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Anti-soiling and highly transparent coatings with multi-scale features☆

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ABSTRACT

Soiling of optical surfaces due to sand and dust accumulation is the main cause for decreased efficiency of concentrating solar power and photovoltaic installations in desert areas. Nanostructured coatings with tailored surface roughness can reduce the rate of soil accumulation and maintain the high optical performance of the solar mirrors and cover glass. Here, we investigate the correlation between the size and structure of the surface features of the coating and its anti-soiling and optical properties. To control the morphology of the surface features we developed two types of coating: (1) based on small size (30–50 nm) silica particles with nanostructured surface and (2) based on unstructured nanoparticles with bimodal size distribution (80 and 35 nm). We tailored the surface features of the coatings to achieve synergistic improvements over different length-scales and thus decrease the adhesion force between the soil particles and the surface. Adhesion force measurements were performed using atomic force microscopy. The adhesion force and energy required to separate a silica particle from the surface of coated solar glass was significantly lower than the respective values from the surface of uncoated solar glass. A falling sand abrasion test, modeled after the procedure in ASTM D968, was performed. The optical properties of coated and uncoated solar glass were measured before and after the soiling test. Coated solar mirror samples were tested in the field. The results of the field test provided evidence that the anti-soiling coating is effective at reducing soiling and improving the specular reflectances of the coated mirrors. The use of the developed anti-soiling coating can be extended to other power-grid applications where reducing the soil accumulation is valuable.

1. Introduction

Soiling is the predominant cause for increased maintenance costs, and reflectivity and energy loss in concentrating solar power (CSP) and photovoltaic (PV) installations [1,2]. Mitigation of the soil accumulation is imperative to increase the long-term energy efficiency, and energy generation of solar power installations and to protect critical infrastructure from environmental deposits. Anti-soiling technology can be passive, as in the case of coatings or thin films that can repel and shed dust and organic matter, or it can be active, as when the dust is electrostatically charged to shed dust. Electrostatic charging is accomplished by embedding transparent electrodes between transparent dielectrics and using electric power to electrostatically activate the dust removal [3–5]. The passive coatings, which are the focus of this study, are designed to minimize the adhesion force between the surface of the coating and pollutant particles such as sand and dust. A feasible and scalable approach for decreasing the adhesion force is to generate nanosize surface features and thus increase the surface roughness [6–9]. Nanostructured anti-soiling coatings are typically based on aggregates of hydrophobic SiO_2 or photocatalytic TiO_2 nanoparticles [10–12]. In

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the preceding decade, several formulations and application methods have been investigated. However, the dispersion and adhesion of the nanoparticles on the glass surface are still major challenges for the design of high-performance and environmentally durable anti-soiling coatings. The nanoparticles can be adhered to the glass surface using sol-gel techniques [11,13,14], silane coupling agents [15,16], or organic binders [17,18]. The particle size and distribution must be tailored in order the size of the surface features to be smaller than the wavelength of the incident solar radiation to minimize light scattering and the coatings must be highly transparent over the entire terrestrial solar spectrum. Therefore, the size and morphology of the surface features must be tailored to minimize the contact area between the soil particulates and the surface, while maintaining or enhancing the optical performance of the coating.

To tailor the surface roughness and minimize the contact area between the soil particulates and the surface, we developed nanostructured coatings based on two different nanoparticle assembly configurations. The first configuration is based on silica particles with nanostructured features on their surface. The anti-soiling properties of the assembled particles can be attributed to the multi-scale roughness produced by their surface nano-features (mesoscale roughness) and their agglomerated particle structure (macroscale roughness). The second configuration is based on assemblies of unstructured nanoparticles with a bimodal size distribution. In both configurations, the particles were functionalized with fluorocarbons to endue them with water repellent (superhydrophobic, SH) properties in order to minimize the water condensation on the surface of the coatings.

The chemical composition of the soil particulates can vary significantly depending on the geographical region. Herein, we focus on sand (silica) and dust particulates as these are the main contaminants of CSP and PV installations in desert environments. Atomic force microscopy (AFM) was used to quantify the adhesion force as well as the energy that was required to remove silica-based pollutants from the nanostructured surface. The optical properties of the coatings can be used to evaluate their efficacy to reduce soiling. The anti-soiling effectiveness of the coatings was evaluated using a falling sand test method and the UV–vis transmission properties of the coatings were measured before and after the soiling test. Coated and uncoated mirror samples were field-tested in a CSP facility and the daily degradation rate of the coatings was calculated. The developed anti-soiling coatings are applicable to surfaces other than glass and are suitable for retrofitting and refinishing in the field. They can also be utilized in other power-grid applications. Additional information regarding other power-grid application is provided in the Supporting section.

2. Experimental

Ethanol and tetraethylorthosilicate (TEOS) were purchased from Fisher Scientific. Tridecafluoro-1,1,2,2-tetrahydrooctyl trichlorosilane (Gelest) was used for the particle functionalization [17]. To attach the particles on the solar mirror surface, two commercially available binders were used: polydimethyl siloxane (PDMS) (Sylgard 184 purchased from Dow Chemicals) and Cerakote MC-156 polymer-based liquid ceramic binder (purchased from NIC Industries). The particles were suspended in a solution of isopropyl alcohol (IPA), and Cerakote binder in a weight ratio W_{IPA}: W_{binder}: $W_{particles}$ = 20:1:2. The suspension was sonicated for 1 h in an ice bath and then centrifuged at 4000 rpm for 5 min to sediment the large particle aggregates and remove them from the suspension. Solar (low iron) glass and second-surface solar mirror samples were thoroughly cleaned with a solution of 1 wt% Alconox detergent (purchased from Sigma-Aldrich) and rinsed with distilled water prior to the coating process. The particle-binder suspensions were used to spin-coat solar glass samples [17,19]. The adhesion of the nanostructured particles on the bare glass surface was poor, thus the glass surface was pretreated with PDMS prior to the particle deposition to increase the adhesion. For the glass pretreatment, PDMS was spin-coated with processing times of 30 s at 1000 rpm followed by 30 s at 2000 rpm. The PDMS-coated solar-glass samples were air cured in a furnace at 80 °C for 8 h, followed by air curing at 60 °C for 12 h, prior to the application of the anti-soiling coating. The coatings based on particles with a bimodal size distribution were applied directly on the solar glass without PDMS pretreatment and were bound to the surface with Cerakote. Details on the experimental setups that were used for the X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM), energy dispersive X-ray (EDX) spectroscopy, transmission electron microscopy (TEM), atomic force microscopy (AFM), water contact angle measurements (WCA), and optical characterization, and falling sand abrasion test are provided elsewhere [17,18,20,21]. AFM cantilevers with an attached silica sphere (15 µm diameter) were purchased from NanoAndMore USA. A test dust made from desert sand, which conformed to the particle size distribution specified for coarse dust in international standard ISO 12103-1A4, was purchased from Powder Technology Inc.

3. Results and discussion

3.1. Assemblies of nanostructured particles

Silica particles with nanometer size features were synthesized in a solution of tetraethyl orthosilicate (TEOS) and ethanol [22]. The nanostructured features on the particle's surface are shown in the TEM images in Fig. 1. The size of the particles is approximately 30–50 nm (SEM image of the particles is shown in Fig. S1 in Supporting information). The chemical composition of the nanoparticle's surface was analyzed using XPS techniques. Narrow energy range core level spectra were acquired for C, F, Si, and O for the non-functionalized and the functionalized silica nanoparticles.

The XPS energy spectra and the best peak fittings are shown in Fig. 2. For C 1 s, the spectrum was fitted with six different peaks representing the C-C/C-H bonds (~ 284.8 eV); C-O bonds (~ 286.5 eV); C=O bonds

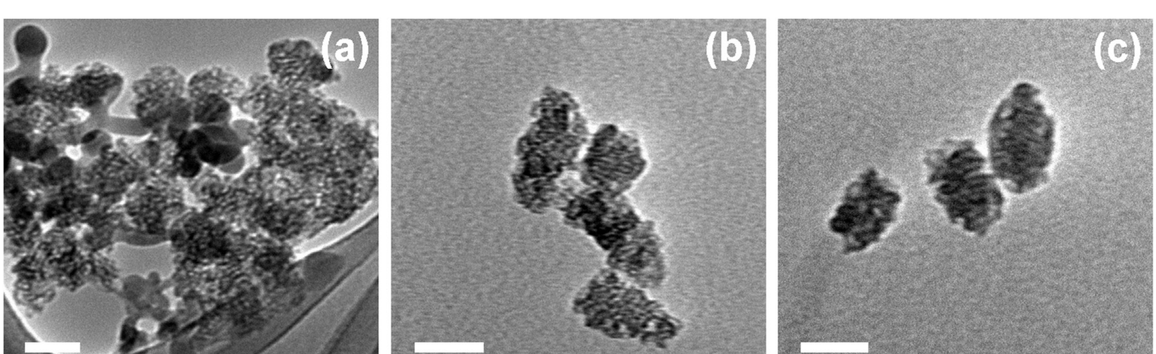

Fig. 1. TEM images of nanostructured silica particles synthesized using sol-gel techniques. The scale bars are 40 nm. (a) Agglomeration of aggregated particles, (b) a small agglomeration of aggregates, (c) aggregated silica particles.