3. Results and Discussion

3.1. Micro-Nanotopography and Coating Characterization

Structures created from dislocation-selective etching with hydrochloric acid have the form of rectangular deep cavities with large lateral distances and flat regions [35,36]. Coating of such structures with a hydrophobic layer can barely transform them to superhydrophobic, and usually their contact angle is lower than 150°, and even if the static contact angle reaches 150°, high hysteresis is recorded. Therefore, a second roughness scale is required to obtain a stable superhydrophobic state with a low hysteresis angle. This second scale roughness is created though the boehmite process on the microstructured
surfaces, as shown in Figure 2c,d. The hierarchical topography fabricated after this two-step process transformed the surfaces A3, B1 and B2 to superhydrophobic after hydrophobic coating deposition.

Figure 2. (a,b) Microstructures on aluminum surface after dislocation-selective etching in 9.25% aqueous solution of HCl at magnifications of ×500 and ×2000; (c,d) hierarchical micro-nanostructures after the boehmite process at magnifications of ×500 and ×2000; (e,f) hierarchical structures of (c,d) at the higher magnifications of ×10,000 and ×20,000.

The nanostructuring step using the boehmite process is not necessary when applying the 2.5% drop-cast and the 50% spin-coated liquid PTFEs, since the second scale topography is introduced by the PTFE particles of the solution, as shown in Figure 3. Although a high-temperature annealing step at 370 °C (for 60 min) was performed after the coating of the liquid PTFEs, which melted the particles, it was evident that during cooling to room temperature an additional roughness scale was formed, which transformed the surfaces to superhydrophobic, as is evident in Figure 3.
In this section, the wetting properties of all the tested hydrophobic coatings are presented, as well as the properties of the fabricated micro-nanotextured superhydrophobic aluminum surfaces. Additionally, data concerning their thickness and surface energy are also provided. It should be noted that the evaluation of the coating’s wetting properties was performed on coatings deposited on flat Si wafer.

Table 1 shows that the coatings fabricated from 2.5% low Mw PTFE and 50% high Mw PTFE liquid solutions exhibited surface energy values above 26 mN/m. Disordered fluorocarbon coatings exhibited surface energy values of 18–20 mN/m (the surface energy for polytetrafluoroethylene (PTFE)) [39], whereas lower surface energies (<10 mN/m) were reported for perfluorinated monolayers [40]. The relatively high surface energy values measured here can be attributed to poor coating homogeneity. In particular, the drop-casting method results in a relative thick coating without precise control over its thickness and homogeneity. Spin coating offers control over the thickness of the fabricated coatings.
However, spin coating of a liquid solution containing PTFE particles is not feasible in high rotational speeds, due to the centrifugal ejection of the particles, which reduces the PTFE concentration in the solution and leads to non-uniform coating after thermal annealing. In contrast, in the case of Teflon-AF, ultra-thin and homogeneous coatings with a thickness lower than 100 nm were prepared by adjusting the spin-coating speed to 6000 rpm. This is the main reason behind the impressively low surface energy value of ~15 mN/m of the spin-coated AF1600.

Table 1. Wetting characteristics of the different hydrophobic coatings tested on flat Si wafer.

<table>
<thead>
<tr>
<th></th>
<th>2.5% Low M_w PTFE Drop</th>
<th>50% High M_w PTFE Spin Coating</th>
<th>1% w/v Teflon AF 1600 Spin Coating</th>
<th>CHF₃ Plasma Deposition</th>
<th>C₄F₈ Plasma Deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Used in Surface</td>
<td>A1</td>
<td>A2</td>
<td>A3</td>
<td>B1</td>
<td>B2</td>
</tr>
<tr>
<td>CA (°):</td>
<td>106 ± 1°</td>
<td>109 ± 1°</td>
<td>123 ± 1°</td>
<td>105 ± 2°</td>
<td>108 ± 2°</td>
</tr>
<tr>
<td>Hysteresis (°):</td>
<td>&gt;20°</td>
<td>&gt;20°</td>
<td>~20°</td>
<td>&gt;20°</td>
<td>&gt;20°</td>
</tr>
<tr>
<td>Surface energy [mN/m]</td>
<td>26.91 ± 0.12</td>
<td>27.34 ± 0.3</td>
<td>15.34 ± 0.3</td>
<td>23.69 ± 0.2</td>
<td>22.75 ± 0.2</td>
</tr>
<tr>
<td>Coating thickness on flat Si</td>
<td>2–3 μm</td>
<td>1–2 μm</td>
<td>~100 nm</td>
<td>60 nm</td>
<td>30 nm</td>
</tr>
</tbody>
</table>

Coatings derived from plasma deposition exhibited surface energy values of 23 ± 1 mN/m, values which are close but lower than those reported for PTFE, primarily due to their lower –CF₃ content. These coatings consist predominantly of –CF₂ and –CF groups formed by the polymerization of the gas inside the plasma. Despite this, they are expected to provide good hydrophobic properties, especially the coating resulting from the polymerization of C₄F₈ gas, which exhibits a lower surface energy value. In addition, the deposition rates for the C₄F₈ and CHF₃ plasmas were 30 nm/min and 12 nm/min, respectively, allowing precise control of the coating thickness and homogeneity. In Figure 5, the wetting characteristics of all the microtextured (for particle PTFEs solutions), as well as the micro-nanotextured superhydrophobic aluminum surfaces, are demonstrated.

Figure 5. Hysteresis and contact angles of the different superhydrophobic surfaces fabricated (2.5% low M_w PTFE drop cast (A1), 50% high M_w PTFE spin coated (A2), 1% w/v Teflon AF 1600 spin coated (A3), CHF₃ plasma deposition (B1), C₄F₈ plasma deposition (B2)).
Figure 5 shows that in all microfabrication methods tested, high static contact angles (>150°) were obtained. The main difference observed was in the hysteresis contact angle and the 1% w/v Teflon AF 1600 spin coating, as well as the two plasma-deposited coatings from C₄F₈ and CHF₃, exhibited hysteresis below 4°. More interestingly, the hysteresis trend follows the trend of the surface energy. In contrast, the thicker coatings realized using the liquid PTFE solution exhibited higher hysteresis of 10–12°. This difference is attributed to non-uniformity in the nanoscale features created from the nanoparticles and the insufficient coverage of some topography features (edges), as shown in Figure 3.

3.3. Durability of the Superhydrophobic Coatings during Immersion in Hot Water

To evaluate the macroscopic coatings’ durability, the surfaces were immersed in hot water of 90 °C for up to 10 h. This test simulates the conditions that superhydrophobic surfaces are under in most common applications. At elevated temperatures, the molecular diffusivity of the plastron increases, thus facilitating the transition from the Cassie to the Wenzel state. The temperature of 90 °C ensures that the coatings will not be damaged by near-the-wall bubble collapse. The wetting properties of each surface were measured every hour of immersion, thereby evaluating the coatings’ durability. Figure 6 shows the change in contact and hysteresis angle of the tested surfaces after each hour of immersion in hot water.

Figure 6 shows that the surface exhibiting the minimum change in its static and hysteresis contact angle was the micro-nanotextured surface coated using C₄F₈ plasma deposition. This surface remains superhydrophobic with hysteresis below 7° after 10 h of immersion in hot water, whereas its contact angle remains almost unchanged and higher than 150°. The second most durable surface among those tested is the micro-nanotextured surface coated with Teflon AF1600, which remained superhydrophobic with hysteresis below 10° after 7 h in hot water, and slightly increased to 12° after ten hours of immersion. The static contact angle of the surface coated with Teflon AF1600 remained constant throughout the immersion test. The micro-nanostructured surface coated using CHF₃ plasma deposition failed faster, as its hysteresis increased above 10° after 4 h of the immersion test. Although the hysteresis decreased, its static contact angle remained unchanged and higher than 150° throughout the 10 h immersion test, indicating that the wetting of the surface transitioned from the Cassie–Baxter to partial Cassie state, also known as the rose-petal effect [41]. The two micro-structured surfaces coated using the deposition of the aqueous solutions of PTFE particles had poor durability of immersion in hot water, as their initial hysteresis was higher than the others. Specifically, the hysteresis of the surface coated with the aqueous solution of 2.5% LMw PTFE increased above 10° after 3 h of immersion and its contact angle oscillated around the limit of 150° after the 10 h immersion test. In contrast, the hysteresis of the surface coated with the aqueous solution of 50% HMw PTFE increased above 10° after the first hour of immersion, whereas its static contact angle decreased below 150° (which is considered the limit of superhydrophobicity) after the sixth hour of the immersion test.

The difference in surface durability during immersion in hot water at 90 °C lies in the uniformity and surface energy of the coatings resulting from each deposition method. The surface coated through the C₄F₈ plasma deposition had the greatest durability due to the combination of the high uniformity, that plasma deposition offers, and the low surface energy of the polymerized fluorocarbon. Although the coating resulting from the deposition of Teflon AF1600 had ultra-low surface energy, its slightly worse performance, compared to the C₄F₈ plasma-deposited surface, was due to the poorer coverage of all the topography features, which possibly created defects that, over time, affected the stability of the coating. It should be noted that spin coating on rough surfaces can create “shadowing” effects in some regions between the micro and nanostructures, resulting in poorer coverage and uniformity. In terms of mechanical strength, for both the C₄F₈ plasma-deposited coating and the spin-coated Teflon AF1600, in our previous works, we performed nanoscratch experiments to calculate the coefficient of friction and probe the adhesion of the coatings.
on polymeric micro-nanotextured surfaces. Additionally, we performed repeated nano-scratch tests and immersion in low surface tension liquids. Both coatings demonstrated good adhesion, low friction, and stability against liquids with surface tension down to 35–40 mN/m [42]. The surfaces coated with the aqueous solutions of particle PTFEs had lower durability in hot water immersion, as the uniformity of their coatings was not conformal and many defects appeared at the structure’s edges. These defects, which were responsible for the higher initial hysteresis of the surfaces, were not covered with plastron, thus creating hydrophilic spots which eventually caused the delamination of the coating and increased the hysteresis during the immersion test.

![Graph](image_url)

**Figure 6.** (a) Change in static contact angle for the different superhydrophobic surfaces fabricated (2.5% low Mw PTFE drop-cast (A1), 50% high Mw PTFE spin coated (A2), 1% w/v Teflon AF 1600 spin coated (A3), CHF₃ plasma deposition (B1), C₄F₈ plasma deposition (B2)) tested over 10 h of immersion in hot water; (b) change in the hysteresis of the same surfaces over 10 h of immersion in hot water.
3.4. Durability of the Superhydrophobic Coatings over Steam

In order to further evaluate the durability of the developed coatings under conditions typical for most superhydrophobic surface applications, the surfaces were exposed to hot steam flow. A simple testing apparatus was assembled, with samples placed on a metallic mount fitted with a thermocouple at the level of the tested surface. A beaker with DI boiling water was placed below the sample to generate hot steam, which was directed onto the surface. The metallic mount was cooled using an air chiller to achieve a temperature difference of 40 °C between the steam and the surface. This temperature difference is crucial for inducing intense condensation on the surfaces, with nucleation inside the micro and micro-nanotopography, thus evaluating the coatings’ durability in the inter-structural regions.

For the durability evaluation, surfaces were exposed to hot steam for 1 to 4 h, and the contact angle and hysteresis contact angle were measured versus exposure time. The data are shown in Figure 7. Higher hysteresis values are interpreted as defects in coating coverage and adhesion. We expect that during the test if the coating adhesion and coverage are not optimum, steam will gradually enter between the coating and the topography and cause delamination and other defects in the coating.

Figure 7a shows that for all surfaces, except for the one fabricated using the 50% high Mw liquid PTFE solution, the water static contact angle remained above 150°. In particular, in the surface fabricated using the 50% high Mw liquid PTFE, the water static contact angle decreased rapidly after the two first hours and reached 120° after 4 h. The same trend was observed in the hysteresis of this surface, which reached 30–35° after the first two hours. Figure 7b indicates that the most durable coatings were the 1% w/v Teflon AF 1600 spin coating and the plasma-deposited coating using C₄F₈ gas. The coating deposited with CHF₃ gas was losing its superhydrophobic properties after 1 h of testing. Lower hysteresis values were measured for the plasma-deposited coating using C₄F₈ gas and the spin-coated 1% w/v Teflon AF 1600 on the hierarchical micro-nanotextured surfaces. Another interesting finding is that although the hysteresis in the 2.5% drop-cast PTFE coating was higher compared to other surfaces (10–12°), it remained stable for 2 h of hot steam impact, but in the third hour it started to increase, reaching 20°.

The durability trend of the coatings extracted from the steam impact test is in agreement with the results of the immersion test. As illustrated in Figure 7, the surfaces failed more rapidly during the steam test compared to the immersion test, and this is due to the nucleation of steam within the topographical structures. When a water droplet nucleates between the structures, the capillary forces between the droplet and the surface developing in this region are significant. Thus, when the droplet departs from the surface, it can drag along parts of the coating if the coating’s adhesion to the substrate is not high enough.

Coating durability, under the harsh conditions of immersion in hot water and the impact of steam at 100 °C, shows the applicability of these methods in a wide range of applications, involving high temperatures and high humidity environments. However, coating durability is not the only characteristic that has to be considered when using superhydrophobic surfaces in real-life applications. A less durable coating may be more suitable because of its small environmental impact, low cost and ease of application compared to another which is more durable but has a severe environmental impact. Thus, in our case, although Teflon AF has great potential for usage in many applications due to its high durability, ease of applicability to various surfaces, scalability, and strong anti-wetting properties, its environmental impact is severe due to the fluorinated solvent FC770 which is used in the preparation of the hydrophobic solution. On the other hand, the coatings fabricated through plasma deposition, especially the one using the C₄F₈ gas, exhibit high durability against hot steam flow with minimal environmental impact. The smaller environmental impact is because plasma deposition is a dry method operating on RF mode (lower energy-consumption requirements), requiring small amounts of the gas for the coating formation, and producing no liquid waste. The best results in terms of contact angle hysteresis (criterion for high mobility) are obtained from plasma deposition using
C₄F₈ plasma, which can lead to fabrication of an ultra-thin Teflon-like coating, remaining superhydrophobic, with hysteresis lower than 8°, after 10 h immersed in hot water, and 4 h under hot steam flow impact.

![Graph](image-url)

**Figure 7.** (a) Change in static contact angle for the different superhydrophobic surfaces fabricated (2.5% low Mw PTFE drop-cast (A1), 50% high Mw PTFE spin coated (A2), 1% w/v Teflon AF 1600 spin coated (A3), CHF₃ plasma deposition (B1), C₄F₈ plasma deposition (B2)) tested after 4 h over hot steam flow; (b) change in the hysteresis after 4 h over hot steam flow.

Aside from their applicability in heat transfer applications, we have demonstrated in our recent work [43] that micro-nanotextured Al surfaces are also effective against fungi proliferation and their anti-fungal properties are stable even after immersion in
fungi-containing solution for up to 14 days. Thus, such surfaces can be real candidates for heat transfer-related applications in which cooling water may come from natural water sources containing various microorganisms that can create fouling and compromise power generation performance [44].

4. Conclusions

In this work, different methods of obtaining superhydrophobic aluminum surfaces are investigated, involving coatings obtained through drop casting and spin coating of PTFE-nanoparticle solutions, spin coating of Teflon AF 1600, and plasma deposition using two different gases. After fabrication, the coating durability was tested under conditions of immersion in hot water for ten hours and hot saturated steam impact for up to four hours. The hot water immersion test showed that the most durable coating under hydrolytic stress was the one fabricated by C₄F₈ plasma deposition on a micro-nanostructured surface, retaining a hysteresis angle of 7° after 10 h in water of 90 °C. Besides the C₄F₈ plasma-deposited coating, the 1% w/v Teflon AF 1600 spin coating maintained its hysteresis under 10° for 7 h in hot water, and increased only to 12° after the 10th hour in the immersion test. Similar to the immersion test, the best results, in terms of durability under the steam impact test, were obtained from the coating fabricated through C₄F₈ plasma deposition and the spin-coated 1% w/v Teflon AF 1600 on the hierarchical micro-nanotextured surfaces, exhibiting minimal changes in their wetting characteristics during the test, showing the applicability of such surfaces in heat transfer-related applications.

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