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Increase buoyancy of a solid fragment using micropillars

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ABSTRACT

When a solid fragment has a higher density than water, it may still float on water surface due to the support of surface tension. However, once the solid fragment is completely immersed inside water, it sinks down to water bottom due to elimination of the surface tension. In this work, we demonstrated that, after the incorporation of micropillars on such a solid fragment, it may still get back to water surface. Air is trapped between micropillars. This increases the space that the solid fragment occupies under water. Accordingly, the buoyancy is increased. The critical values of trapped air, micropillar-covered area, micropillar height and water depth for a micropillar-covered fragment to rise up to water surface were formulated. Four micropillar-incorporated SU-8 fragments were fabricated and tested to validate the derived relationships. Experimentally determined critical values of micropillar-covered areas and trapped air volumes had good match with theoretically predicted ones.

In addition, through force analysis, we showed that surface tension at the triple lines between water, micropillars and trapped air retains the volume of the trapped air but does not provide any lifting force to make the fragment rise up to water surface. Since the incorporation of the micropillars may make a completely immersed fragment get back to water surface from under water, the presented results have potential applications in developing miniaturized devices, such as submarines and water robots, that may need to rise up to water surface.

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1. Introduction

Surface tension is an effect within the surface layer of a liquid. It causes this layer to behave like an elastic sheet. Surface tension makes a small object capable of displacing more water than its volume [1]. Accordingly, the buoyancy is increased due to the presence of surface tension, making small, heavy objects, such as sewing needles, water striders [2], mm-scaled boats [3], cm-scaled flotillas [4], and mm-scaled circular disks [5], able to float on water surfaces.

On the other hand, once a solid fragment that is denser than water is completely immersed inside water, it may sink down to water bottom due to elimination of the surface tension. In this work, we demonstrated that, when micropillars were incorporated into such a solid fragment, it might still move up to the water surface from under water. Air was trapped between micropillars. This increased the volume that the solid fragment occupied under water. Accordingly, the buoyancy was increased, enabling the fragment to move up to water surface.

It was observed that some so-called "self-clean" plants, such as Lotus and Colocasia, can form spherical (super-hydrophobic) water droplets on their leaves in rain, fog and dew to avoid getting wet. This phenomenon is often called "Lotus effect" [6]. It was found that the micropillar-like structures on the leaves took a great role in this effect [7]. Accordingly, rectangular and circular micropillars have been widely applied to enhance surface hydrophobility [8–11]. In this work, we showed a new application of such micropillars. That is, they could also be used to increase buoyancy of a solid fragment.

The paper is organized as follows. Theoretical relationships are derived in Section 2. Design and fabrication procedures are presented in Section 3. Experimental results and discussions are given in Section 4. Finally, in Section 5, this work was summarized and concluded.

2. Theoretical modeling

Without loss of generalization, in this work we consider the case that an array of micropillars is incorporated on the bottom of a solid fragment (Fig. 1). The analysis below also applies to the case that the micropillars are incorporated on the top of a solid fragment. Let V_s and t denote the volume and thickness of the solid fragment, separately. Micropillars may have rectangular or circular cross-sections (Fig. 1(b) and (c)). In Sections 2.1 and 2.2, we first consider the situation that rectangular micropillars are used to increase buoyancy of a solid fragment. The corresponding results are then modified for the case of circular micropillars in Section 2.3. Set a_1, a_2, and t_p, respectively, denote the length, width and height of a rectangular

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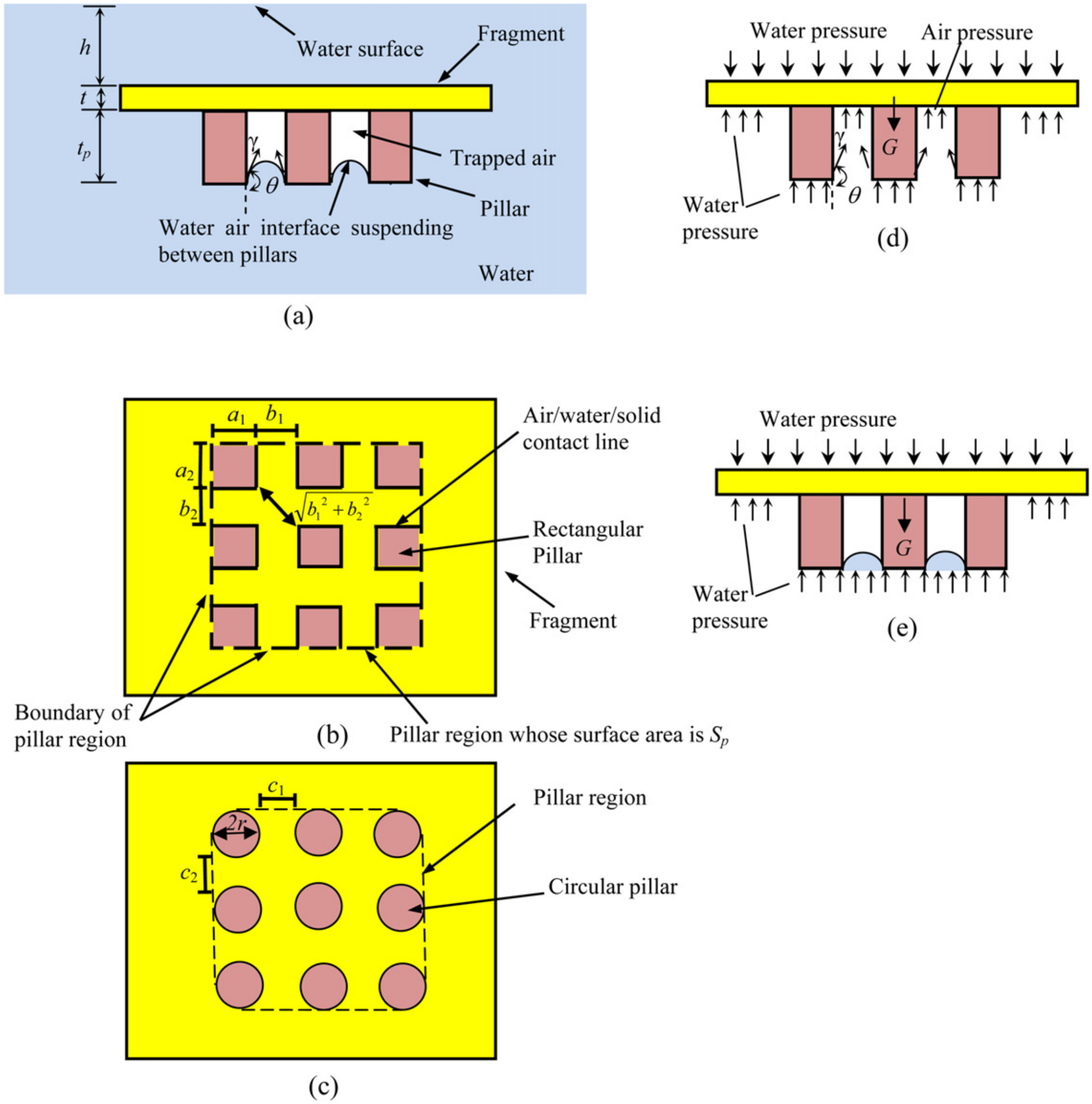

Fig. 1. (a) Side view of a micropillar-incorporated fragment. Bottom views of this fragment when it was incorporated with (b) rectangular or (c) circular micropillars. (d) Free-body diagram of a micropillar-incorporated fragment. (e) Free-body diagram of the object formed by the micropillar-incorporated fragment, trapped air, and small neighborhoods of air/water interfaces. Only three pillars are drawn in (a) to have enough space to show air/water interfaces clearly. Thick, solid lines in (b) are air/water/solid contact lines. Also, only vertical components of water and air pressures were considered in the two free-body diagrams.

micropillar (Fig. 1(b)). Let b_1 and b_2 denote the distances between neighboring micropillars along two lateral dimensions, respectively. Set S_p to be the surface area of the region covered by the rectangular micropillars (Fig. 1(b)). We consider two cases. In the first case water does not get into the gaps between micropillars when a solid fragment is placed under water. This implies that air/water interfaces are suspended at the top edges of the micropillars, and that air trapped in the gaps between micropillars is not much compressed. However, in the second case, water gets into the gaps between micropillars, air/water interfaces are stationary on the side surfaces of the micropillars, and trapped air is compressed. These two cases are considered in Sections 2.1 and 2.2, respectively.

2.1. The case when the gaps between micropillars are not filled with water

When the micropillar-covered fragment is released under water, along the vertical direction the fragment suffers four forces (Fig. 1(d)): gravity, water pressure-induced force, air-pressure induced force, and surface tension-induced force. Let G, F_w, F_a, and F_s, respectively, denote the magnitudes of the vertical components of these four forces. Set p_0 to be atmospheric pressure. Since the trapped air is not much compressed, its pressure is still considered to be p_0. Based on this point and pressure distributions, we have

$$\begin{aligned} G &= \rho_s g V_s + n\rho_p g a_1 a_2 t_p, \quad F_w = \rho_w g(V_s + n a_1 a_2 t_p) \\ &\quad - (S_p - n a_1 a_2)[p_0 + \rho_w g(h+t)], \quad F_a = p_0(S_1 - n a_1 a_2), \\ F_s &= -\gamma \cos\theta L, \end{aligned} \tag{1}$$

where ρ_w, ρ_p and ρ_s represent densities of water, pillars and solid fragment, respectively, n is the number of micropillars generated on the fragment, γ is surface tension of water, L is the total length of air/water/solid contact lines (these lines are marked in Fig. 1(b)), and θ is local contact angle on the micropillars (Fig. 1(d)). Set θ_e to be intrinsic contact angle on the micropillars. Since these micropillars are considered to have hydrophobic surfaces, $\theta_e > 90^\circ$. When air/water interfaces are suspended on the top edges of micropillars, $90^\circ < \theta \le \theta_e$ [12,13].

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