Testbed for Lunar Extreme Environment Wear Tolerant Applications

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Abstract

The abrasive dust from lunar regolith poses significant long-term durability and performance challenges to materials, vehicles, mechanisms and structures that will be used for the next generation of lunar exploration. The development of advanced materials, coatings and device technologies that can withstand these abrasive particles and extreme environmental conditions is critical. However, the lack of standardized and accessible methods for evaluating such materials and devices in a facsimile of the harsh lunar environment hinders progress in dust-tolerant technologies. To address this challenge, NASA Langley Research Center is creating an extreme environment testbed. This reconfigurable testbed will allow rapid, repeatable wear testing of material and candidate mechanisms under vacuum conditions, facilitating the development of critical materials technologies for lunar exploration. Preliminary results from exposing an actuating mechanism similar to a pin joint to lunar regolith simulant under high vacuum are reported.

Introduction

To ensure the success of long-duration, sustainable missions on the Moon's surface, it is imperative to develop materials and devices that can withstand the harsh lunar environment. Numerous environmental challenges threaten durability of space suits, roving vehicles, habitats and other critical technologies on extraterrestrial surfaces. Lunar dust, characterized by its fine particle size, rough surface morphology, and highly abrasive nature, poses a significant threat to the durability of components and vehicles [1]. Low lunar gravity free floating lunar dust particles are typically < 100 micrometers (µm), capable of accumulating within cracks and crevices where cleaning tools cannot readily access [2]. These particles can erode, adhere to, or embed in surfaces and within confined device geometries, which increases the potential for premature failure of gears, bearings, interlocking systems, and other critical components. Abrasion and jamming of mechanisms with mating surfaces, such as gears and hinges, as a result of lunar dust incursion in space suits were noted during Apollo missions [3]. Soft goods such as outer-layer fabrics for space suits and flexible webbing for inflatable habitat structures are particularly sensitive to wear by dust [4]. Exposure to the vacuum of space with intense ultraviolet (UV) radiation and large temperature gradients results in degradation of materials and technologies [5] relevant for use on the Moon.

Maturation of technologies that can persist in extreme environments necessitates the ability to test and validate in such conditions. Developmental barriers to exposure of materials to space and lunar environments are being reduced due in part to commercialization of flight experiments. These include the Materials International Space Station Experiments (MISSE) [6] and the Commercial Lunar Payload Services (CLPS) initiative [7]. However, restrictions such as size, geometry and weight of specimens or the type of exposure (e.g., duration, static lunar surface, etc.), and access (e.g., long lead times, ride-along nature of experiments, etc.) limit testing in authentic, controlled environments. Accessible testing that simultaneously considers effects of abrasive regolith, vacuum, temperature and radiation for lunar technologies is an enormous market opportunity. A sustainable presence on the Moon via Artemis and a burgeoning lunar economy fostered by government, industry, and universities require rapid, repeatable testing to advance concepts capable of persisting in the extreme lunar environment. The prime factors include atmospheric pressures down to 10^{-12} Torr, temperatures ranging from -20°C to 120°C, and ultraviolet (UV) solar particle-driven electrostatic charges.

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To address this need, the Surveying Lunar Dust Influence on Device Efficacy (SLIDE) testbed is being developed as a reconfigurable platform to evaluate the wear performance of material and device candidates due to lunar dust simulant exposure (continuously or cyclically) under high vacuum. The goal of the SLIDE testbed is to identify and rapidly advance needed technologies from concept to device level. In parallel with testbed establishment activities, a pilot assessment of wear performance of a titanium alloy was conducted in the SLIDE testbed. The approach adopted in establishing the SLIDE testbed are outlined, and preliminary results are presented herein.

Materials and Methods

<u>SLIDE Apparatus Configuration</u>

The SLIDE apparatus consists of a stainless-steel vacuum chamber with multiple ports and feedthroughs, as shown in Figure 1(a). The diameter of the primary chamber door is 61 centimeters (cm) and sealed using nuts, bolts, and a copper gasket. The pumping system, consisting of a roughing pump and a single turbomolecular pump, is capable of base pressures down to approximately 10^{-6} Torr. The turbomolecular pump is mounted on a 90-degree bend attached to a gate valve to mitigate dust incursion into the pump. The initial pump-down occurs through the roughing pump only. A gate valve on the chamber is closed until the roughing pump drops the chamber pressure to 10^{-3} Torr level. The gate valve is then opened and the turbomolecular pump further drops the chamber pressure to 10^{-6} Torr level. The test mechanism onto which dust is deposited operates within a containment housing to minimize dust contamination within the chamber, as shown in see Figure 1(b). The approximate working volume is 86 cm (length) by 46 cm (width) by 51 cm (height).

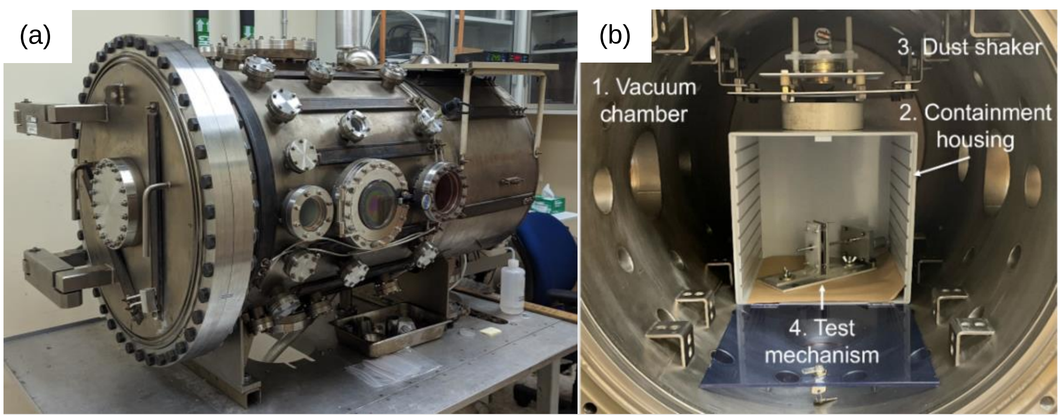

Figure 1. (a) Exterior and (b) interior images of SLIDE chamber[2]

<u>Dust Shaker Device</u>

Prior to use in the dust shaker device, the lunar dust simulant was passed through a stack of sieves with decreasing mesh opening sizes of 106 µm, 53 µm and 45 µm prior to testing to separate coarse particles from the fine particles. The fine particles (i.e., less than 45 µm in diameter) were utilized in the experiment. Sieving prior to testing ensured that the dust simulant would pass freely through the dust shaker sieve with mesh opening of 106 µm during testing.

A custom dust shaker device was fabricated to release controlled amounts of lunar dust simulant (LHS-1D, Exolith Lab, Oviedo, Florida[1]) onto test articles within the SLIDE chamber. The shaker mechanism consisted of a sieve with stainless steel mesh (mesh opening of 106 µm) with an acrylic cover secured to a base plate using nylon bolts. The acrylic cover had a single vent hole with a diameter of 0.635 cm drilled

[1] Specific vendor and manufacturer names are used only to accurately describe the test hardware or software. The use of vendor and manufacturer names does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration nor does it imply that the specified equipment or software is the best available.

[2] All image credits to NASA

into the top to minimize dust movement during the chamber evacuation process. The shaker base plate was supported by four rubber boots that surrounded nylon bolts attached to the chamber mounting plate. A rotating copper weight was affixed to a variable 24-volt (V)-DC electric motor (maximum rotational rate of 5300 RPM) to induce a vibration on the base plate and sieve and dispense the lunar dust simulant, as shown in Figure 2.

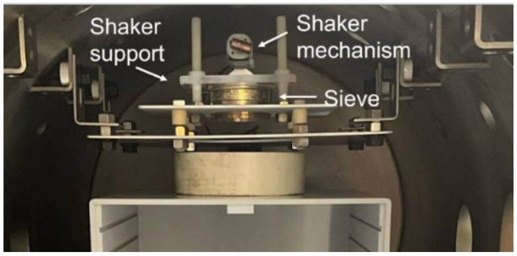

Figure 2. Dust Shaker Device

The deposition rate of lunar dust simulant at ambient pressure was determined through a series of dust shaker trials by powering the electric motor at 6 V and 24 V. A programmable 30 V power supply (KORAD KA3305P) was used. At the start of each trial, approximately 5 grams (g) of lunar dust simulant was loaded into the sieve. The acrylic cover was placed onto the sieve and then secured onto the base plate of the dust shaker device. The distance from the bottom of the sieve through which simulant passed was situated approximately 33 cm from the collection surface below. The dust shaker device was then actuated for a discrete interval ranging from one minute to three minutes of continuous actuation. The dust simulant that passed through the 106 µm sieve was collected on an aluminum foil. The area over which the dust settled was measured to estimate areal coverage. The dust simulant that was collected was then weighed using a high-precision scale capable of measuring to 0.00001 g. The surface accumulation loading was averaged over three deposition cycles at each electric motor voltage level.

<u>Pilot Assessment of Material Wear Performance</u>

In order to evaluate the performance and efficacy of the SLIDE chamber, a test mechanism was fabricated to mimic the abrasive wear motion on material surfaces in a simplified pin-joint mechanism as shown in Figure 3. The mechanism design was influenced by the Lunar Surface Manipulation System [8] to replicate aspects of the two-body abrasive wear encountered by two dissimilar materials in a pin-joint-like configuration. Lunar dust simulant could be selectively introduced to enable capturing aspects of a three-body wear test. The drive shaft ran through a hole in the center of the active disc with diameter of 0.8 cm, and the test coupons had dimensions of 3.8 cm x 3.3 cm as shown in Figure 4. The active disc was secured to the shaft using two set screws, and the coupons were secured to their respective L-brackets that held them in place against the active disc. The L-brackets were then aligned and secured such that the test surface of the coupon was flush with the surface of the active disc. The drive shaft was then coupled to an electric drive motor that turned the active disc at a rate of 1.3 RPM. The assembled test mechanism apparatus was situated directly below the dust shaker device within the SLIDE chamber to ensure even dust deposition onto the active disc and test coupons during wear testing.

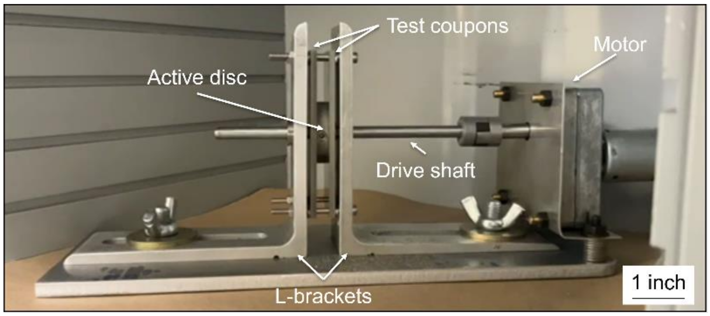

Figure 3. Pilot Test Mechanism

The test procedure involved initiating pump down of the vacuum chamber and waiting for approximately 15 minutes (min.) until a vacuum pressure of < 10^{-4} Torr was reached. The dust shaker and the electric motor that rotated the active plate were then powered to start a wear test. In the exploratory assessment of material wear, a test duration of 3 min. was selected to simultaneously actuate both the dust shaker device using an electric motor supplied with 6 V and active plate rotation at 1.3 RPM after a vacuum pressure of 8.6 x 10^{-5} Torr was reached.

The materials used in the pilot assessment included an active disc of polytetrafluoroethylene (PTFE) or aluminum-6061 alloy (Al6061) and test coupons of titanium-aluminum-vanadium alloy (Ti-6Al-4V) (as shown in Figure 4). PTFE was selected as a more compliant material having a comparatively low coefficient of friction compared to Al6061 and Ti-6Al-4V [9], while Al6061 and Ti-6Al-4V were selected due to frequent use in aerospace applications [10]. The test coupons and active discs were polished using silicon carbide paper up to 1200 grit followed by polishing with an alumina colloidal suspension (median particle size 0.05 µm) to ensure a consistent surface finish prior to testing. The test surface of each coupon that came in contact with the active plate was characterized using a FormFactor FRT Microprof 100 profilometer (Livermore, CA). Data was collected with 2.5 µm between data points and 12.5 µm between data lines to assess the surface of the test coupon before and after a test with or without flowing dust in the SLIDE chamber. Preliminary roughness parameters, such as average roughness, R_a, and root mean square roughness, R_q, were calculated using FormFactor FRT III analysis software to compare surface roughness for three regions approximately 1 mm x 1 mm before and after wear testing. An F-test was performed to determine if the data sets possessed equal variances, which determined whether a t-test with equal variances (homoscedastic) or a t-test with unequal variances (heteroscedastic) was utilized. Then, a two-tailed t-test was used to ascertain statistical significance. Both F- and t-tests were calculated using the Microsoft Excel functions. Resultant p-values less than 0.05 indicated significant statistical difference.

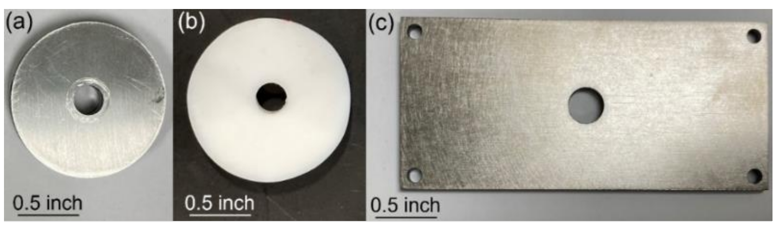

Figure 4. (a) Al6061 Active Disc, (b) PTFE Active Disc and (c) Ti-6Al-4V Test Coupon

Preliminary Results and Discussion

Surface Accumulation Loading of Dust via Dust Shaker Device

Preliminary surface dust accumulation loading results from both dust shaker trials are presented in Table 1. Lunar dust simulant was observed to deposit over a circular area with diameter of nominally 7.6 cm, which corresponded to the diameter of the dust shaker sieve through which lunar dust simulant passed. The average surface dust accumulation was determined to be 183.3 g/m^2 ± 68.9 g/m^2 after one minute of dust shaker motion at an electric motor drive voltage of 24 V. After three minutes of dust shaker motion at an electric motor drive voltage of 6 V, the average surface dust accumulation was 141.8 g/m^2 ± 88.6 g/m^2. The large standard deviation in surface dust accumulation observed in the dust shaker device trials may be attributed to a number of variables, such as lunar dust simulant particle size distribution, that could influence the rate of particle deposition. Additional trials will be performed to assess and optimize the amount of dust deposited under different electric motor drive voltages and cycle conditions, including using lunar dust simulant pre-sieved to a finer mesh size and utilizing a sieve with small mesh size in the dust shaker device.

Though data from lunar surface operations are limited, surface accumulation loading for human-generated surface transported dust (particle size <500 µm) has been reported as <40 g/m^2 based on estimates from Apollo walking and rover video archives [2]. Thus, approximately 50 seconds (sec.) or 15 sec. of dust shaker actuation at an electric motor drive voltage set at 6 V or 24 V, respectively, could achieve loadings comparable to those of human-generated surface transported dust relevant to lunar surface operations.

Table 1. Preliminary Surface Accumulation Loading Results from Dust Shaker Device Trials

Electric Motor Drive Voltage (V)	Surface Accumulation Loading (g/m^2)	Test Duration (min.)
24	183.3 ± 68.9	1
6	141.8 ± 88.6	3

<u>Results of Pilot Study on Assessment of Material Wear</u>

Preliminary optical and profilometry results for a Ti-6Al-4V coupons tested in contact with an Al6061 active disc after wear testing with lunar dust simulant in vacuum are shown in Figure 5. The circular wear pattern was evident in optical and profilometry data of the coupon tested without and with lunar dust simulant compared with the pristine starting surface.

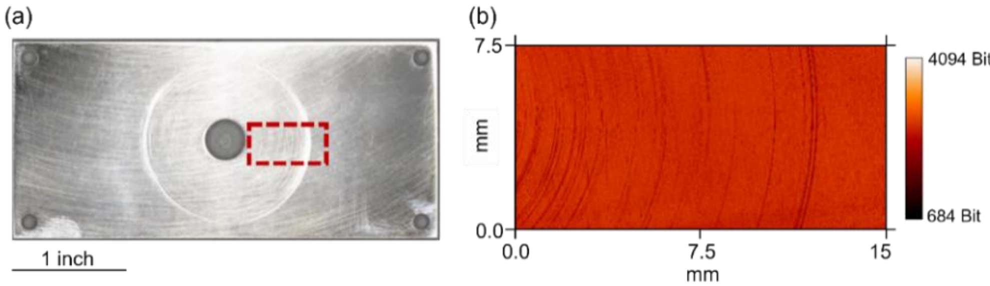

Figure 5. (a) Optical image of Ti-6Al-4V test coupon after SLIDE testing with lunar simulant exposure. The red rectangle corresponds to the region from which the profilometry intensity plot (b) was collected over wear path.

The wear test performed with the PTFE active disc without lunar dust simulant resulted in R_a and R_q values that were statistically similar to those of the as-polished surface prior to testing, suggesting that the wear interaction between the PTFE disc and Ti-6Al-4V coupon surface did not result in an appreciable change in surface roughness, as would be anticipated. In the case of wear testing with the Al6061 active disc and without lunar dust simulant, R_a and R_q parameters increased by approximately 0.003 µm and 0.004 µm, respectively, both of which were statistically higher in comparison with R_a and R_q of the as-polished Ti-6Al-4V coupon surface.

Table 2. Summary of Selected Surface Roughness Parameters for Ti-6Al-4V Test Coupons before and after Wear Testing in SLIDE with or without Dust.

Test Coupon Material	Active Disc Material	Lunar Dust Simulant	R_a (µm)	R_q (µm)
Ti-6Al-4V	N/A (Control)	N/A	0.005 ± 0.001	0.006 ± 0.001
Ti-6Al-4V	PTFE	No	0.006 ± 0.001	0.007 ± 0.001
Ti-6Al-4V	PTFE	Yes	0.012 ± 0.003	0.014 ± 0.003
Ti-6Al-4V	Al6061	No	0.008 ± 0.001	0.010 ± 0.001
Ti-6Al-4V	Al6061	Yes	0.014 ± 0.002	0.019 ± 0.002

Introducing a lunar dust simulant loading of ~ 141.8 g/m^2, as determined during the pilot assessment, resulted in an increase in surface roughness parameters of the Ti-6Al-4V test coupon surface after the wear test with PTFE active disc. The change in surface parameters was a factor of two greater than for those measured for both the starting coupon and the coupon wear tested without lunar dust simulant. Similarly, the addition of lunar dust simulant during wear testing with the Al6061 active disc resulted in a nearly three-fold increase in R_a and R_q values. This statistically significant increase in surface roughness parameters suggested that the introduction of lunar dust simulant resulted in a higher degree of wear of the Ti-6Al-4V surface than in wear tests without lunar dust simulant. Protective coatings could impart dust tolerance in certain applications [11]. These preliminary findings point to the importance of testing materials and devices with controlled dust exposure. These critical data will help ensure material and device performance in extreme environments, such as the lunar surface that is rife with dust, and play a vital role in mission success.

Summary and Continuing Efforts

In response to the need for evaluating material and device wear testing in the presence of lunar dust simulant under high vacuum conditions, the SLIDE testbed was developed to enable rapid advancement of critical technologies from conceptual stages to practical device implementation. The dust surface loadings that were achieved with the custom SLIDE dust shaker device varied from 141.8 ± 88.6 g/m^2 for 3 min. of actuation with an electric motor drive voltage setting of 6 V to 183.3 g/m^2 ± 68.9 g/m^2 for 1 min. of actuation at 24 V, respectively, with lunar dust simulant particle sizes less than 45 µm. Dust surface loadings could be tailored by adjusting the voltage supplied to the electric motor that actuated the dust shaker device and duration of actuation to achieve human-generated surface transported dust loadings relevant to lunar surface operations. Initial wear tests involving a Ti-6Al-4V coupon and a PTFE or Al6061 active disc were conducted within the SLIDE testbed under this apparatus' maximum achievable vacuum pressure with and without lunar dust simulant. Preliminary results revealed increased surface roughness of the Ti-6Al-4V coupons tested with dust compared to that of the coupons tested without dust exposure. The reconfigurable nature of the SLIDE platform allows for testing various materials, devices, and mechanism types under lunar dust simulant and reasonably high vacuum conditions. Compounding environmental effects, such as thermal gradients, cryogenic exposure, UV radiation, and electrostatic exposure, will be explored to test under such conditions. Testing will be tailored to incorporate aspects of other extraterrestrial environments, such as Mars, by utilizing Martian dust, regulating pressure and incorporating carbon dioxide. By testing in a combination of conditions, material and device concepts can be rapidly vetted and matured to end-use applications benefiting lunar and planetary exploration.

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