Optimizing fiber cross-sectional shape for improving stability of air–water interface over superhydrophobic fibrous coatings

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In this letter, a mathematical force-balance formulation is developed that can be used to predict the critical pressure, the hydrostatic pressure above which the surface starts to depart from the non-wetting state, for superhydrophobic surfaces comprised of highly aligned fibers (e.g., biased AC-electrospun coatings) with arbitrary cross-sectional shapes. We have also developed a methodology for optimizing the fiber cross-sections to maximize the critical pressure of the surface, using the Euler–Lagrange equation. A case study is presented to better demonstrate the application of our method. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4711800]

Superhydrophobicity is brought about by combining micro- and nano-scale surface roughness with the hydrophobicity of the bulk material, resulting in static contact angles greater than 150°.[1,2] This is due to the formation of entrapped air pockets in the micro- and/or nano-pores of the surface, leading to a reduced solid surface area in contact with water—an effect that can lead to reduced skin-friction drag on submerged moving objects.[3] Superhydrophobic surfaces, however, are reported to transition from the Cassie (non-wetting)[4] state to the Wenzel (fully wetted)[5] state if exposed to excessive hydrostatic pressures.[6–9] There have been recent studies dedicated to developing mathematical formulations to predict the so-called "critical pressure," the pressure above which a superhydrophobic surface starts departing from the Cassie state.[10–15]

Producing superhydrophobic surfaces made up of electrospun fibers has been reported in variety of studies conducted in the past decade (see Ref. 16 for a review). In a conventional electrospinning process, the fibers are ejected from a nozzle and are drawn into thinner strands by aerodynamic and electrostatic forces as they travel toward the collector. The fibers eventually deposit onto a substrate attaining random in-plane orientations (see Ref. 17 for a review). The first attempt to predict critical pressure for electrospun surfaces was made by Tuteja *et al.*[18] These authors considered a simplified geometry of equally spaced parallel fibers with circular cross-sections placed on a flat surface, and developed two criteria for the evaluating the stability of the air–water interface in the grooves formed by the fibers under elevated pressures. Although it was not discussed by Tuteja *et al.*,[18] the formulations given by these authors were actually more appropriate for fibrous surfaces comprised of aligned fibers, as opposed to those having random in-plane orientations. Such anisotropic fibrous structures can be produced by modifying the traditional electrospinning process. Among different techniques, the biased AC-electrospinning of Tepper and his co-workers[19,20] has shown promising control over fiber orientation, as can be seen in Figure 1. In a recent study, we simulated the influence of the fibers' in-plane orientation on the critical pressure and discussed the role of microstructural parameters of a fibrous surface on its resistance against elevated hydrostatic pressures using the so-called full morphology method.[21] The focus of the current paper, on the other hand, is on the effects of fibers' cross-sectional shape on the critical pressure. In particular, we have developed a rigorous mathematical method to predict the critical pressure of electrospun superhydrophobic coatings. As the 3-D morphology of fibrous coatings with random fiber orientation is prohibitively complicated from a mathematical point of view, our formulations are developed in two dimensions and so are more accurate for coatings made up of aligned fibers, e.g., biased AC-spun fibrous coatings. The mathematical framework developed in this study, however, allows the fibers to have any arbitrary cross-section, and more importantly, is capable of optimizing the fibers' cross-sectional shape to maximize the critical pressure of the coatings. Such information is particularly important for designing fibrous superhydrophobic coatings for underwater applications where resistance against elevated hydrostatic pressures is crucially important.[21–27]

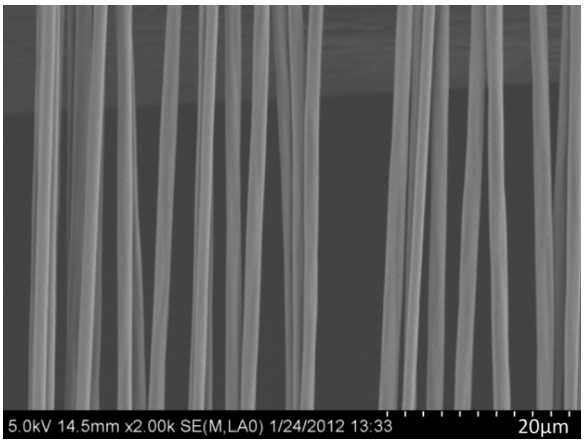

FIG. 1. An example of a fibrous coating consisting of highly aligned polystyrene fibers produced via biased AC-electrospinning.

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