Surface & Coatings Technology 356 (2018) 123–131

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Water-free dedusting on antireflective glass with durable superhydrophobicity

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ARTICLE INFO

Keywords:
Porous glass
Superhydrophobic
Phase-separation
Transparent

ABSTRACT

In arid and water-deficient areas, contaminants on solar panels seriously affect the conversion efficiency of solar cells, since they are not removed by rainwater. This study introduces a superhydrophobic silica surface with special self-cleaning characteristics. Even in arid areas, dust on the surface is removed autonomously via the departure of dew drops: the self-jumping behavior of drops dramatically improves the dedusting efficiency and cleans the surface in a short time. This coating is prepared via a unique method in which interpenetrating nanosized silica pores are formed in sodium borosilicate glass. After surface modification, the treated glass has higher light transmission and better superhydrophobic and oleophobic properties, and subsequent heat treatment ensures good mechanical stability. We investigated different scenarios for particle removal from surfaces via condensate self-jumping for different particle numbers, sizes and types. The results provide new ideas and insights into the application of self-cleaning materials in optical instruments.

1. Introduction

In recent years, clean energy development has been a hot topic, with solar cells representing a significant proportion of this research. As an important component of solar cells, glass panels play a key role in protecting the internal structures [1]. However, solar cells need to function in complicated environments in which contaminants such as dust, dew, oil, and frost are often deposited on their surfaces, seriously reducing the glass transmittance and thus the efficiency of photoelectric energy conversion [2,3]. Previous studies revealed that the most significant contaminant is dust. Experimental results have shown that dust accumulation during rainless periods of > 60 days reduces the production of photovoltaic systems by 15%, thereby causing huge economic losses. Therefore, keeping the glass surface clean is an urgent problem that needs to be solved.

At present, the most common methods for cleaning glass surfaces are manual or mechanical washing. However, manual washing is inefficient and can easily damage the device. For mechanical washing, the cleaning equipment is usually expensive and leaves some unclean corners that may cause damage. In addition, both of these methods use water to clean the glass, but most solar cells are located in water-deficient areas [4].

Therefore, coatings to achieve dustproof surfaces have come to the foreground in recent years. Superhydrophilic films are a representative type of coating suitable for this purpose [5]. Water drops in the air can rapidly wet and cover superhydrophilic surfaces, and then isolate dust and organic pollutants on the surface. Thus, contaminants are easily removed by natural wind or rain. However, this dedusting mechanism cannot function without incoming droplets or favorable external forces, which severely restricts practical applications of superhydrophilic films in arid areas. Superhydrophobic coatings are also widely studied because of their unique structure [6] and low surface energy [7,8], which can reduce the adhesion of dust and organic contaminants [9,10]. Pollutants are then easily removed by rolling water drops or an external force. Piliougine et al. [11] studied the energy generated by photovoltaic modules with and without antifouling paints, and found that the average daily energy loss was 2.5% for treated components, compared to 3.3% for untreated components. Quan and Zhang [12] prepared transparent coatings with different levels of hydrophobicity on silica glass using silica sol and silica, and studied adhesion and desorption processes on the coatings in a dust environment. The results showed that the coated samples had a better dustproof effect than untreated glass.

The results mentioned above indicate that superhydrophobic coatings on solar cell systems are of great significance. Many methods can be used to prepare superhydrophobic coatings [13–17], such as sol–gel, template, and reactive ion etching approaches. However, simultaneous achievement of transparency, oil repellency, and durability is difficult

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https://doi.org/10.1016/j.surfcoat.2018.09.064
Received 21 August 2018; Received in revised form 25 September 2018; Accepted 26 September 2018

using the existing methods. Ye et al. [14] prepared subwavelength-sized structures on fused silica via reactive ion etching, which yielded very high transmissivity of 96.2%, but the oil repellency and durability properties were not reported. Aytug et al. [18] used metastable spinoidal phase separation in glass-based materials to prepare a coating that comprised an interconnected network of nanoscale pores. As a result of this modification of the surface chemistry, surface reflection is suppressed via matching of optical impedance between interfaces. However, the oil repellency and abrasion resistance [19] of the coating were not discussed.

The dustproof effect of superhydrophobic surfaces is largely due to the impact or rolling of water droplets. However, solar cell systems are often located in arid areas and small particles are hard to remove via wind, gravity, and other external forces. Therefore, jumping of condensation droplets due to the large temperature difference between day and night has become an important measure for dust removal in arid areas. At present, self-jumping effects of condensates on superhydrophobic surfaces and the cleaning effects have been done by some workers [20,21]. In fact, this is well-known for superhydrophobic surfaces with droplets in the Cassie-Baxter state, for which the bouncing mechanism is based on the surface energy released by water droplets combined. Most reported surfaces are specially processed to form nanoarrays and achieve jumping of condensation. Our team has also reported a coating which can also achieve self-jumping effects of condensates before. But these surfaces must be prepared with complex process, and all of them are opaque [21,22], so they are confined to theoretical research and can't be applied in practical solar cell systems. In addition, scholars have only studied the self-jumping phenomenon of individual dust particles, but in practical use, the situations of covered dust particles are often complex and not regular.

This study introduces a transparent superhydrophobic coating that allows self-bouncing of condensate droplets. We investigated the particle removal performance for different particle numbers, sizes, and types during the condensation process. Interpenetrating nanosilica holes formed in borosilicate glass after phase separation and a differential acid treatment, yields both superhydrophobic behavior and good light transmission. Subsequent heat treatment ensures good mechanical stability. Even in brutal environments, the coating retains self-cleaning properties and is therefore very promising for application in solar cells or other optical instruments.

2. Experimental section

2.1. Fabrication of nanostructured coating

Borosilicate glass (Nanjing Fiberglass Research Institute) comprising Na_2O (8 wt%), B_2O_3 (23 wt%), and SiO_2 (69 wt%) was annealed in air at temperatures ranging from 600 to 720 °C for 30 min to 24 h to allow phase separation into an interpenetrating pattern consisting of alkali-borate- and silica-rich phases. After prolonged heat treatment, the surface composition of the glass becomes enriched in SiO_2 due to volatilization of sodium oxide and boron oxide, which has a significant effect on the subsequent acid etching process. The phase-separated glass was immersed into a dilute mixture of deionized water and 6:1 homemade buffered oxide etchant (v/v, 50:1) at 25 °C for 2–5 min for acid pretreatment. Then the porous structure was formed under acid etching with ultrasonic activation in a dilute mixture of 100 ml of deionized water and 5 ml of 98% sulfuric acid solution and 5 ml of 40% nitric acid (Sinopharm Chemical Reagent Co., Ltd.) for 5–10 min. Finally, the glass was rinsed with deionized water to remove the residual acid solution on the surface.

The nanostructure on the glass surface is fragile after acid etching, so samples were subjected to heat treatment in a muffle furnace at 500–550 °C for 12 h to improve its strength. To achieve water repellency, the glass was then immersed in anti-fingerprint solution (Hunan SNTO Nano material Co., Ltd.). The main components of the solution are perfluoropolyether(PFPE) and a silane coupling agent. It is a commonly used glass surface treatment solution on the market. The perfluoro polyether chain part provides properties such as hydrophobic oil repellency, anti UV, low refractive index, smoothness and high chemical stability. The siloxane provides good bonding between the molecule and the substrate, which solves the problem of poor wear resistance. After 15–30 min of soaking, the samples were washed with isopropyl alcohol to remove the unreacted silane residues and then oven annealed at 60–180 °C for 2–5 h.

2.2. Abrasion test

Mechanical stability is of great importance for the practical application of transparent superhydrophobic coatings, so the abrasion durability of the coatings was evaluated using the method illustrated in Fig. S1. A new method of abrasion testing is applied here, which is usually used to test the friction resistance of anti-fingerprint coatings on the cellphone's transparent screen or other electronic devices. An eraser serving as a friction surface with a contact area of 1 cm^2 and a load weight of 500 g was moved back and forth at a speed of 10 mm/s.

2.3. Condensate decontamination test

Samples were placed on a cooling stage inclined at an angle of 15° and observed under a stereo microscope during the condensation process. The ambient temperature was 25 °C, the temperature of the cooling stage was 2 °C, and the relative humidity was 70%.

Silica particles (Sinopharm Chemical Reagent Co., Ltd.) and dust (Nanjing South East University) of different sizes were used to simulate pollutants. Silica particles were used to study the removal of surface contaminants for different coverage levels and sizes. Samples of 0.2 g of silica particles with diameters of 20, 60, and 100 μm were separately dispersed in 100 ml of ethanol. Then, different amounts of particle solution were transferred via pipette onto the surface of samples to prepare silica-covered surfaces, denoted as (X μm–Y g/m^2), where X is the silica particle diameter and Y is the particle coverage (0.25, 1.25, and 2.5 g/m^2).

2.4. Characterization and instruments

The microstructure of the samples was observed via field-emission scanning electron microscopy. The wettability of coatings was measured using a Dataphysics OCA 20 contact angle system at ambient temperature with droplets of 5 μl. Sliding angles were measured by tilting the samples after depositing a static droplet of 10 μl. The optical transmittance was measured using a UV spectrometer (Cary 5000, Australia). Images of condensation and particle jumping states on the horizontal surface in a vertically downward direction at different times were collected using a JSZ6S stereo microscope. Images of water droplet bouncing tests and particle removal were captured with a Photron FASTCAM Mini UX100 high-speed camera equipped with a Navitar 6000 zoom lens.

3. Results and discussion

3.1. Superhydrophobicity and transparency

The method for preparing transparent coatings is shown in Fig. 1a, beginning with high-temperature phase separation. Owing to silica enrichment on the surface after prolonged heating, acid pretreatment is essential. Fig. 1b shows the surface structure of the coating after acid pretreatment, with many tiny bulges apparent. An EDS spectrum for the glass surface (Fig. S2) suggests that excess silica was removed by acid pretreatment. Although the surface elemental composition of the glass after acid pretreatment is similar to that of the original glass (Table S2), there is excess silicon before acid pretreatment (Table S1).