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Lotus effect in wetting and self-cleaning

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ABSTRACT

Self-cleaning surfaces based on lotus effect with a very high static water contact angle greater than 160° and a lower roll-off angle have been successfully studied by researchers and applied in fields of self-cleaning windows, windshields, exterior paints for buildings and navigation of ships, utensils, roof tiles, textiles, solar panels, and applications requiring a reduction of drag in fluid flow, e.g. in micro −/nanochannels. In this feature article, we summarize recent research progress and synthesis technologies about the design and fabrication of self-cleaning surfaces. We hope that, this review article should provide a useful guide for the development of self-cleaning surfaces.

1. Introduction

Over thousands of years of natural selection, living organisms including all plants and animals on our earth are evolutionarily optimized functional systems. One of their most fascinating properties is the ability of self-cleaning which means that the surfaces can repel contaminants such as solid particles, organic liquids, and biological contaminants by the action of rolling-off water drops. This kind of self-cleaning surfaces has both the ability of superhydrophobicity and self-cleaning properties, and with lotus leaf as the typical representative, therefore is known as "Lotus effect". [1–8] During the past few decades, a large number of studies have been conducted to a full understanding of the functions, structures, and principles of self-cleaning surfaces. The conclusion recognized that the requirements for a self-cleaning surface are superhydrophobic property with a very high static water contact angle greater than 160°, and a very low roll-off angle, i.e. the minimum inclination angle necessary for a droplet to roll off the surface. [3,9] By now, many different synthesis technologies have been developed to design and fabricate self-cleaning surfaces. [10–14] Today, a great variety of self-cleaning surfaces based on lotus effect have also been commercialized with the range from window glasses to solar cell panels. [15–18].

In this feature article, we summarize recent research progress in the field of bio-inspired self-cleaning surfaces based on lotus effect about the mechanism, fabrication, and application. At first, we discuss the impact of multi-scale roughness and low energy waxes on the self-cleaning property, respectively. And in the next section, we briefly summarize and discuss the conventional self-cleaning methods. We categorize recent progress in this area into two aspects as the technologies of constructing hierarchical roughness structure onto the hydrophobic surfaces and the technologies of coating low energy materials onto the rough surfaces. Furthermore, the review introduces briefly the application prospects and challenges of self-cleaning surfaces based on lotus effect. We hope, this review article should provide a useful guide for the development of self-cleaning surfaces.

2. Lotus effect—the self-cleaning property of lotus leaf surface

As we known, the lotus leaf has long been regarded as the symbol of sacred purity in China, and sang praises by number of poets. The verse of "the lotus and leaves all over the pond, and breeze blows beads roll down" described that water drops falling onto the leaves can bead up and roll off, with washing dirt from the lotus leaves so that they are self-cleaning, which is known as "Lotus effect". This phenomenon of lotus effect is not restricted to lotus leaf surface. Some other plants and insects also evolved self-cleaning surfaces. For instance, the droplets of water on the rice leaves [19,20], *Salvinia molesta* [21,22], butterfly wings, fish scales, shark skin [20,23] and mosquito eyes [24] (as shown in Fig. 1) can roll off following a preferential direction dictated by the structural features.

For an understanding of the functions, structures, and principles of various objects that exhibit self-cleaning found in living nature, a large

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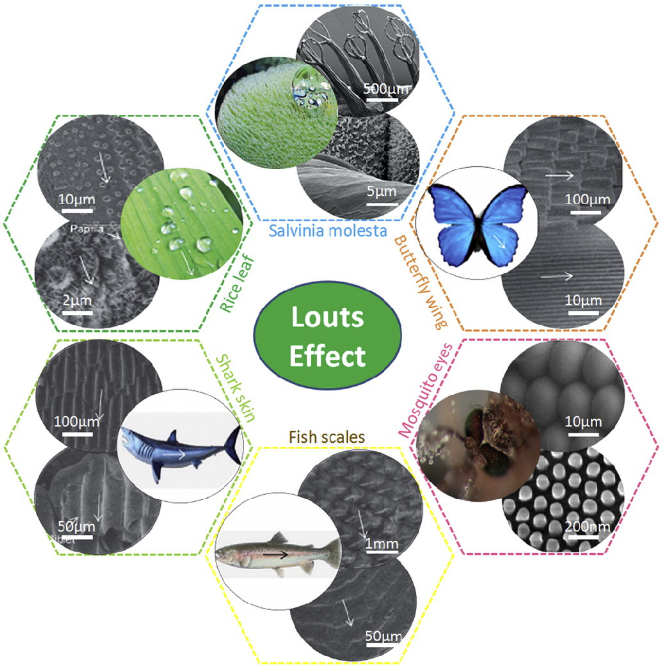

Fig. 1. The typical self-cleaning surfaces in nature and their SEM images.

number of studies have been conducted onto surface structure and chemical composition.

2.1. Effect of the hierarchical roughness of the lotus leaf surfaces

In order to reveal the roles of the roughness and waxes covered over the entire surface of lotus leaf on the self-cleaning property, many scientific research workers carried out extensive researches. Neinhaus and Barthlott investigated nearly 300 kinds of plant leaf surface, and indicated that this self-cleaning property is caused by both the rough structure and the hydrophobic epicuticular waxes. [2,3].

In 2002, Jiang reported a new discovery, indicating that, there are fine branch-like nanostructures covered on the every micro-papilla of the lotus leaf surface. [25] And this kind of micro- and nanohierarchical composite structure of the lotus leaf surface realized superhydrophobic and low adhesive performance.

Fig. 2b shows a typical scanning electron microscopy image of a lotus leaf. We can see that lotus leaf surfaces possess randomly distributed micro-papillae with diameters ranging from 5 μm to 9 μm. Fig. 2c shows a high-resolution SEM image of a single papilla which proves that on each papilla and the gaps of surface among papillae, fine branch-like nanostructures with diameter of approximately 120 nm have been observed. These nanostructures would effectively prevent the underside of leaf from being wetted. The multi-scale structures combined with micro-papillae and nano-hairs provide air pocket formation, thus, water can interact with only the peaks of the roughness surface instead of by wetting the entire surface, both the peaks and valleys. In this case, the apparent contact angle, θ_{CB}, is given by the Cassie–Baxter (noted as CB) equation for wetting on composite surfaces made of the solid and air, [26]

$$\cos\theta_{CB} = f_s\cos\theta + f_s - 1 \quad (1)$$

where f_s is the fraction of projected planar area of the drop in contact with the solid. In the limit of $f_s \rightarrow 0$, the macroscopic contact angle θ_{CB} approaches 180°, leading to superhydrophobic behavior. That is to say, the multi-scale structures result in the lowest contact area between lotus leaf surfaces and water droplets. And drops in the Cassie-Baxter state can easily roll because of low resistance from the air pockets. [27,28] Therefore, we can say that, this kind of micro- and nano- hierarchical structure amplifies the apparent contact angle and is responsible for the rolling behavior of the drops.

Cheng and Rodak et al. studied the influence of micro- and nano-scale structures on the wetting behavior of lotus leaves by separated the effects of nano-scale features from micro-scale roughness on the wetting behavior. [29] They annealed the leaves for 1 h at 150 °C, and examined by SEM (as shown in Fig. 2d). The result showed that all the nano-scale hair-like structures from the leaf were removed, leaving behind only micro-structure surface. The wax present on the surface of the untreated and annealed lotus leaves does not appear to undergo any gross chemical change, based on the IR data. For comparison, the static water contact angles on the untreated lotus leaf, annealed lotus leaf and smooth of carnauba wax were measured. And the result values were 142.4 ± 8.6°, 126.3 ± 6.2°, and 74.0 ± 8.5°. These results indicate that the carnauba wax is not very hydrophobic because of its many hydrophilic functional groups, which is also consistent with Wagner's conclusion. [30] Thus, the micro-scale roughness on lotus surfaces is effective in increasing the static contact angle, and the presence of the nano-scale hair-like structure is responsible for the additional increase of 16° in contact angle from 126° to 142°.

In addition, while water drops placed on the lotus leaves roll off at the slightest incline, the same size drops become sticky drops on the annealed leaf, adhering to the surface even when the leaf is tilted 90°

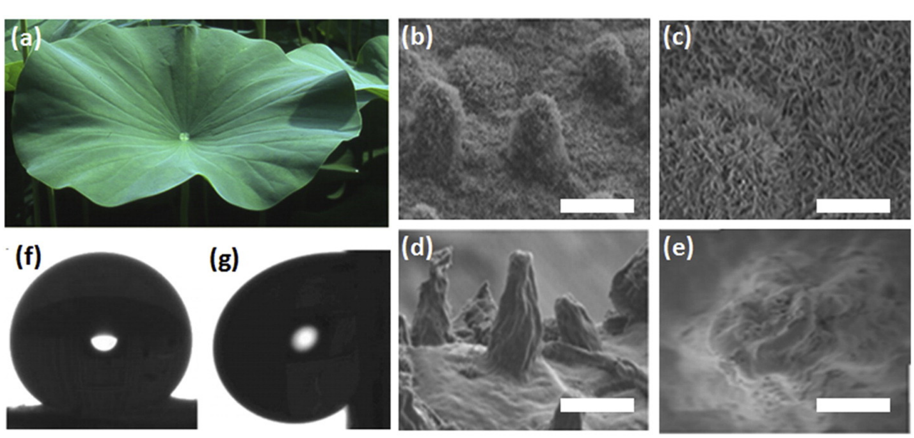

Fig. 2. Image and SEM images of lotus leaf surface. (a) A fresh lotus leaf in nature (b) the micro-structure of lotus leaf (c) the nano-structure of lotus leaf (d) the micro-structure of annealed lotus leaf (e) the nano-structure of annealed lotus leaf (f) a droplet placed on an untreated lotus leaf, and (g) a droplet placed on an annealed lotus leaf, then tilted to an angle of 90°. (Scale bar: (b and d) 10 μm, (c and e) 3 μm).

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