Surface & Coatings Technology 313 (2017) 17–23

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Hot embossed micro-textured thin superhydrophobic Teflon FEP sheets for low ice adhesion

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ARTICLE INFO

Article history:
Received 25 July 2016
Revised 31 December 2016
Accepted in revised form 9 January 2017
Available online 10 January 2017

Keywords:
Superhydrophobic
Thin sheet
Hot embossing
Ice adhesion

ABSTRACT

Various efforts have been conducted by researchers to create synthetic superhydrophobic surfaces. However, most of these fabrication procedures are convoluted and not suitable to be applied on surfaces with complex shapes and sizes. We report a simple and low cost fabrication of a thin superhydrophobic sheet (127 μm thick) of low ice adhesion strength by laser micro-texturing an aluminum master substrate followed by hot embossing on a Teflon fluoroethylene propylene (FEP) sheet for a water contact angle and roll-off angle of 160° and 4°, respectively. The micro-textured aluminum master substrate could be used multiple times to emboss the FEP sheet for a reduction in fabrication complexity and cost. The fabrication procedure also ensured that the structure of the sheet remains intact, therefore allowing it to be wrapped and adhered to target surfaces of different shapes. Ice adhesion experiment on the superhydrophobic sheet showed ice detachment strength at approximately 20 kPa on average, which was <2% of the ice detachment strength of an aluminum substrate, 33% of the ice detachment strength of a smooth non-textured Teflon FEP sheet and among the lowest superhydrophobic ice adhesion strength reported in literature. Potential applications of the superhydrophobic sheet include evaporator icing control in refrigeration systems and low ice adhesion surfaces for architectural structures.

1. Introduction

The extreme water-repellency of superhydrophobic surfaces can provide solutions in a variety of applications such as anti-icing for refrigeration systems, architectural and aerospace industries, anti-fouling and corrosion protection in marine applications, self-cleaning for solar cells, etc. Superhydrophobicity, often quantified by a contact angle (>150°) and roll-off angle (<10°) wettability measurements, is induced by creating micro/nano-textures on an inherently hydrophobic material [1,2]. The combination of low surface energy and asperities lead to a Cassie-Baxter wetting state, whereby air pockets are trapped in between the gaps of the surface roughness and hence resulting in water suspension on the tips of the micro/nano-features [3]. This drastically increases the mobility of a water drop on a surface. In contrast, a Wenzel wetting state is a wetting condition whereby water penetrates into the surface asperities to fill the gaps between the micro- textures [4]. The increased contact area between the water-surface interfaces reduces water drop mobility on the surface which is often associated with a high roll-off angle, and in certain conditions can also cause water drop pinning.

The attractiveness of superhydrophobic surfaces in providing broad application solutions have prompted researchers to create synthetic water-repellent surfaces using a variety of techniques. These include, but are not limited to, surface etching techniques (plasma, laser, chemical) [5–7], lithography (photolithography, electron beam, X-ray) [8,9], electrochemical deposition processes [10,11], electro-spinning techniques [12], etc. Although these techniques do successfully result in superhydrophobicity, they are complex and are often associated with high fabrication cost. In addition, they could be challenging to implement on applications since target surfaces are often in complex shapes and sizes. For example, the leading edge of an aircraft wing is curved for aerodynamic efficiency. As such, the goal of this work is to create a thin superhydrophobic sheet that is lightweight, flexible with low ice adhesion strength, so that it could be wrapped and adhered to target surfaces of different shapes for ice protection without adding a significant weight.

The creation of a superhydrophobic sheet requires that the sheet material to be of inherent low surface energy. We chose a fluorinated ethylene propylene (FEP) sheet of 0.005 in./127 μm (Teflon FEP, DuPont) and imparted micro-textures on the sheet via hot embossing from a micro-textured aluminum master substrate. The selection of the DuPont Teflon FEP sheet is due to its all-round robust characteristics. For example, it is chemically inert and resistant to virtually all chemicals, has high resistance to impact and tearing and also inert to outdoor exposure (no measurable change after 20 years in a test conducted at Florida) [13]. More importantly, it has a lower melting temperature than Teflon polytetrafluoroethylene (PTFE) at between

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http://dx.doi.org/10.1016/j.surfcoat.2017.01.026

250 °C to 280 °C. This allows the hot embossing procedure to be conducted at lower temperatures. Texturing of Teflon materials for superhydrophobicity has been conducted by various researchers by a variety of different techniques [14–18]. However, to the author's best knowledge, there have not been any publications which attempted to texture a Teflon sheet as thin as 127 μm while maintaining the structural integrity of the sheet, with high contact angles (>150°). In addition, ice adhesion properties of these sheets have not been reported. A majority of the work has been focused on texturing bulk Teflon material, such as Liang et al. [14] who ablated PTFE blocks by femtosecond lasers, Nilsson et al. [15] who roughened solid PTFE by sandpaper and Glaris et al. [16] who thermally annealed a 4 mm thick PTFE block for the creation of texture. Jucius et al. [17,18] did hot emboss a thin 200 μm PTFE sheet to create superhydrophobicity but was only able to achieve a contact angle of 145°.

The current fabrication of the superhydrophobic thin sheet requires 4 steps. The first step is to use laser irradiation on an aluminum substrate to ablate the surface and to create micro-textures. The second step involves embossing the previously ablated micro-textured aluminum surface on a fluorinated ethylene propylene (FEP) thin sheet at high temperatures. The third step is to peel off the textured FEP sheet under low heat from the aluminum textured surface, and finally, the fourth step is to post-treat the textured FEP sheet to smoothen any curved edges and wrinkles. A schematic of these four steps is shown in Fig. 1. It should be noted that after the completion of Step 1, the micro-textured aluminum master substrate could be used multiple times for hot embossing and creation of micro-textured FEP thin sheets. This drastically simplifies the fabrication steps and reduces the fabrication cost as well. The ice adhesion properties of this superhydrophobic sheet were then investigated. In addition, the repellency of the sheet from liquids consisting of different surface tensions was studied.

2. Experimental methods

2.1. Fabrication of the superhydrophobic thin sheet

A 532 nm wavelength pulsed ytterbium fiber laser (Model YLP-G-10, IPG Photonics) was used to irradiate a square aluminum master of approximately 2.54 cm by 2.54 cm in dimension. This laser system has the capability to generate 10 W of average laser power with a pulse of 1.3 ns and a focused spot size of 25 μm. In order for the entire surface area of the aluminum master to be laser irradiated, a galvanometer (SCANcube 14, SCANLAB) was utilized to deflect the laser beam so that the beam could traverse in longitudinal and lateral directions for a fast and accurate scanning. The parameters of the pulsed laser processing were optimized so that micro-textures on the aluminum were approximately uniform in height and spacing. These parameters were as follows: a laser pulse energy of 3.9 μJ/pulse, a pulse repetition rate of 400 kHz, a scanning speed of 6 cm/s and a laser deflection lateral length of 14 μm. This lateral length was intentionally chosen to be lower than the spot size of the laser beam so that initial laser irradiation areas would be partially processed again. This was to ensure a uniform micro-texturing of the aluminum master surface without any apparent gaps between textured areas. It should be noted that this laser irradiation technique have been previously used by Bhagat et al. [19] and Nayak et al. [20,21] to successfully micro-texture common materials, such as, polycarbonate, silicon, titanium, aluminum, copper and stainless steel.

Step two of the fabrication process involved hot embossing of the previously micro-textured aluminum master on a FEP thin sheet (Teflon FEP Fluorocarbon Film, DuPont) of 127 μm thickness. This virgin FEP sheet is optically transparent and offers a good balance of sheet flexibility and mechanical strength. For example, the sheet could be elongated 300% without break with a folding endurance of 10,000 cycles. These property values show that this product is a good candidate for withstanding the processes of hot embossing and peel-off with minimal effect on the integrity of the sheet. First, an approximately 2.54 cm by 2.54 cm FEP sheet was cut and placed on the micro-textured aluminum sheet and placed on a hot plate. Two kg of weights was used to provide embossing pressure necessary to replicate the micro-textures on the FEP thin sheet. This amount of weight on the samples equate to approximately 30 kPa of embossing pressure. Since the surface of the weight was rough, a polished aluminum substrate was placed underneath the weights to avoid direct contact between the FEP thin sheet and the weights. An additional polytetrafluoroethylene (PTFE) thin sheet (50 μm Teflon PTFE, McMaster) was sandwiched between the FEP thin sheet and the polished aluminum substrate. This was because the FEP thin sheet would be heated past its melting temperature to potentially cause adherence on the polished aluminum. Since the PTFE has a higher melting temperature (~320 °C), it will prevent adherence problems

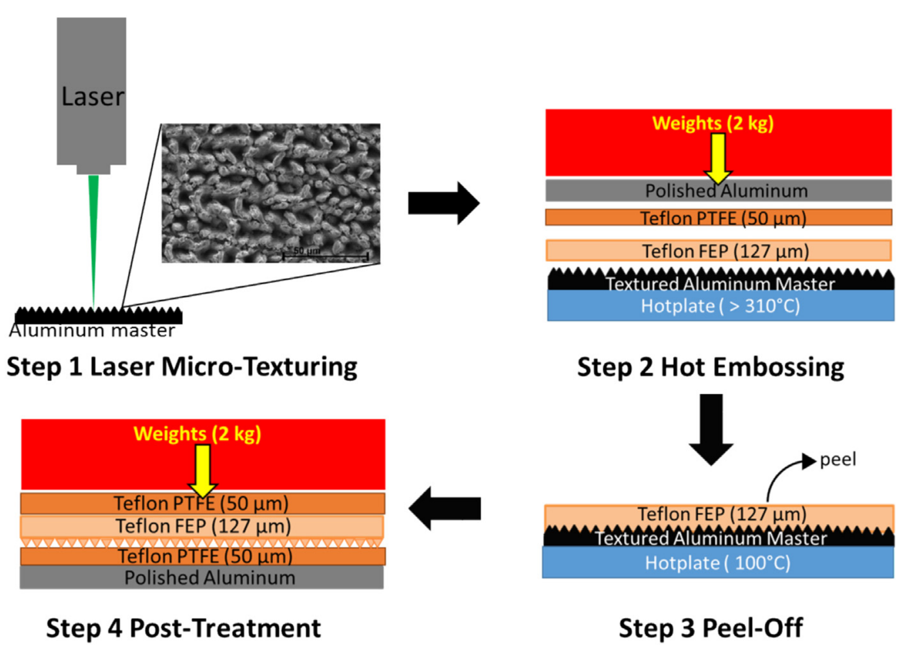

Fig. 1. Schematic showing the four steps required to fabricate a FEP micro-textured superhydrophobic thin sheet.