# Bio-inspired surface structures to mitigate interfacial particle adhesion and erosion- A review

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**Introduction**

Lunar dust known as regolith is a huge challenge for lunar exploration missions. Formed over millennia by a complex process involving impacts of meteoroids and micrometeoroids on the lunar surface, lunar dust is porous, highly abrasive with sharp jagged edges, chemically reactive, electrostatically charged and sometimes magnetic [1]. The chemical composition and thickness of the dust layer also varies in different regions of the lunar surface. From samples obtained by previous lunar missions, the average particle size is below 100 microns [2]. This dust has the tendency to strongly adhere to any exposed surfaces, and often degrades the material functionality to eventually cause failure. Any material on the lunar surface is also subject to harsh temperature cycles ranging from -178˚C to + 123˚C and extreme ultraviolet radiation.

While on the lunar surface, different classes of materials would be required for different applications. Advanced materials have been and will be used throughout the lunar lander, habitat, and mission equipment. Examples include: polymeric materials for astronaut protective clothing; metals and ceramics for the lunar lander legs and habitats, and excavating equipment; and semiconductors for solar panels and on-board electronics. In all these applications, the surfaces of the materials are expected or understood to be exposed to the extreme lunar environment condition that includes the regolith dust. During the Apollo missions, the dust clung to and abraded the astronaut’s suits, degraded seals, optics, clogged sensors and reduced performance of thermal radiators [3]. The lunar dust adheres to the surface by various mechanisms, which include electrostatic and Coulombic interactions, Van-der-Waals forces, magnetic forces, mechanical interlocking, chemical bonding and donor-acceptor interactions [4].

There are three primary strategies for developing technologies to minimize the lunar dust adhesion: active, passive and a combination of active and passive. In the active approach, an external energy is needed to prevent or remove particles from collecting on the surface. Mechanically powered brushes and electrodynamic dust screens are two examples. In the passive approach, no external power is needed, and the material surface properties are able to mitigate dust adhesion.  
A well-known example of this strategy is the low work function coatings for non-stick surfaces. In most cases a combination of active and passive methods might be needed to optimally manage the lunar regolith. The passive method is significantly more attractive as it does not require any external power or an additional control subsystem.  
These approaches optimize the mission payload and reduce risk. Surface modification to minimize the dust adhesion is thus very important to lunar missions [5]. Here, naturally evolved surface structures might provide guidance for solutions.

There are several factors that have to be considered for minimizing particle adhesion to a surface. These include the substrate material properties, surface topography, chemistry, and the characteristics of the adhering particles. When engineering a surface, the substrate material chosen would be dependent on the needs of the application. Tailoring the surface microstructure or chemistry opens up more possibilities for its optimal utilization.

**Bio-inspired surfaces for dust mitigation**

Inspired by Nature, many groups have conducted research worldwide on particle adhesion mitigating surface structures of plants, animals and insects, from lotus and colocasia leaves to cicada wings. [6–8]. However, few research publications have specifically investigated bio-inspired surfaces for lunar dust adhesion mitigation. Among those is the lotus leaf coating, that showed good adhesion mitigation properties. The lotus leaf has been researched widely for its low surface energy and anti-adhesive properties, and many applications have been developed based on it [9]. A coating material was developed by NASA Goddard Space Flight Center (GSFC) (in collaboration with nGimat, Georgia, USA, currently Engi-Mat, Kentucky, USA) mimicking the lotus leaf surface using a proprietary chemical vapor deposition process to create the nanostructured architecture of the lotus leaf surface [10]. The researchers found that this biomimetic coating (referred to as Lotus coating) shed the simulated lunar dust particles more effectively compared to a non-coated substrate. Work remains unfinished in the making of the coating formulation, its uniform surface application, and demonstration that it will be able to survive and perform in the lunar environment. Figure 1 demonstrates the self-cleaning ability of a Lotus-coated radiator surface when contaminated with JSC1 lunar simulant. It is observed that the coated surface shows significant dust adhesion mitigation properties.



Figure . Anti-contamination/self-cleaning properties assessment of untreated and treated Lotus coated radiator samples. Image reproduced from [10] with permission from publisher and authors.

In another set of investigations at NASA Langley Research Center (LaRC), the surface chemistry and topography of a polyimide substrate was modified by creating a passivating silica type coating that reduced surface energy [11]. Research was also done to emulate the contact self-cleaning properties of gecko toes for lunar dust mitigation by modifying polypropylene films to create the hierarchical surface topography of gecko toes. While the low surface energy silica coating successfully reduced adhesion, it was subject to losses due to dust particle abrasion. The gecko toe patterned surfaces were tested using silica-alumina microspheres of 1-5µm size. In nature, geckos remove dry particles from their feet by stepping on a clean surface, and a similar method was followed to test for adhesion. It was found that the particles were shed significantly, however there was also embedment and entanglement due to the pliable substrate material and topographical dimensions. Further research would be needed to investigate the effect on a less pliable material. The researchers were able to conclude that a patterned surface performed better than a flat surface to minimize adhesion, and that the surface chemistry also played a significant role.

The extreme lunar environment is more closely matched by the hot and arid deserts of the world. Natural surfaces that evolved to survive and thrive under these harsh conditions have to withstand abrasion, erosion and wear by sand particles. The lunar dust is also composed mostly of silica. Activities that disturb the lunar dust layer include plume surface interactions during and after lunar landing, abrasion during walking and vehicle operation, erosion and wear of excavating equipment material surfaces, in addition to the natural processes resulting in dust levitation and transport which are concentrated at the terminator. There are a few known examples of desert dust mitigation found as part of our terrestrial ecosystem.

An excellent example is the tamarisk plant with its special surface microstructure that minimizes erosion during sandstorms [12]. Numerical simulation modelling of a bionic V-type groove surface designed on the morphology of the tamarisk bark was found to exhibit good erosion resistance. A centrifugal fan with steel bionic blades based on that design showed improvement in anti-erosion performance of the impeller by 28.97%.

Another applicable adaptation is the skin of the sandfish lizard, so named due to its ability to ‘swim’ easily through the desert sands. The sandfish skin exhibits extremely low adhesion, friction and wear. In experiments on 100Cr6 steel alloy that was laser textured to have scale like morphology, the dry sliding friction was found to be reduced by 40% compared to untextured surfaces [13]. A bionic bilayer metal and polymer composite sample inspired by this design showed erosion weight loss of 10% per unit time compared to contrast samples [14].

The desert scorpion carapace may also provide guidance for passive erosion mitigation for mission structures that are in contact with lunar regolith. Researchers found that bionic surfaces inspired by the desert scorpion showed improved anti-erosion properties compared to a smooth surface. Three types of microstructures, bumps, groove-shape and curvature were investigated by 3D printing the structures on ABS polymer and stainless steel [15]. The erosion test was conducted by sand blasting with silica particles with an injection angle of 30° and 30m/s velocity. Mass loss measurements were taken every 10 seconds. It was found that grooves and bumps increased the anti-erosion property by 10 and 25 percent respectively. This was because bumps reduced the area of impact on the surface as well as changed the impact angle of the impinging particles. In another study, hexagonal pit structures on the desert scorpion back were also shown to have good erosion resistance by changing the direction of motion and impacting velocity of the impinging particles [16]. Here also, the biomimetic stainless-steel structures were 3D printed and tested with three different sizes of quartz sand particles from a blasting jet machine at an injection angle of 30° and 25m/s velocity for 90 seconds. It was found that samples with a combination of three different biomimetic structures, V-groove, convex hull and hexagonal pits led to a 31.9 % average improvement in the erosion rate compared to samples with smooth surfaces.

These as well as other biological particle erosion reducing surfaces have been researched by several groups globally. Advanced manufacturing techniques have been used for reverse-engineering and fabricating these biomimetic surfaces. These include: laser engineering, lithography, additive manufacturing, micromachining, chemical processing, and embossing. By combining the results and insights from these bio-surfaces along with the different fabrication techniques and newer materials, novel biomimetic surfaces might be developed that can effectively reduce lunar dust adhesion and wear.

**Bio-mimetic surface fabrication and outlook**

Fabrication techniques that have been traditionally used to create biomimetic surfaces include physical processing, chemical processing, and lithography [17–19]. Innovative methods that combine these techniques could lead to more efficient and widely applicable products.  
Using such a combinatorial approach, a scalable, simple to use and cost-effective lotus leaf like surface was made from reduced graphene oxide using soft lithographic duplication. The complex nano-structured surface was superhydrophobic and remained stable when subjected to heating at 150˚C for 24 hours [20]. This could find possible applications as dust mitigating astronaut clothing, and dust mitigating surfaces on different materials both inside and outside the lunar habitats.

Lasers have been used widely to create micro- and nano-surface structures on different classes of materials. Laser induced periodic surface structures (LIPSS) mimic the ripples, grooves and spikes found on natural surfaces, and have exhibited properties such as super hydrophobicity, antireflection and drag resistance [21]. Laser based approaches have also been demonstrated to fabricate complex hierarchical and spatial structures that mimic natural surfaces. A recent article on the laser engineering of biomimetic surfaces provides a comprehensive review of current state of the art for the different laser processing methodologies for creating such surfaces [22]. While the lotus leaf, desert scorpion carapace, tamarisk bark, and sandfish skin have already been laser patterned investigated, there are numerous other natural surfaces waiting to be explored. By using lasers to mimic such surfaces on different material substrates, adhesion and wear mitigating surfaces could be customized for various lunar exploration needs.

Additive manufacturing is another common method that is used to create bio-inspired surface microstructure. For example, lotus leaf and shark skin inspired surfaces were 3D printed by a multiscale stereolithographic process and the additively manufactured surfaces demonstrated superhydrophobic and drag reduction properties that mimic the natural materials [23]. The additive manufacturing advantage lies in its speed, flexibility of customization, relatively lower cost, scalability and ability to create complex structures [24]. A growing range of materials can be printed using an additive manufacturing process. The most widely used materials are ABS polymer and stainless steel. In-mission additive manufacturing has the potential to be widely used in extraterrestrial environments to fabricate parts in-situ. Additive manufacturing methods could be used to rapidly create adhesion and wear minimizing surfaces on lunar rover vehicle parts and habitats.

Hot embossing is another scalable replication technique that is efficient, economic, and convenient [25,26]. Polymeric photovoltaic cell covers with the surface structure of rose petals were fabricated on to three different polymers using the hot embossing method. This involved two consecutive template steps to create a high-fidelity positive replica of the original surface. These covers showed superior light harvesting properties as well as self-cleaning nature when a fluorinated polymer was used [27]. This approach could be applied to the lunar solar panels to minimize dust interference and maximize efficiency.

The lotus coating developed at NASA GSFC used a proprietary atomizing flame spray gun to deposit the nanomaterial on the surface. This method did not need a vacuum chamber environment that is traditionally required by the combustive chemical vapor deposition technique. Radiator surfaces coated with this material showed self-cleaning properties as well as promising UV and thermal cycling fatigue capabilities [10]. Such coatings could be applied on exposed habitat surfaces to offer protection from the lunar environment.

A combination of bio-inspired surface structure with innovative coating technology can also be used to create adhesion and wear resistant surfaces. NiCrBSiFe alloy was thermally sprayed onto high speed steel (HSS) substrate using a high velocity oxygen fuel process (HVOF). The coating was remelted and compacted using a Nd:YAG laser at a power level of 525 W. Bionic structures inspired by the scarabaeus beetle were then micromilled onto this smoothened laser melted surface. The shell of this beetle exhibits enhanced wear resistance in a desert environment.  
It was found that the bio-inspired micromilled surface showed a reduction in friction by 25% compared to the laser smoothened surface [28].

In another study, aluminum oxide/titanium carbide (Al2O3 /TiC) ceramics were laser surface textured with a shark skin pattern. The biomimetically patterned surface showed a 32% decrease in friction compared to only polished surfaces. A low friction, dry lubricant, tungsten disulfide (WS2) coating of around 40 µm thickness was also applied to the surfaces using electrohydrodynamic atomization process. The shark skin pattern improved the coating-substrate adhesion strength. The coated surface exhibited an 84% reduction in friction and extended wear life compared to polished samples [29]. This type of approach could be used on the lunar surface for use on lunar lander legs and excavating equipment.

**Conclusions**

There exists a vast potential for bio-inspired surfaces for lunar dust adhesion and erosion mitigation. While a few candidate natural surfaces have been investigated, many more remain to be explored. These surface topographies combined with innovative fabrication methods and material combinations can be used to customize novel surfaces suited to meet the unique needs for lunar missions. However, it should be noted that the lunar environment is very different from Earth, and only by sending these samples to the Moon can the performance results be accurately tested and measured. Experiments are being designed for this purpose, and those materials, surfaces and processes which are successful will enable bringing long term lunar habitation closer to reality.

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