Investigation of Capillary and Electrostatic Forces in Anti-Dust Nanostructures

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Passive dust mitigation is one of the grand challenges for the explorations of the lunar and other extraterrestrial environments. The Apollo missions discovered this challenge when seals were clogged, spacesuits were damaged, and mechanical components on the craft were quickly degraded[1,2]. The key challenge for creating passive dust mitigation is minimizing the adhesion forces, which depends on the surface chemistry and contact area. In prior work, we demonstrated that surface nanostructures can minimize the adhesion force of particulates by reducing contact area and result in dust-mitigation properties[3]. Our results demonstrated that structures with a 500 nm period can reduce coverage area of lunar dust by up to 93.1%. However, questions regarding the contributions of electrostatic and capillary forces in varying environmental conditions remain.

In this work, we investigate changes in anti-dust performance of nanostructured surfaces as a function of environmental humidity. The samples studied are fabricated using nanocoining and imprint lithography, as described in previous work. The structure is shown in Figure 1(a), and mitigates particle adhesion by reducing the contact radius. In a high humidity environment, electrostatic charge dissipates through the air, reducing adhesion. Simultaneously at high humidity, capillary forces increase adhesion by the formation of a meniscus between a contaminate and the substrate[4]. On the other hand, electrostatic forces are expected to dominate at low humidity, when the low water vapor leads to negligible capillary forces. Therefore, through utilizing an environmental chamber capable of 5-95%RH, the contributions of both electrostatic and capillary forces are controlled. This work investigates the balance of these forces across a range of humidity levels and investigates options of transparent surface coatings to tune the response.

Initial results are shown in Figure 1(b), where the dust coverage area is found when the particles were removed using gravity force, at both extremes adhesion increases due to one of these forces dominating. Here both nanotextured and planar surfaces are coated with a variety of surface coatings to control surface energy and roughness. These currently include 5 nm thick coatings of Al_2O_3, TiO_2, Au, and a monolayer of trichloro(octyl)silane which were chosen due to their difference in conductivity and resulting surface roughness. High conductivity surfaces allow for removal of the electrostatic force through the dissipation of charge on particles as they contact the grounded surface. This results in significantly less dust coverage at low humidity levels where electrostatic charge is high. Improvement is also seen for relatively insulating oxide surfaces. This improvement can be attributed to nanoscale roughness which creates poor contact and further reduces the van der Waals forces[5,6]. These coatings in combination with the periodic nanostructures create a hierarchical roughness which is able to prevent adhesion for a wider range of particle diameters than previously investigated. Additionally, AFM measurements will be taken such as that shown in Figure 2(a), to identify the RMS roughness of each surface. AFM pull off force testing will also be presented to aid in understanding the full picture of how these surface coatings reduce adhesion. This research has a broad reach of beneficiaries as contamination causes many problems for space exploration and terrestrial applications as well, including in the optics, energy, aerospace, and healthcare industries. We will discuss the structure fabrication, testing procedure, and characterization results.

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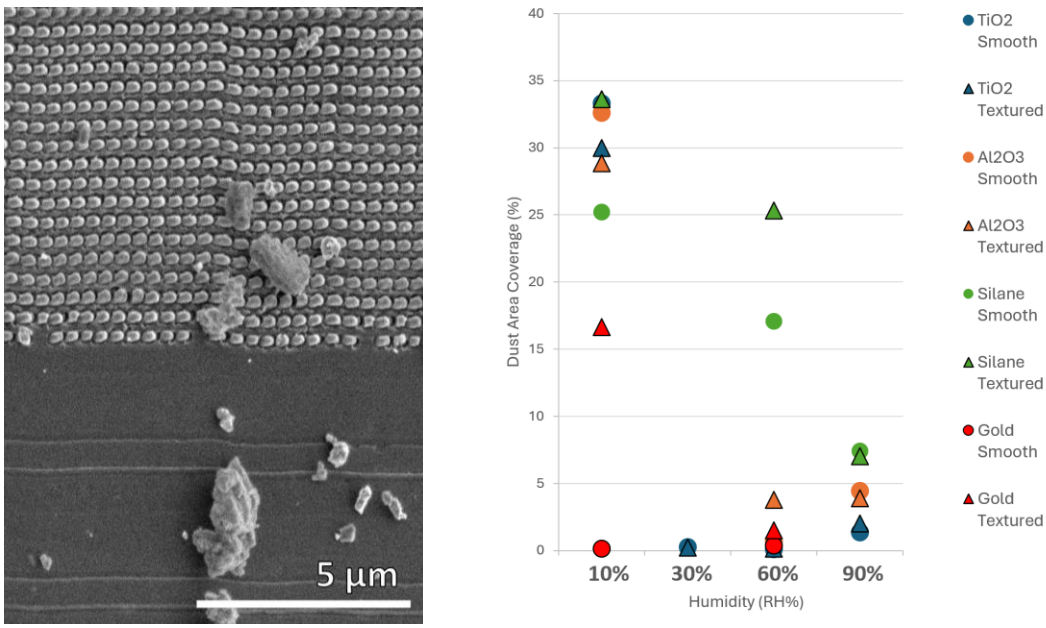

Figure 1. (a) SEM of surface coated with dust, nanotextured top and planar bottom. (b) Plot of dust surface area coverage at varying humidity levels. Substrates have a variety of surface coatings to alter conductivity and nanoscale roughness. Each surface coating was applied to substrates with smooth and textured with 400 nm periodic structures.

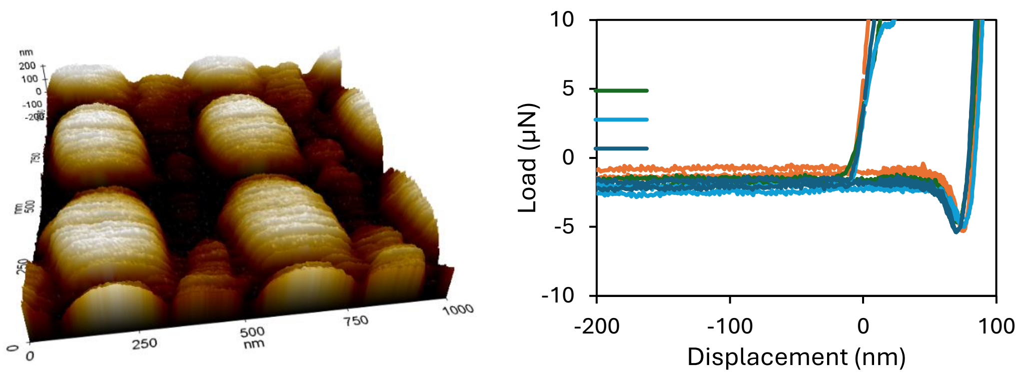

Figure 2. (a) Preliminary AFM measurement of 400 nm periodic nanotextured surface. (b) Preliminary pull-off force testing on nanotextured TiO_2.

References:

1. Afshar-Mohajer, N., Wu, C.-Y., Curtis, J. S. & Gaier, J. R. Review of dust transport and mitigation technologies in lunar and Martian atmospheres. *Adv. Space Res.* **56**, 1222–1241 (2015).
2. Dove, A. *et al.* Mitigation of lunar dust adhesion by surface modification. *Planet. Space Sci.* **59**, 1784–1790 (2011).
3. Lee, S. S. *et al.* Engineering Large-Area Antidust Surfaces by Harnessing Interparticle Forces. *ACS Appl. Mater. Interfaces* **15**, 13678–13688 (2023).
4. Isaifan, R., Johnson, D., Ackermann, L., Figgis, B. & Ayoub, M. Evaluation of the adhesion forces between dust particles and photovoltaic module surfaces. *Sol. Energy Mater. Sol. Cells* **191**, 413–421 (2019).
5. DelRio, F. W. *et al.* The role of van der Waals forces in adhesion of micromachined surfaces. *Nat. Mater.* **4**, 629–634 (2005).
6. Jacobs, T. D. B. *et al.* The Effect of Atomic-Scale Roughness on the Adhesion of Nanoscale Asperities: A Combined Simulation and Experimental Investigation. *Tribol. Lett.* **50**, 81–93 (2013).