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# Experimental investigation of lunar dust impact wear

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ABSTRACT

Future lunar bases may require multiple start and landing operations for resupply or sample return during their life cycle. Landings and take-offs would most likely take place in the vicinity of the base, like the Apollo 12's Lunar Lander, which landed close to the Surveyor 3 probe. The exhaust jet of the Lunar Lander's engine stirred up the lunar soil and sandblasted the surface of Surveyor 3, which lead to significant erosion effects. This shows that close landing operations may cause damage to infrastructure elements. In this work, an experimental setup was used to analyze the impact wear from impacting lunar dust particles. The tests were conducted using the lunar simulant JSC-1A, which was sieved down to approximately 250–350 microns. During landing operations these particles might be accelerated by the spacecraft's exhaust plume to velocities up to 400 m/s. To achieve representative particle velocities the study was conducted using an electromagnetic eddy current accelerator. Metallic and optical media were chosen as impact targets to test their resistance against impact wear, which was characterized by the changes of surface roughness and optical performance. The tests also, showed that ductile plastics are more affected by the sticking of particles than brittle materials.



## 1. Introduction

### 1.1. Literature review

Earth's moon is not just a highly interesting object for science but it is also a technically very challenging place. There are extreme temperature gradients between shaded areas and parts directly exposed to light, high vacuum and radiation, but as Gene Cernan stated after returning from the Apollo 17 mission, the lunar dust might be one of the greatest challenges for further lunar missions:

*"I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust"*

[Gene Cernan, Apollo 17 Technical Debrief].

Lunar dust or, more generally, lunar regolith distinguishes from terrestrial soil in the way that it is not subject to erosion by wind or water. Regolith was formed by particles such as micrometeorites impacting the surface. The lack of subsequent erosion processes results in very sharp-edged particles, which is the main reason why regolith is a very abrasive medium. The physical properties (sharp edges, fine diameter) also lead to the interlocking of particles. Therefore the friction angle and the cohesion are larger compared to terrestrial soils [1]. The adhesive character of regolith is furthermore a result of electrical charging through incident radiation [2]. Therefore, lunar dust might cause significant problems for technical systems and astronauts. The main complications for technical systems are expected to arise via the covering and wear or abrasion of surfaces and the ability of lunar dust to pass through seals. All three effects impacted the spacesuits during the Apollo missions, e.g., a sun shade was abraded, several suit fabrics wore off [3], and regolith passed into the suit of Gene Cernan. Fig. 1 shows him inside the Apollo Lunar Lander covered with a fine layer of regolith.

A further problem related to lunar dust is caused by human activity, such as the erosive impact wear during landing operations. Every soft landing operation on a celestial body with significant gravity and nearly no atmosphere like Earth's moon is done via retrograde rockets fired against the surface of the body. When close to the surface, the plumes of these rockets interact with the regolith and accelerate dust or even larger regolith particles, which may cause damage to nearby structures. Already before the first Apollo landing tests were conducted to study the effects of jet erosion during landing [5]. The hazard that might be caused by landing or departing spacecraft can be seen in the example of Surveyor 3. In 1969 the probe was hit by a large amount of dust particles, which were raised up by the landing Apollo 12's lander. The landing took place approximately 155 m from the Surveyor 3, so the astronauts were able to inspect the damage caused by the impacting particles and also took parts of

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**Fig. 1.** Gene Cernan, dust-covered, inside the Apollo Lunar Lander [4].

the probe back to Earth for further investigations. These tests showed that the particles actually caused significant erosive wear damages. A subsequent NASA report shows that these parts looked as if they were sandblasted [6]. Later some of these parts were reinvestigated via electron microscopy by Immer et al. [7]. The authors supported the statement that most of the damages were caused by impacting dust particles accelerated by the landing Apollo 12's lander. Immer et al. [7] also stated that only parts of the dust spray reached the probe. If Surveyor 3 had been completely exposed, the eroding effects of the impacting particles would have been much larger. For a future return to the moon that goes beyond flags and footprints, lunar bases will need multiple start and landing operations for resupply or sample return during their lifecycle. These landings and take-offs would most likely take place in the vicinity of the base. As the example of Surveyor 3 shows proximity landing operations can endanger the previously landed systems. Additionally, protective structures such as berms would also degrade through recurrent dust impacts [8]. This demonstrates that a better understanding of the effects of accelerated dust particles is crucial for the success of further lunar missions.

Today, due to significantly increased computer power, it is possible to simulate the effects of plume impingement during Lunar Landings. This was, among others, done by Lane et al. [9], who conducted several Computational Fluid Dynamics (CFD) analyses to get a better understanding of the interaction of the plume created by a rocket engine with dust particles during landing. In this study, Lane et al. [9] also implemented a trajectory model of the traveling particles to calculate their velocity corresponding to the particle diameter for different lander altitudes. Lane et al. [9] stated that the particle velocities of the different calculations match well for particles sizes larger than 200 μm but differ for smaller grain sizes. Morris [10] and Kahila [11] also studied plume impingement effects of retrograde rocket fire via CFD and Direct Simulation Monte Carlo (DSMC) analysis. Morris [10] characterized the particle motion for very small particles and for different lander altitudes with a simulated Lunar Landing Module, while Kahila [11] conducted a similar study with an Astrium S400-15 rocket engine. Additionally, Kahila [11] investigated a significantly larger range of particle diameters. A further study by Immer et al. [12] estimated the number of traveling particles per volume and their ejection angle via video analysis of the Apollo landings.

The erosive damage of impacting lunar soil particles onto glass surfaces was studied by Wittbrodt et al. [13]. The study was conducted with sieved JSC-1A in the range from 450 to 1000 μm, which are relatively large particle sizes compared to the mean grain size of 45–100 μm for lunar soil [14]. These particles were accelerated up to 90 m/s with a sandblaster and impacted onto a glass specimen. After impact; the samples were inspected using the Portable Handheld Optical Window Inspection Device (PHOWID), a white light interferometer pen. These tests showed that the glass samples were damaged by the simulant particles but, according to the authors, no significant correlation between impact size and velocity was found. Similar tests on impact damage of regolith were done by Mpagazehe et al. [8] using the Dust Erosion Experimental Rig (DEER), which made it possible to accelerate JSC-1AF particles up to 105 m/s. The resulting erosive wear damage was tested for three different materials, acrylic glass, aluminum and steel. The volume loss of all specimens was measured and results confirmed the assumption of significant erosive damage by impacting dust particles. Additionally, the change of surface roughness and reflectance of the metallic samples and the change of transmittance of the acrylic glass were evaluated, which also substantiated their hypothesis. A further investigation by Mpagazehe et al. [15] investigated erosive wear and damage on solar concentrators. In that study the TOPAS Solid Aerosol Generator accelerated JSC-1AF particles up to 105 m/s. The experiments on solar concentrators showed that impacting particles have a significant influence on the material. Even while only one half of the concentrator area was exposed to the dust spray, the output current of the tested concentrators decreased to 60% of normal capacity compared to a second non-eroded specimen. All these studies show that impact wear of lunar dust poses a significant problem for future lunar missions with repeated landings and launches at the same site, and even rather slow traveling particles might cause significant damage on particular materials. Table 1 shows a summary of the different experimental studies concerning lunar regolith impact wear describe in this section.

### *1.2. Motivation and rationale*

As mentioned in Section 1.1, lunar regolith consists of sharped-edged particles, which might have a significant influence on impact wear. But, only a few hundred kilograms of the actual lunar regolith were returned to Earth [14]. Therefore it is necessary to use a simulant of the actual regolith particles. The simulant should reproduce the essential properties with respect to impact damage, such as particle shape, size and material. The easiest material to use is sand or dust, but these materials are more or less round shaped and therefore cannot represent the lunar regolith. The current study used JSC-1A, a representative simulant for the lunar mare regions, which was developed by the Johnson Space Flight Center. Despite the fact that the simulant was not created by impacting particles like the actual lunar regolith, but instead by a special milling technology, JSC-1A exhibits sharp-edged particles as required for this study. A further reason to choose JSC-1A for our initial study was that some prior wear studies [8,15,16] used the same simulant; however these studies were conducted with the fine fraction JSC-1AF. The current study was restricted to larger particles of a size between 250 and 350 μm, which were sieved from the actual JSC-1A simulant. These grain sizes were chosen because, in this grain size range, the various CFD simulations done by Lane et al. [9] match well as previously described in Section 1.1. The related particle velocity of about 360 m/s for 250–350 μm particles can be achieved with our electromagnetic accelerator, which is described in detail in Section 2.1.

The electromagnetic eddy current accelerator was used because it is able to accelerate simulant particles to velocities which are more representative for lunar dust impact wear caused by landing vehicles than other accelerators used in previous studies. A further advantage of the electromagnetic eddy current accelerator is the very well defined mass of particles, in this case 10 mg of JSC-1A, can be accelerated. It would also be possible to accelerate only one, or a certain small number of particles, which could be well characterized before the impact experiment. At low