Anti-condensation behavior of bamboo leaf surface (backside) and its bionic preparation

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Abstract
Condensation often leads to a decrease in the efficiency of engineering equipment and an increase in energy consumption. Therefore, preventing or delaying condensation on the metal surface is of great significance for practical applications. Here, we report that the main microstructures on the bamboo leaves (backside) are microgrooves, pores and nano-needle-like waxy layers, which have good hydrophobicity and anti-condensation performance. Combined experiments and theoretical analyses reveal that, the hydrophobic surface increases the thermodynamic barrier during the condensation process, which makes the liquid droplets appear in a dropwise condensation mode on the surface, thereby increasing the heat transfer coefficient. In addition, when the condensed droplets merge, their low surface energy and nano-needle structure drive their spontaneous bounce. Here, imitated the backside surface of bamboo leaf, an anti-condensation on the aluminum alloy surface is achieved by laser processing and sol-gel method-hydrothermal method.

1. Introduction
Aluminum alloy is widely used in heat exchange equipment due to its unique properties, but its good thermal conductivity can easily cause condensation on its surface. This will cause equipment efficiency to decrease or even malfunction, and limit the use of aluminum materials in industry. In order to solve the problem of condensation, people have adopted various methods, such as desiccant dehumidification, coating of chemical reagents or physical heating. Although these methods can delay the occurrence of condensation to a certain extent, undoubtedly will consume energy and cause additional waste of resources.

Recently, many researchers have explored the condensation characteristics of different materials and structures [1, 2]. Previous studies reported that the lotus leaves possess a high static water contact angle (160°) and a very low sliding angle (2°), but the anti-condensation properties are not ideal. During the condensation process, maintaining the Cassie state so that the droplets can easily detach from the surface is the key to the anti-condensation surface [3, 4]. Feng et al found that condensation droplets on the surface of sisal-like nanostructures can achieve spontaneous bounce. The Cassie state before the merging of the droplets has a decisive effect on the spontaneous bouncing behavior of the merged droplets. A sufficiently narrow nanostructure is beneficial to promote the transition of the droplets from the Wenzel state to the Cassie state [5].

In this paper, we report that the bamboo leaf (backside) has the characteristics of dropwise condensation and spontaneous bounce, which is inseparable from the micro-nano structure. Simultaneously, in the process of exploring the anti-condensation mechanism of bamboo leaf surface, we tried to prepare an aluminum alloy surface with anti-condensation performance by imitating the microstructure of bamboo leaf, which provided reference basis for the development and application of functional materials.
2. Experimental

2.1. Materials and equipment
Early spring bamboo leaves were collected from Baihuayuan, China. The test material was 6061 aluminum alloy (10 mm × 10 mm), and the polished with different size of sandpapers. And then rinsed with ethanol and deionized water. The chemical reagents used during the experiment include, Zn(Ac)₂·2H₂O, ZnCl₂ and 1H,1H,2H,2H-perfluorodecytriethoxysilane (FAS-17). The microstructure of aluminum alloy surfaces was fabricated by YLP-ST20E fiber nanosecond laser marking machine.

The surface morphology was observed by scanning electron microscope (SEM, Zeiss, EVO MA25, Germany). Before the observation of bamboo leaf samples, the surface of the samples was treated with sputtering gold. The test droplets are deionized water (4 μl). Observe the condensation characteristics of the sample surface through the built-up condensation test bench. The relative humidity in the test bench was kept at 80%, and the sample surface temperature was 0 °C.

2.2. The design of bionic bamboo leaf (backside) aluminum alloy surface
Inspired by the bamboo leaf (backside), we designed a micro-nano composite structure on the surface of the aluminum alloy. Firstly, laser processing was used to construct a microgroove structure and molten particles. The laser processing distance is 0.1 mm, and the processing power is 12 W. The average width of the groove is 121.4 μm. The average spacing of the grooves is 722.7 μm. The average depth of grooves is 297.8 μm. Then the nano-needle structure was prepared by sol-gel-hydrothermal method. The concentration of the hydrothermal reaction solution is 0.05 mol l⁻¹, and the reaction time is 8 h. Finally, a low surface energy material (FAS-17) was used to modify the surface.

3. Results and discussion

3.1. Surface morphology and wettability of bamboo leaves
It was found that the groove (110–140 μm) and ridge structure (30–60 μm) on the back of the bamboo leaf is composed of two or three narrow grooves and ridges. The groove structure is arranged with spherical structures and cone-shaped convex structures (40–80 μm in diameter). When zooming in, we noticed that the surface is covered with nano-needle structures (figure 1(a)). No similar nanostructures were found on the frontside of the bamboo leaves.

Previous research showed that the waxy crystal structure on the surface of each organ of Brachypodium erba is flaky. This is similar to the nano-needle structure on the backside surface of the bamboo leaf. The waxy layer covering the surface of plants is easily removed by external forces, high temperatures or organic solvents [6]. We found that the bamboo leaves became smooth after soaking in acetone solution (group II) and high-temperature baking treatment (group III), and the needle-like nanostructures almost disappeared (figures 1(b), (c)). It can be seen that the bamboo leaf(backside) is covered with a waxy layer, while the material composition of the nano-needle structure is waxy. Both the soaking in acetone solution and the baking at high temperature respectively damaged the waxy nano-needle structure on the backside surface of bamboo leaf.
From the results of the wettability test, we found that the backside of the bamboo leaf before and after the treatment are all hydrophobic surfaces. The waxy layer structure on the surface of bamboo leaves can affect the wettability of the surface by reducing the surface energy. The damage of the waxy layer structure on the backside surface of bamboo leaves in group III was higher than that in group II, so that the contact angle decreased the most, and the hydrophobicity decreased.

3.2. Condensation characteristics

It is easily understood that the condensation occurred on the micro-nanostructured surface are a complex dynamic process, which includes [7, 8]: the water vapor phases into a nucleus on the surface of the bamboo leaf by overcoming the thermodynamic barrier, the liquid core continues to grow by absorbing water vapor molecules when the radius of the liquid core is greater than the critical radius [9], the adjacent droplets merged finally. Since the thermodynamic barrier is closely related to the surface characteristics, the time for the formation of micro-droplets on the surface of each group is different. According to the theory of phase transition thermodynamics, the thermodynamic barrier \( \Delta G_C \) (Gibbs free energy difference) that needs to be overcome when water vapor forms a liquid core on the bamboo leaf is:

\[
\Delta G_C = \frac{4\pi}{3} r_c^3 \gamma f(\theta)
\]

(1)

where, \( r_c \) is the critical radius, \( \gamma \) is the surface tension, \( f(\theta) \) is the contact angle influence function, and its expression is:

\[
f(\theta) = \frac{(2 + \cos\theta)(1 - \cos\theta)^2}{4}
\]

(2)

According to equations (1) and (2), it can be found that the value of function \( f(\theta) \) can directly affect the size of thermodynamic barrier. On the premise that the composition of the surface substance remains unchanged, when the contact angle increases, \( f(\theta) \) will increase, which will lead to an increase in \( \Delta G_C \) and a decrease in the nucleation rate of water vapor. That is to say, the surface wettability has a direct effect on the phase transformation of water vapor into a nucleus. The better the hydrophobicity, the more difficult it is for water vapor to form a liquid nucleus. In addition, the surface wettability will also affect the density of the liquid core at the initial stage of condensation, that is, the better the wettability, the higher the density of the liquid core, and the greater the speed of droplets merging, which ultimately leads to a large number of micro-droplets gathering form a water film.

In the condensation experiment, it was found that only a few tiny droplets appeared on the surface when the test time was 60 s, and the droplets on the surface appeared dropwise (figure 2(b)). At 90 s, there are some dew drops that are approximately half-drops distributed on the surface and are relatively sparse (figure 2(c)). And at 433 s, the three droplets merged into one droplet, and the combined droplet spontaneously bounced off the surface after 1 s, revealing the dry leaf surface again (figures 2(d)–(f)). We can clearly observe the nucleation, growth, merging and spontaneous bouncing of droplets. In the 500 s condensation experiment, the amount of condensation on the surface of bamboo leaves was only 4.435 mg. After organic solvent and heat treatment, the anti-condensation properties are destroyed to varying degrees, the amount of condensation is relatively high, and only nucleation, growth, and merging occur.
The spontaneous bouncing behavior triggered when the micro-droplets merge is driven by the surface energy released by the micro-droplets. There is a Laplace pressure between the liquid droplets condensed in the microstructure gap and the microstructure. This Laplace pressure is the difference between the pressure on the liquid side and the atmospheric pressure, and its formula is:

$$\Delta p = p - p_0 = -\frac{\lambda \cos(\theta - \alpha)}{R_0 + h \tan \alpha}$$

where, $p$ is the pressure on the liquid side, $p_0$ is atmospheric pressure, $\lambda$ is the surface tension of water, $\theta$ is the static contact angle, $\alpha$ is the angle of inclination, and $R_0$ is $1/2$ of the bottom side width of two adjacent microstructures. The narrower micro-nano structure can bring greater Laplace pressure and push the micro-droplets to spontaneously bounce. The main factors hindering the bounce of the droplet are the gravitational potential energy of the droplet and the retarding work produced by the hysteresis of the contact angle [10]. The nano-needle structure covered on the bamboo leaf (backside) reduces the contact area between the micro-droplets and the surface. The retarding work is reduced, making it easier for the droplets to leave the surface.

3.3. Bamboo leaf (backside) inspired aluminum alloy surface
SEM image of anti-condensation aluminum alloy surface imitating bamboo leaf surface is shown in figure 3(a). Nano needle is formed on micron groove. The micro-nano composite structure on the bamboo leaf surface was simply imitated (CA 164.2 ± 1.5°).

In the condensation experiment, the time for the micro-droplets to appear on the bionic surface is about 50 s (smooth surface 18 s). Then, the droplet merging and spontaneous bounce were observed on the surface. Due to the small inclination angle and narrow spacing, the ZnO needle like structure on the bionic surface provides a larger Laplace pressure to drive the droplets upward [11, 12]. After 15 min, the amount of condensation no longer increased significantly, and the mass of drops increased and bouncing off reached a dynamic balance in per unit time. The bionic surface shows a certain degree of anti-condensation performance.

4. Conclusion
The micron morphology and nano-waxy needle-like structure of the bamboo leaf surface (backside) are the keys to its anti-condensation properties. The high contact angle increases the thermodynamic potential required for the phase transformation of water vapor into a nucleus, thus delaying the appearance of droplets. The retarding work of the droplet is reduced through a waxy layer and a small contact area, while the nano-needle structure provides a larger Laplace pressure, which drives the droplet upward movement. The surface energy released when the micro-droplets on the bamboo leaf (backside) merge drives the droplets to bounce, which delays the condensation process to a certain extent. This kind of dew condensation delay system has practical application value in energy saving and anti-corrosion.
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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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