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Adhesion mechanisms on solar glass: Effects of relative humidity, surface roughness, and particle shape and size

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ABSTRACT

To better understand and quantify soiling rates on solar panels, we are investigating the adhesion mechanisms between dust particles and solar glass. In this work, we report on two of the fundamental adhesion mechanisms: van der Waals and capillary adhesion forces. The adhesion was determined using force versus distance (F-z) measurements performed with an atomic force microscope (AFM). To emulate dust interacting with the front surface of a solar panel, we measured how oxidized AFM tips, SiO_2 glass spheres, and real dust particles adhered to actual solar glass. The van der Waals forces were evaluated by measurements performed with zero relative humidity in a glove box, and the capillary forces were measured in a stable environment created inside the AFM enclosure with relative humidity values ranging from 18% to 80%. To simulate topographic features of the solar panels caused by factors such as cleaning and abrasion, we induced different degrees of surface roughness in the solar glass. We were able to 1) identify and quantify both the van der Waals and capillary forces, 2) establish the effects of surface roughness, relative humidity, and particle size on the adhesion mechanisms, and 3) compare adhesion forces between well-controlled particles (AFM tips and glass spheres) and real dust particles.

1. Introduction

Since the outset of photovoltaic (PV) research and development, the goal of lowering the cost of solar energy has focused primarily on improving efficiency, production costs, and reliability. However, over the last decade, the deployment of solar panels has increased exponentially and costs have been driven down. Therefore, other issues such as soiling are now becoming important factors. Several aspects of the influence of dust/dirt on the performance of solar panels—and other devices such as solar energy collectors—have been studied for many years, at different locations, and with different climate conditions [1–3]. However, the focus has primarily been on measuring the energy losses due to soiling. For instance, many studies consider dust accumulation over years on panels deployed all over the world, and how the soiling process varies with weather conditions and pollution at each location. Currently, although there are many studies on the interaction between small particles and different materials, no comprehensive study exists on the individual adhesion mechanisms responsible for soiling of PV modules, and how the mechanisms correlate to each other. Limited literature targets PV systems [4–6], and most studies using glass spheres or particles are applied to other fields [7–10] and are not related to soiling on solar panels.

In this work, our goal is to create the foundations to determine the basic adhesion mechanisms that operate in the first stages of the soiling process in solar panels. Furthermore, we will establish how real-life parameters—such as relative humidity, surface roughness, and the shape and size of particles—influence the initial soiling processes. Our objective is also to be able to use this work as the base to understand more complex soiling mechanisms such as cementation [11,12] in the future, and to provide guidance to the solar industry on production and maintenance procedures to reduce the effects of soiling on deployed solar modules.

2. Experimental results

An atomic force microscope (AFM) was used to measure the force interaction between the particles and surfaces in force-distance mode [13]. The specific microscopes used for these measurements included Bruker Dimension 5000 and Dimension 3100 AFMs, both using Nanoscope V controllers. The Dimension 3100 was also used to measure the surface roughness of the glass used in this work, as well as for cantilever preparation (described later).

Support work to determine shape, size, and composition of the particles used a field-emission scanning electron microscope (FE-SEM) Nova NanoSEM 640 (FEI Company), in secondary-electron mode, and an energy-dispersive X-ray spectroscopy (EDS) system (Pegasus system

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Table 1
Root-mean-square roughness of the glass coupons after polishing with diamond lapping films with different grits.

DLF grit (µm)	R_{rms} (nm)
No polishing	0.3
0.1	1.7
1	8.1
9	22.2
30	321.0

from EDAX, Inc.).

The substrates used in this work are solar float glass coupons from Saint-Gobain Glass Company. Some of these coupons were deployed in several locations around the world for subsequent soiling studies. Here, we cut the glass in small pieces (~ 1 cm^2) and, before use, cleaned them by sonication in acetone for several minutes, followed by rinses with acetone, isopropyl alcohol, and finally, deionized water.

Causes for the roughness on solar panels deployed on the field over the years include cleaning processes, dust particles impinging on the glass surface due to wind, deterioration of the antireflection layer, and corrosion. To simulate different degrees of roughness on sample surfaces, we polished several samples in a MultiPrep polishing system (Allied High Tech Products, Inc.) using diamond-lapping films (DLF) with the following grits: 30, 9, 1, and 0.1 µm. Each grit removes a different quantity of material, leaving the sample surface flat, but with topographic features. The lower the grit the lower the surface roughness. For each roughness, we polished the surface using a different last grit. The measured value of root-mean-square (RMS) roughness for each grit is shown in Table 1 (notice that the roughness value is not the same as the grit value). Fig. 1 shows AFM three-dimensional images and linescans for an as-received sample and for a sample after polishing with 1-µm DLF for 1 min. The difference in roughness is significant (notice the scale difference on the z axis).

Initially, to study a well-controlled process, we used oxidized AFM Si probes and AFM cantilevers with 5-µm- and 20-µm-diameter silica spheres mounted at their ends. After we understood the basic adhesion mechanisms, we proceeded with the experiment using real road dust particles collected in Arizona. These particles were glued to tipless cantilevers. The cantilevers used in this work had their force constants measured, which allowed the adhesion force to be determined.

To study the force at different relative humidity (RH) conditions, we initially tried to establish a constant humidity environment inside the enclosure of the Dimension 3100 AFM using a beaker of water kept at different temperatures. This procedure was feasible, but we realized that it would take a long time to equilibrate the humidity environment, even at lower temperatures. We therefore developed a more-efficient procedure using saturated salt solutions in deionized water [14]. The solutions were kept at room temperature, and a fan inside the AFM enclosure homogenized the environment. To establish different RH values, we used different salts. Fig. 2 shows RH curves for both procedures, which clearly indicates the advantage of the latter method. After several hours, the RH values using the saturated salt solution stabilized within about 1% of the equilibrium value during the period of measurement. We measured the RH values with a Lascar EL-USB-2-LCD Humidity Data Logger. Note that the stabilized RH values were always well below the values reported by Young [14] at the same conditions, probably due to openings that we were unable to close in the AFM enclosure (the AFM enclosure was constructed to minimize vibrations, not to establish a controlled environment). For instance, to reach an RH value close to 80%, we used a saturated ammonium dihydrogen phosphate ($NH_4H_2PO_4$)/deionized water solution, which has an equilibrium RH value equal to 92.7%. To study the forces at zero humidity, we made the measurements with the Dimension 5000 system, which is located inside a glove box with concentration of H_2O and O_2 lower than 0.1 ppm.

3. Results and discussion

3.1. Adhesion forces measured using AFM probes and glass spheres

We started our study using simulated dust, in the form of AFM tips and SiO_2 spheres attached to the end of tipless cantilevers. This was done to avoid effects of particles with uncontrolled shapes and sizes on the force measurements, and consequently, to establish the basic interactions between particles and surfaces in the ideal case. The first

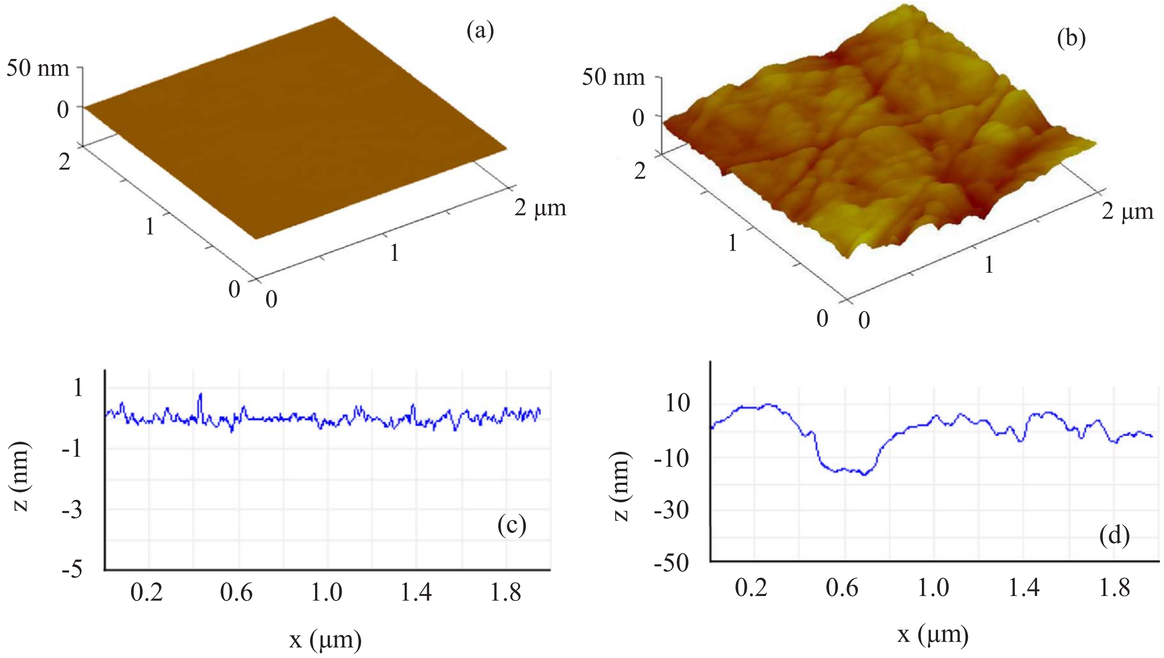

Fig. 1. AFM 3D images of (a) non-polished glass coupon and (b) glass coupon after polishing with 1-µm DLF for 1 min; and (c), (d) AFM linescans for the two respective samples. To allow for the observation of topographic features, the x and z scales were made different. For the same reason, the z scale in the linescans are different for the non-polished and polished samples.

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