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Shape evolution of water and saline droplets during icing/melting cycles on superhydrophobic surface

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A B S T R A C T

In this study, bright nickel coating and superhydrophobic nickel film with micro-nano cones were prepared by electrodeposition. The topography and morphology of films were characterized by SEM and AFM. The evolution of shape parameters of water droplet including contact angle and contact diameter were measured by successive icing/melting cycles at $-10/+25$ and relative humidity of 30 ± 2%. In addition, the freezing delay time was measured as a function of the surface topography and morphology. In presence of micro-nano cones, longer freezing delay time (110 min) observed in comparison with bright nickel (34 min). Power spectral density of AFM images showed that the superhydrophobic film has higher roughness distribution in all frequencies than bright nickel film. Also, it was shown that saline droplet has similar contact angle with water droplet on superhydrophobic surface (slightly changes from 156 ± 2° to 154 ± 1.5°) in ambient temperature. Furthermore, it was observed that contact angle of pure water and saline droplets was decreased in single icing/melting cycle to 141 ± 2° and 138.6 ± 1°, respectively. The reason was attributed to formation of concave ice, capillary condensation and frosting. Finally, electrochemical measurements showed that after 40 icing/melting cycles (2 h icing at − 20 °C and melting at 25 °C for each cycle) by immersing in pure water and saline solutions, corrosion resistance of the superhydrophobic nickel film presented fairly less protection level, particularly in saline solution.

1. Introduction

Adhesion and excessive accumulation of ice and snow on environmental equipment and structures are well known to cause serious problems in aircraft, telecommunication towers, ships, antennas, wind turbines, oil platforms, exposed pipe in atmosphere, refrigerator and etc. [1–4]. Each year, numerous failures due to ice accumulation are reported in Canada, Russia, Norway, Finland, Iceland and USA [5–8]. To counter this problems and performance improvement, various techniques that include melting and anti-icing processes have been developed [1,4,9,10].

The phenomenon which the water droplet bead up on the surface is called "Lotus effect" [11]. Inspired by this phenomenon, researchers have recently made significant progress in fabrication of superhydrophobic surfaces with a high contact angle (CA > 150°), low sliding angle (SA < 10°) and low contact angle hysteresis (CAH) [11–15]. These properties are important parameters for designing and manufacturing of anti-icing or icephobic and superhydrophobic surfaces [2,7,10,16–18].

The surface energy and texture, both play important role in adhesion strength and formation of frost on surfaces. Therefore, superhydrophobicity may be stated as a combination of surface chemistry (hydrophobicity) and structure (roughness) [7,8,16,19,20]. To explain the effect of surface roughness on hydrophobicity, Wenzel and Cassie/Baxter put forward their independent theories of Wenzel's and Cassie's state. According to Wenzel's theory, water droplets penetrate to the rough surface in contact mode and demonstrate low CA while in Cassie/Baxter model, a water droplet rest on the heterogeneous surface due to presence of air packets in grooves [21–23].

Superhydrophobic surfaces can be beneficial to prevent ice formation through condensation of water droplets and also they are able to lower adhesive strength between solid and water [16,20]. Recently, researchers demonstrated that with increase in freezing delay time, problems such as high adhesion strength and formation of frost will be lowered [1,7,24–27]. Indeed, freezing delay time is related to delay in the ice nucleation process and according to the classic theory of nucleation, this can be described by the kinetics of crossing the energy barrier between ice/water which cause water solidification [7,26]. Based on above explanations, surface energies seem to play a significant role in freezing delay time.

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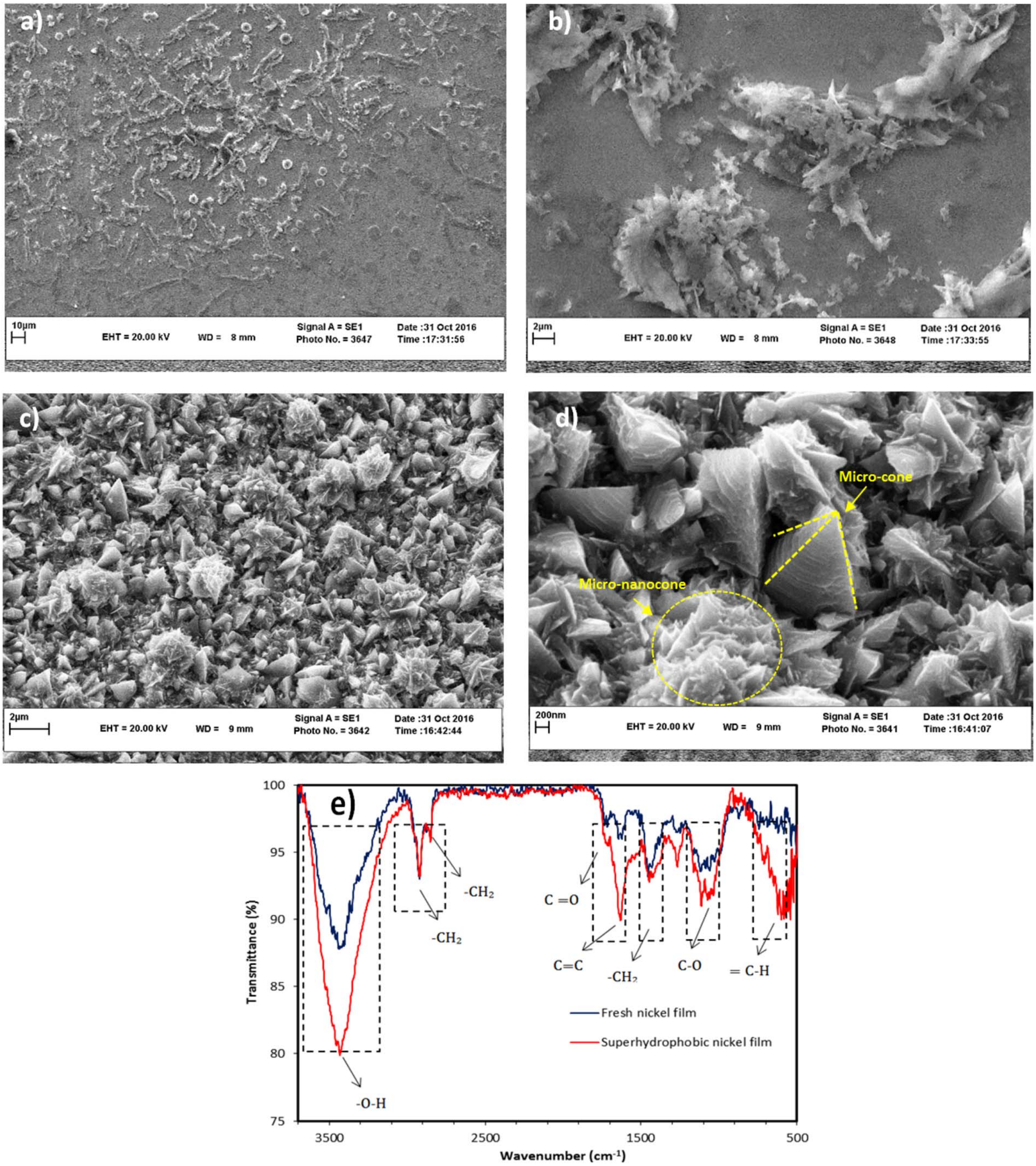

Fig. 1. SEM images of nickel surface fabricated by electro-deposition. (a, b) bright nickel film (c, d) the nickel MNCs, and (e) FT-IR spectra of nickel MNCs, black line: before exposing to air; red line: after exposing to air for 16 days. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Water is not pure in the nature and industrial areas and has some suspended and dissolved species such as dust and different salts [28–30]. In addition, icing/melting cycles have negative effects on the mechanical and corrosion properties of engineering structures near frozen saline soils in cold regions [29,31,32]. Wang et al. investigated the wettability of superhydrophobic copper surfaces; it was shown that the saline droplets have a high CA on copper surfaces [33]. Freezing point depression is a phenomenon where the freezing point of a solvent is decreased by the presence of salts. Also, it is noted that the lowering of freezing point does not depend on the nature of the solutes, rather only number of dissolved molecules and ions [29,31,34,35].

In this paper, we investigate the following items: A) effects of icing/melting cycles on shape parameters of water droplet on superhydrophobic nickel and bright nickel films and its correlation with surface roughness. B) Topography effects on freezing delay time. C) Water and saline droplets melting process and its effect on contact angle. D) Effect of icing/melting cycles by immersing in pure water and saline solution on corrosion behavior of superhydrophobic film.

2. Experiments and methods

2.1. Substrate material and surface treatment

A 99.5% nickel plate (40 mm × 40 mm × 1 mm) was employed as anode and nickel was deposited on the pure Cu plate as cathode (20 mm × 20 mm × 1 mm). The Cu plate was first ground through