

Article

Abrasion Behaviour of Natural and Composite Polytetrafluoroethylene Seal Materials Against Stainless Steel in Lunar Regolith Conditions

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Abstract: In this paper, the abrasive effects of lunar simulant regoliths (LHS-1, LMS-1) have been investigated. Sealing performance of different sealant pin materials on stainless steel has been tested by the pin-on-disc method. Pin materials included block types such as pure polytetrafluoroethylene (PTFE), composite PTFE, as well as braided PTFE and hybrid-composite braided PTFE. Tribological properties were evaluated based on measured friction, wear, surface roughness and scanning electron micrographs. Most significant differences were observed in the sealing effect of the pins between the braided and the block-type pin materials. The stainless steel/pin pairs showed significantly higher (0.4–0.5) friction coefficients for the braided pins than the block ones (0.2–0.3), while there was not a significant difference in the abrasive effect of the different lunar regoliths. Although significant wear of the steel part occurred only with the block-type pins, this disadvantage was apparent in comparison with the braided pins. The abrasive particles caused deformation and eventually complete disintegration of the braided pins. Both the coefficient of friction and the wear could be estimated by a multiple linear regression model, in which different regolith size was the dominant independent parameter for the various pins.

Keywords: lunar regoliths; sealants; abrasive test; wear; friction



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1. Introduction

The exploration and exploitation of the resources of the nearest celestial bodies are key to advancing humanity's presence in space, offering significant benefits for scientific research, space travel, and extra-terrestrial settlements. Among the numerous challenges posed by the planetary environment, the abrasive properties of extra-terrestrial dust represent a critical area of investigation that has yet to be fully explored.

The behaviour of regolith particles on the surface of the Moon is primarily governed by lunar gravity, the lack of a magnetic shield and virtually no atmosphere. With nothing to shield the surface, it is constantly bombarded by cosmic radiation and even tiny particles. Consequently, this perpetual bombardment influences the lunar regoliths' mineralogical shape. Regolith comprises particles spanning from sub-micron dust to larger grains, contributing to the diverse texture of the regolith located on lunar surface. Lunar dust, made up of fine regolith particles with intricate shapes, presents a serious threat to both machinery and human health due to its abrasive and adhesive characteristics [1,2]. The fine dust has sharp edges that can damage materials and penetrate systems, leading to early wear and malfunction of mechanical components [3]. Sealing is a crucial technique to prevent fine dust from entering various places, particularly in environments where dust particles can threaten human health or the proper functioning of equipment. Although various elastomer seals perform reasonably well, PTFE is typically used and widely investigated due to its reliability over a wide temperature range and outstanding tribological properties in vacuum and also in air. PTFE sealants are reported to show superior performance for anodized aluminium against the abrasive effects of lunar simulant powders [4]. However, a slight deterioration of the shaft's surface could be observed and an unresolved incoherence between the wear of insulating materials and surface roughness. PTFE-based composites have also been tested with glass and carbon fibres, with negligible or non-existent advantages over pure PTFE [5,6]. Other ways to overcome wear problems consist of the use of different coatings, such as diamond-like coatings having supreme hardness, providing high wear resistance, or MoS₂ coatings, with a low coefficient of friction on metallic parts [7,8], as well as the protection of friction surfaces from dust by various low-friction sealants [9]. In addition to the proper selection of material for sealing, understanding the tribological interactions between lunar dust and materials used in space equipment is essential for developing durable technologies that can withstand the prevailing harsh environment and thus ensure the overall success of long-term lunar missions. A number of review articles [10,11] have been published recently about the tribological properties of various aerospace materials, including various polymers [12,13], in extra-terrestrial environments. However, the tribological properties of novel polymer composite pin and braided materials have not been investigated yet. It is important to note that extensive research has been conducted on alternative dust mitigation approaches based on the electrodynamic dust shielding technology. Readers can learn more about this in [14,15].

In this paper, the abrasive friction relationship between stainless steel and four different types of seals (two lip seals and two packings) is described, according to tests conducted with two lunar regolith simulants. In addition, the most significant factors affecting the coefficient of friction and wear properties are revealed by statistical analysis. In this way, insights are provided into the behaviour of these materials and the unique challenges posed by the abrasive effects of lunar regolith on rotating components.

2. Materials and Methods

2.1. Materials

The abrasive effect of lunar regolith was investigated by the comprehensive analysis and evaluation of the results of pin-on-disc tests performed for specific time periods (2, 6, 15 and 30 min).

The disc material was 316L (ASTM)/1.4404 (EN) grade stainless steel, which is typically used as a shaft material, owing to its austenitic structure and thus low-temperature capability, strength and machinability.

Based on the extensive study of seal solutions of moving machine elements subjected to harsh abrasive effects applied in space technology, and in accordance with ESA (Eu-

ropean Space Agency) suggestions, two different types of seals were selected [16]. As commonly applied, lip seals and packings materials (braided structure of polymer fibres) were compared in pin-on-disc abrasive tribo-testing. For the laboratory test systems, cut pieces of lip seals and packings gave the pin specimen. The selected seal samples were

- Ln (natural PTFE single lip seal, Ecoflon 1, spring-loaded);
- Lc (PTFE composite; PTFE/15%GF + 5%MoS2 (Ecoflon 2));
- Pn (PTFE yarn with dry impregnation);
- Pc (PTFE hybrid-composite; PTFE fibre/solid lubricant/aramid fibre)

Two lunar simulant regoliths were used as an abrasive medium, designated as LHS-1 (representative of lunar highland soil, Exolith Lab, Orlando, FL, USA) and LMS-1 (representative of lunar Mare soil, Exolith Lab, Orlando, FL, USA). Table 1 shows the major characteristics of the regoliths.

Table 1. Regolith simulants' key characteristics.

Regolith Simulants	LHS-1	LMS-1
	Lunar Highland Soil	Lunar Mare Soil
Phase Composition	• Anorthosite, 74.4% • Glass-rich basalt, 24.7%	• Pyroxene, 32.8% • Glass-rich basalt, 32.0% • Anorthosite, 19.8% • Olivine, 11.1% • Ilmenite, 4.3%
Physical Properties	• Bulk density: 1.30 g/cm³ • Median particle size: 60 µm • Particle size range: >0.04–1000 µm • Particle shape: sub-angular to angular	• Bulk density: 1.56 g/cm³ • Median particle size: 60 µm • Particle size range: >0.04–1000 µm • Particle shape: sub-rounded to angular
Reference	[17]	[18]

2.2. Test and Analysis Methods

To investigate the tribology of different material systems, tribological tests were performed using a modified pin-on-disc setup. Measurements were taken at the coupon level. Prior to the tests, the discs and pins were ultrasonically cleaned for 10 min in distilled water with 1% EM-300 metal cleaner agent followed by drying for 24 h at 22–24 °C in a drying oven. The tribo-tester utilized was an adapted pin-on-disc device, where the disc's surface was evenly covered with abrasive simulants. The approach illustrated in Figure 1 adheres to a controlled testing protocol, as outlined in DIN 50322 category VI. This system enables the analysis of the complex interactions that occur when simulated materials with flat surfaces slide against each other.

The frictional and three-body abrasion mechanisms, contact zone deformation and surface abrasion were investigated. Micro-geometric surface changes were also observed. To analyse the embedding capacity, abrasive impact, adhesion and grain dynamics of simulants, SEM (Zeiss EVO 40, Carl Zeiss SMT Ltd., Cambridge, UK) and EDX (JEOL JSM-IT700HR, JEOL Ltd., Tokyo, Japan) techniques were used. The system's parameters are detailed below.

In the pin-on-disc setup, the sealing material pin, having dimensions of 8 × 8 × 8 mm, slides along a rotating disc ($n = 36.6$ rpm) made of the same material (Stainless steel 1.4404) as the modelled shaft. The speed of the sliding pin was 0.1 m·s^{−1} on the track, with a radius of 25 mm. Abrasive particles between the surfaces mimic real-life shaft/seal contact, affecting wear and friction resistance. Abrasive friction and wear layer transformation were monitored by on-line measurements.

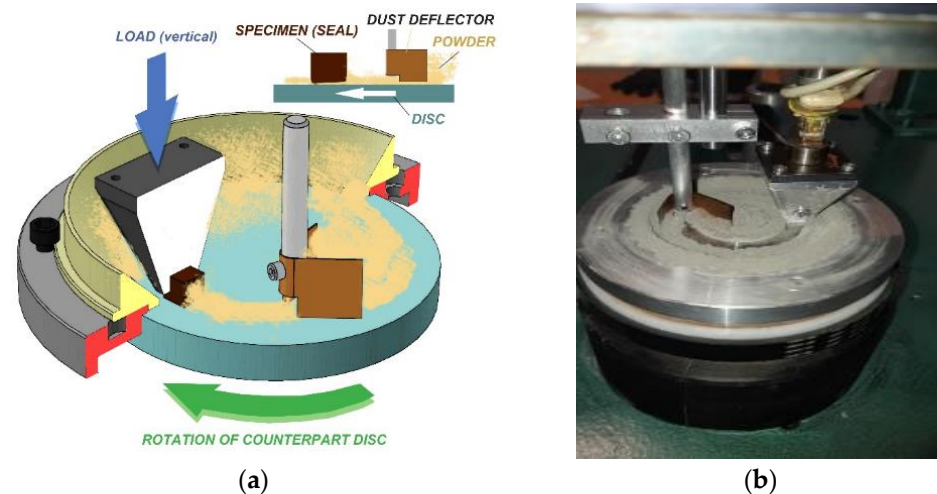


Figure 1. (a) Schematics and (b) photo of modified pin-on-disc measurements.

Tests were repeated at the ambient temperature four times for durations of 2, 6, 15 and 30 min with fresh pins and discs. Friction force and vertical pin displacement (wear) were recorded using a Spider 8 data system. Topographies in 2D and 3D were measured via a 3D optical microscope (Keyence VR 5200, Osaka, Japan). Three-dimensional surface topography data was used to calculate the degree of penetration (D_p), which varies based on the wear micro-mechanism and material hardness. In seal/shaft applications, low-stress abrasion occurred when lightly loaded abrasive particles scratched the surface, causing microscopic cutting and ploughing. According to Kato et al. [19], abrasive wear has three modes, micro-cutting, wedge formation and ploughing, each producing wear particles differently. A critical D_p value of around 0.2 has been identified to distinguish between micro-ploughing and micro-cutting, regardless of the attack angle. All three modes could create grooves due to particle generation and the material's plastic flow, forming ridges along the groove edges. Detailed description can be found also in [20].

2.3. Regression Model

For the statistical analyses, linear and multiple linear regression models were developed using IBM SPSS 29 software. During the statistical analysis, only the 30 min-long runs were considered, as they exhibited nearly parallel behaviour with respect to the other experiments with different lengths. Additionally, running-in phases were omitted from consideration. It is important to note that the duration of a running-in phase is relatively short when compared to the entirety of an experiment and, especially, in relation to the expected operational lifespan of machinery constructed from materials such as stainless steel. Consequently, their exclusion does not introduce any significant bias into the analysis. To smoothen the measured on-line data and enhance the visibility of trends, a moving average with a window length of 500 data points (equivalent to 5 m) was employed. It is important to note that using smaller window lengths, such as 200, can yield similar results with slightly reduced fitting precision. However, the use of excessively narrow windows, e.g., 50 (a smaller scale), results in insufficient data smoothing and hinders the clear identification of trends.

In the models, the displacement of the pin holder (referred to as “wear” hereinafter) and the coefficient of friction were the dependent variables, while the independent variables included sliding distance (d), material properties of cut pieces of seal materials (Shore D hardness, elongation at break, compressive strength for 1% deformation) and the relative ratio of regoliths with different particle size ranges with respect to mass (PR_x , where x represents a proper particle size range; see details in Table 2 below).

Table 2. Definition of variables describing the relative ratio of regoliths with different particle size ranges.

Notation	The Range of Particle Sizes to Which the Notation Applies
PR_0	0–99 μm
PR_{100}	100–124 μm
PR_{125}	125–199 μm
PR_{200}	200–249 μm
PR_{250}	250–314 μm
PR_{315}	315–399 μm
PR_{400}	400–499 μm
PR_{500}	500–799 μm
PR_{800}	800–999 μm
PR_{1000}	1000 μm

For a regression model, the R^2 value indicates the goodness-of-fit of the model to the measured data. In the multiple linear case, due to possible cross effects among the independent variables, the pure effect of a single variable cannot be told clearly. Despite this problem, by considering the absolute values of the standardized (or beta) coefficients of the significant independent variables, the relative magnitude of the effect can be estimated. The effect size is greater if this value is higher.

3. Results

3.1. On-Line Friction and Wear

Figure 2a,b demonstrate the frictional behaviour of the LHS-1 and LMS-1 simulant powders on steel discs using different pin sealants, respectively. The abrasive tests were carried out for various durations (2/6/15/30 min with a constant speed of 0.1 m/s and load of 0.2 MPa) in each examined material pair. Only the plots for the longest duration are shown here for each simulant powder, while the plots of the particular material pairs for limited durations are displayed in the Supplementary Materials (Figures S1 and S2). The coefficient of friction is actually a calculated abrasive friction number characteristic of an open three-body abrasive sliding mechanism. The graphs are plotted with a moving average of 60 data points. The slopes of the curves differ for different steel and sealant pairs, but even also for a given pair of materials for different powders.

For the tests with natural PTFE pins (Ln), the run-in phase varied between 10 and 20 m depending on the regolith and reached a maximum friction of between 0.35 and 0.4. After the run-in phase, the regolith particles have already entered the contact zone, and the resistance of the adhesion changes to a lower sliding resistance (COF: ~ 0.2) due to grain rolling. During the operation, a dynamic zone balance can be seen, and the fluctuation of friction peaks (COF 0.25–0.3) return according to the mechanism of the contact zone. The particles get in, are partially embedded in the softer PTFE surface, and adhere to each other in several layers, as well they roll on the surface, break up, and sometimes become congested with the formation of larger particles and blocks. The results of the parallel test show very good agreement (Figures S1 and S2). With respect to the composite PTFE sealant (Lc: PTFE/15%GF + 5%MoS₂), the run-in section occurred in a wider friction path length range (10–50 m) in the four measurement series (Figures S3 and S4), which shows the uncertainty of the contact zone behaviour. During running the third-body mechanism in the contact zone, the formation of agglomerates, adhesion, rolling, cutting and re-adhesion

caused significant frictional instability. A uniform steady state could not be established in the system, and the abrasive friction factor fluctuated intensively.

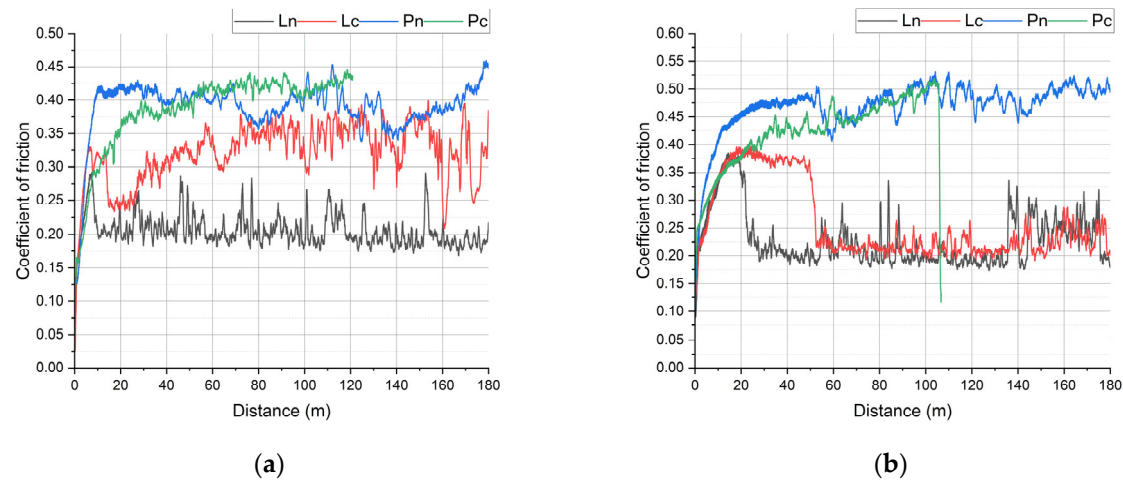


Figure 2. The effect of travelled distance on the coefficient of friction of steel and different sealing material pairs in the case of (a) LHS-1 and (b) LMS-1 lunar regolith simulants.

For the natural PTFE packing pin (Pn), the running-in stage was obtained at about 10 m, at which point the friction process stabilizes at a friction coefficient of 0.4 and 0.5 for LHS-1 and LMS-1 regoliths, respectively (Figures S5 and S6). Thereafter, the oscillation arises from the contact zone transformation; the structure between the fibres and its grain embedding ability causes local transient peaks and frictional instability in the process. At the end of the testing period, the packing structure was completely disintegrated. Comparing the results of the system with the curves of the natural PTFE pin (Ln) block (Figure 1), it can be seen that the friction stabilizes at a higher level for the packing braid than for the block material, but with a more uniform value (smaller local fluctuation and instability ranges around Δ COF 0.03–0.05 instead of 0.05–0.1 for Ln). In both cases, it is true that a stabilization of the frictional resistance occurs, but with different scatter and absolute values.

The running-in section of the composite packing pin (Pc: PTFE/Aramid/solid lubricant) shows a similar trend in the rise of friction for each series (Figure S7) and is relatively short (1–2 m), and the following steady-state friction curves tend to be a saturation-type curve. The friction curves are surprisingly smooth, with minimal fluctuation and instability, but running with an increasing trend. The observed phenomenon—compared to the composite lip seal-material pin and natural packing test specimens—can be found in the composition of the hybrid composite packing. The secondary, braided structure impregnated with wax and solid lubricant significantly blocks the movement and dynamics of the regolith grains and locally lubricates and sticks the grains, as can be seen in the R15 disc photos as well (Figure 3a). In the test with LMS-1 after a sliding path length of 40 m, frictional instability occurs in the sliding, which was accompanied by the disintegration of the braided secondary structure. The measurement had to be stopped after 105 m (Figure S8).

Figure 4a,b show the “wear” curves (vertical displacement of the pin holder, which contains the wear, deformation, particle movements and heat expansions) of the longest tests for the particular systems. In the case of Ln and Lc pins, the wear curves show a perfect match with the friction curves. After the run-in phase, the regolith entering the contact zone raises the pin holder head, resulting in negative wear in slightly different ranges for the two pins and regoliths. The lunar dusts show continuous wear in addition to occasional regolith sticking to the test bodies. The extreme peak values indicate the effect

of the accumulation of larger particles. The curves of repeated tests (Figures S9–S12) show excellent reproducibility.

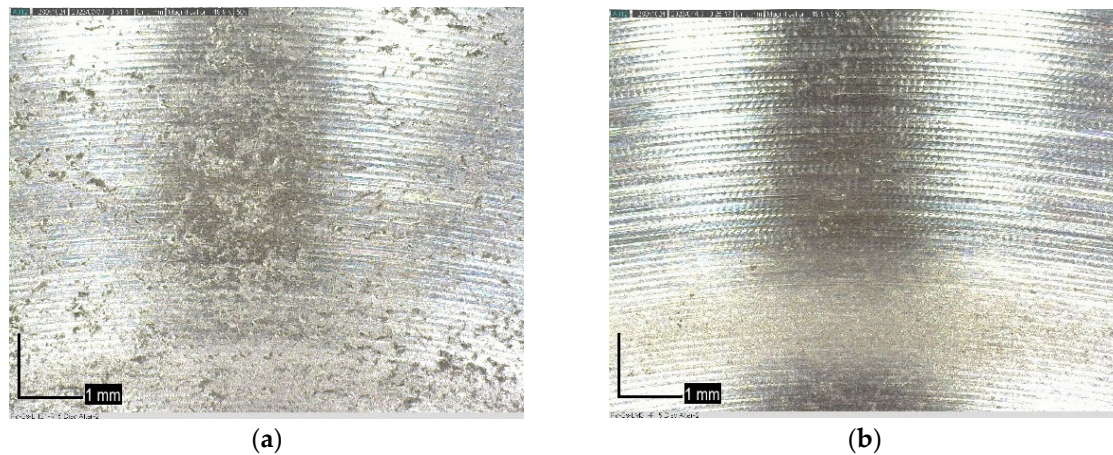


Figure 3. Light microscopy image of steel discs after 15 min of abrasion test with (a) LHS-1 and (b) LMS-1 lunar simulant regoliths in the case of a composite PTFE packing hybrid pin material.

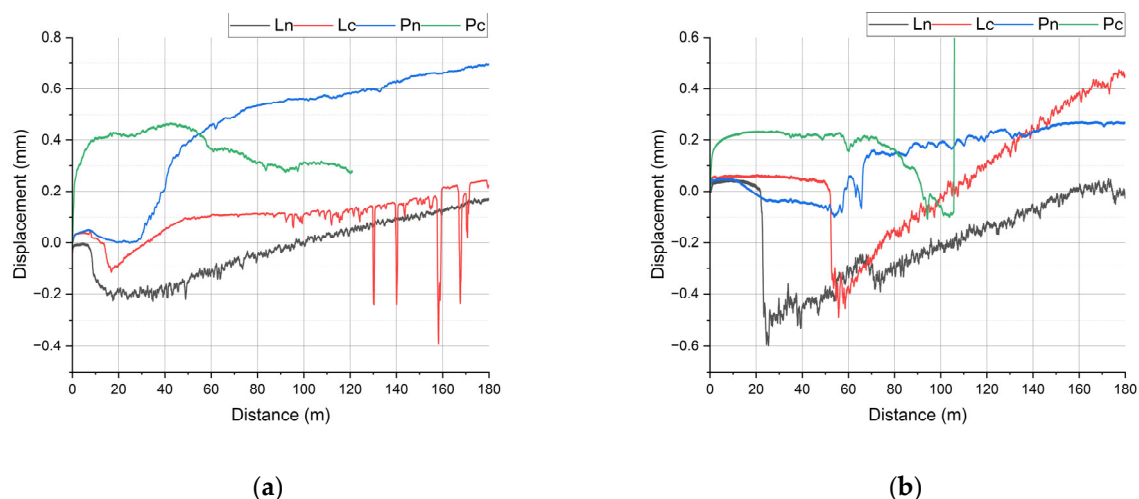


Figure 4. Effect of travelled distance on wear in the case of different sealing materials for (a) LHS-1 and (b) LMS-1 lunar simulant regoliths.

In the case of braided pins (Pn), the wear curves correlate less with the friction curves than was found between the natural bulk PTFE and steel surface. The structure of the braid is disrupted during the slip, and the contact zone is deformed and flattened; this significantly affects the vertical displacement of the pin holder head, which is reflected in the “wear curve”. This primary deformation is complemented by the phenomena of the three-body abrasion mechanism: grain migration, embedment, agglomerate formation and breaking and adhesion. Negative wear means that before the braided structure was crushed, the regolith that entered the contact zone raised the specimen holder head. The high displacement values refer mainly to the deformation of the braided pin. The wear curves of parallel measurements are not uniform (Figures S13 and S14), and there are significant variations between repetitions. This is due to the pin specimen being cut from a longer braid.

The structure of composite braided pin (Pc) also tend to deform and disintegrate, resulting in significantly different “wear curves” (Figures S15 and S16). This process is accelerated by the lubricant between the fibres. Inherent in this phenomenon is regolith

dust getting in-between the fibres, hindering the movement of dynamic particles. The banded adhesion visible in the photos of the steel surface (Figure 3b) also confirms this phenomenon. The main factor of the positive wear values is the deformation of the fibres that slip apart. This is followed by a negatively oriented “wear”, which is due to regolith particles entering and sticking to the contact zone. The specimen holder head is raised. In the case of the LMS-1 regolith, the measurement had to be stopped after 105 m because the pin specimen fell apart.

3.2. Surface Analyses

The employed pin materials are typically much softer, as compared to stainless steel, which is made evident by the higher tendency to wear and/or the deformation of the pins during tests. Their wear behaviour was investigated by optical, scanning microscopy and 3D imaging. Although the main component of all the tested pin materials was PTFE, they showed great variations in their wearing behaviour. The difference is marked between the block and the braided pins. In the case of the block pins, the surface of the pin is completely covered with the used abrasive dust, but in a smaller fraction of its size (Figure 5). The larger particles either intruded into the steel matrix or were hindered to get under the pin. The dominant surface transformation of the counterface was mixed ($D_p > 0.1$, see detailed explanation in Part I.). The surface is plastically transformed through micro-ploughing (distorted surfaces, ridges), while the material is removed through micro-cutting due to the sliding over hard soil particles. As the sliding distance increases, the D_p indicates more micro-cutting and material removal (Table 3).

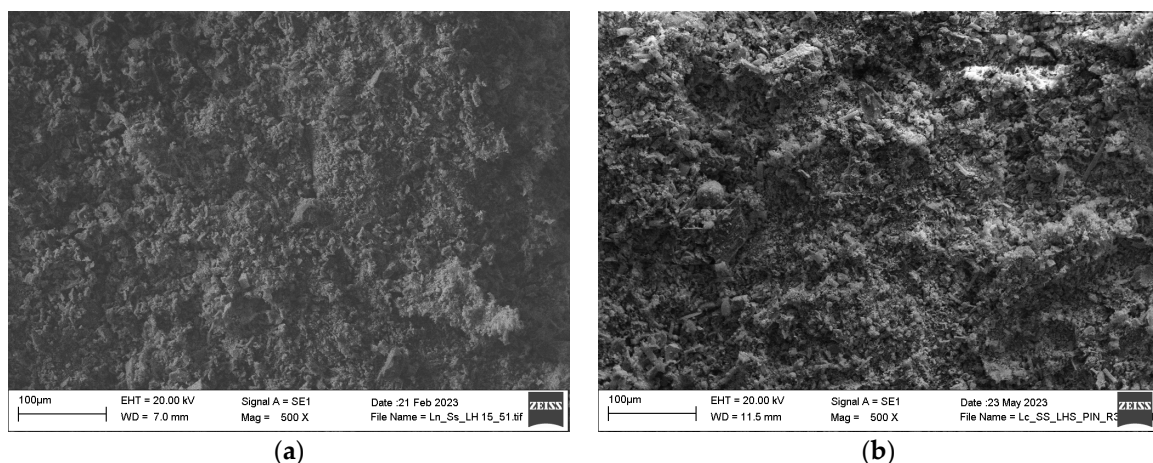


Figure 5. SEM images of block-type pin materials; (a) Ln pin and (b) Lc pin after 30 min pin-on-disc tests.

Table 3. Degree of penetration values for the pin materials after different test periods.

D_p , ($R_z/0.5R_{sm}$)	Lunar Simulant	Test Period (Minutes)			
		2	6	15	30
Ln pin	LHS-1	0.227	0.221	0.244	0.197
	LMS-1	0.181	0.3.372	0.3074	0.239
Lc pin	LHS-1	0.317	0.449	0.304	0.324
	LMS-1	0.225	0.340	0.350	0.283

In the case of the braided pins (Pn and Pc), the increase in test time resulted in distorted, torn packing samples with clearly more visibly accumulated abrasive dust embedded in their surface (Figure 6). The deformed surface and geometry indicate the packing is not functioning properly anymore, and surface roughness analysis is overlooked due to the

largely distorted topography. The damage is visualized in 3D images as well (Figure 6). After the 30 min test period, the original braided (secondary) structure disappeared, fully covered with regolith.

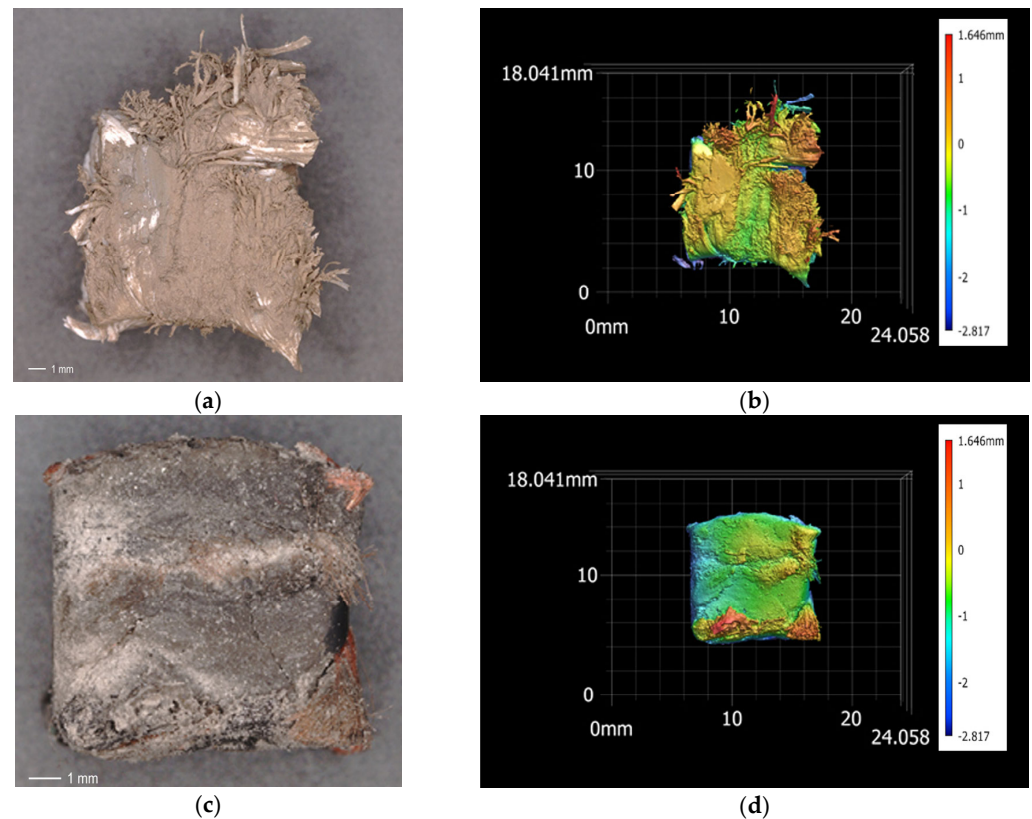


Figure 6. Photos (10 $\times$) and 3D images, respectively, of the worn surfaces of pins (a,b) Pn/LMS-1 contact and (c,d) Pc/LHS-1 contact after 15 min pin-on-disc tests.

Magnified (50 $\times$) light microscope images of the steel discs' surfaces after pin-on-disc tests (Figure 7) confirmed the surface phenomena indirectly observed in the friction and wear curves: adhesion–re-adhesion, particle embedding, detachment–accumulation, dynamics of the three-body mechanism and development of layer thicknesses. Similar to what was observed for the pins, the powders induced different degrees of changes on the disc surface for different pin materials. In the case of solid pins (Ln, Lc), significant dust layer adhesion and embedment were observed. During longer tests, the surface is significantly damaged, and protrusions are formed (Figure 8a,b). Finer particles get embedded throughout the surface. The increasing content of the indicated elements suggests an increased tendency of the dust particles to be embedded into the disc. EDX analyses confirmed that larger embedded particles are mainly composed of calcium–aluminium–silicates, while plenty of smaller particles contain sodium and magnesium as well. The steel surface was polished in the wear track, and the steel topography was transformed by abrasion. The decrease in the change of the total S roughness parameters (Table 4) confirmed this. The micro-mechanism of wear was characterized with degree of penetration (D_p) (Table 3). A $D_p < 0.1$ indicates a dominant micro-ploughing abrasion wear micro-mechanism on the disc surface, with plastic deformation of the material and formation of ridges along the abrasion grooves. Wear tests performed on a smaller radius resulted in slightly higher D_p , indicating more stress–torsion of the surface due to the track curvature. This means the lower D_p in these cases does not exclude the possibility of material removal through abrasion.

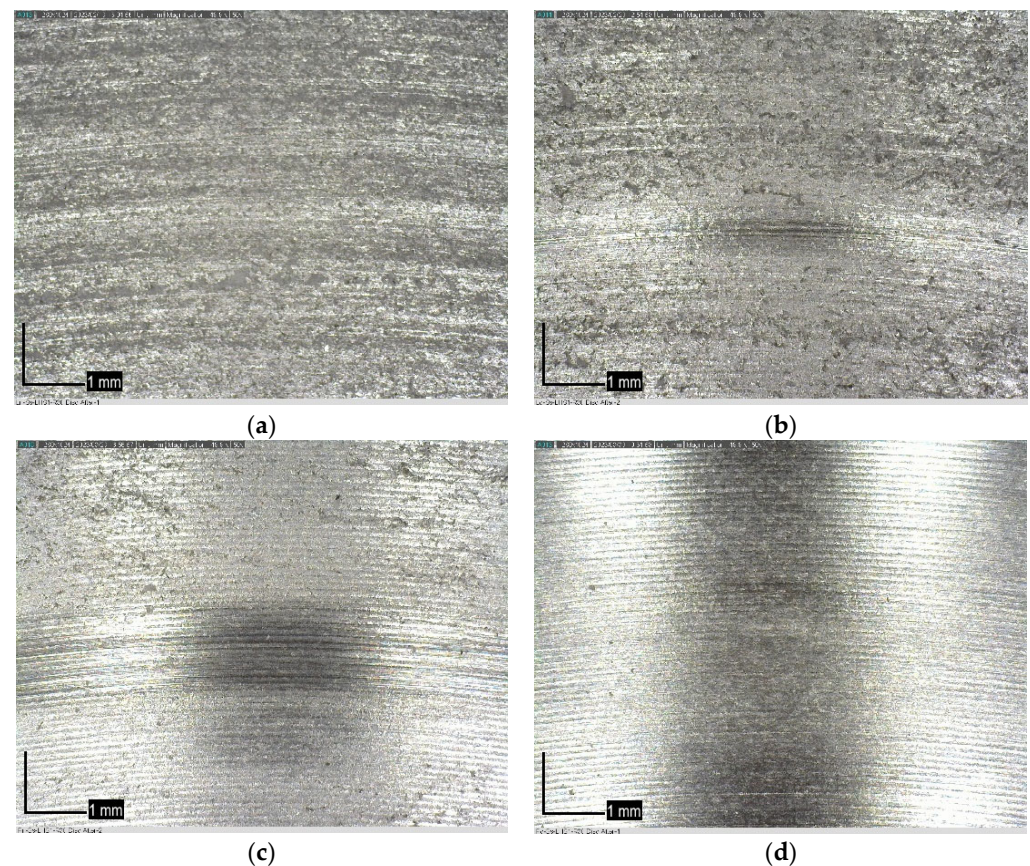


Figure 7. Light microscopy images of steel discs after 30 min of abrasion testing with the LHS-1 lunar simulant regolith in the case of different pin materials; (a) Ln, (b) Lc, (c) Pn, (d) Pc.

Table 4. Major roughness parameters of the steel surface after the abrasion test.

Pin/Simulant	Sa		Sz		Sq		Ssk		Sku	
	Before	After	Before	After	Before	After	Before	After	Before	After
Ln/LHS-1	1.01	0.79	168	19	1.72	1.01	2.34	−0.19	159.8	4.3
Ln/LMS-1	1.02	0.89	171	19	1.85	1.16	3.65	0.05	179.3	4.6
Lc/LHS-1	1.01	0.70	165	32	1.66	1.01	0.31	−0.26	170	10
Lc/LMS-1	1.00	0.80	158	24	1.57	1.08	0.10	−0.04	159	7
Pn/LHS-1	0.98	0.81	118	16	1.42	1.01	4.92	−0.05	122	3
Pn/LMS-1	1.00	0.78	130	16	1.34	0.96	2.95	0.09	148	4
Pc/LHS-1	1.01	0.81	165	32	1.66	1.07	2.91	−0.03	170	14
Pc/LMS-1	1.00	0.80	158	24	1.57	1.08	2.74	−0.04	159	7

Unlike solid pins, the amount of regolith adhering to the steel disc surfaces is significantly smaller for braided pins (Pn, Pc) (Figure 7c,d). At the end of the slip process, regolith deposition-free bands are revealed in the contact zone. By contrast, a significant amount of regolith adhered to the surface of the braided pin and in the valleys of the braided structure. This phenomenon was accelerated by the wax and solid lubricants built into the Pc braided structure. The abrasive effect of this, on the other hand, appeared to a very small extent on the steel disc surface, which is related to the flexibility of the braided pin structure. The disintegration of the braided structure was a common phenomenon, as a result of which the size of the contact zone changed, and the macroscopic deformations significantly changed

the structure of the tribo-system. This phenomenon was a faster process for Pc compared to the Pn measurements. SEM images show that the steel surface was less affected by the abrasion effect of lunar dusts (Figure 8c,d). Despite scratches, embedded particles and pin fragments, the surface damage is almost negligible; the original grooves of the disc are still visible. The very low content of the mineral composing elements on each tested part of the disc confirms the negligible number of embedded particles from the lunar dust. The metal surface microgeometry was exposed to the polishing effect of the regolith grains. It is generally true that the change and decrease of the micro-geometric parameter S on the steel surface were smaller than in the case of the solid natural PTFE pin. The $D_p < 0.1$ values (Table 3) also suggest for these systems a micro-ploughing abrasion wear micro-mechanism on the disc surface with plastic deformation. However, the presence of the transfer layer from the polymer pins and the embedded soil simulant particles could also fill up the abraded wear grooves and make the surface appear smoother; hence, a lower D_p is measured.

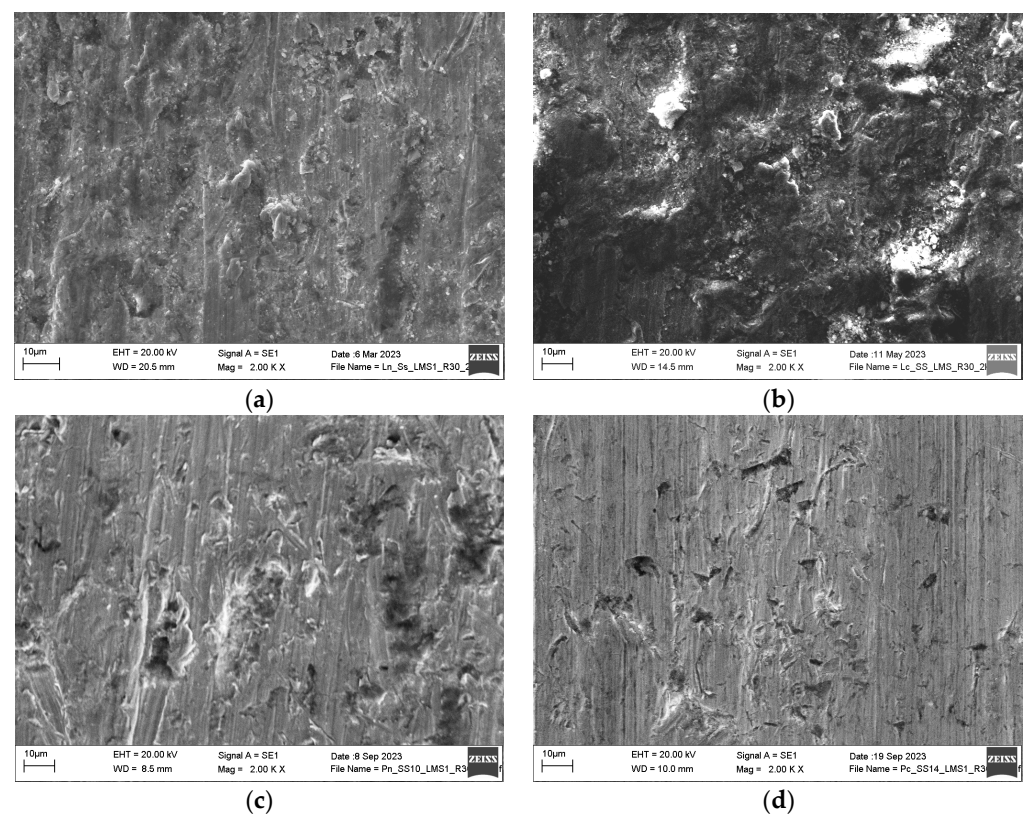


Figure 8. SEM images of steel discs after 30 min of abrasion testing with the LMS-1 lunar simulant regolith in the case of different pin materials; (a) Ln, (b) Lc, (c) Pn, (d) Pc.

3.3. Regression Model Results

To reveal the most decisive parameters affecting wear and friction coefficients in the studied systems, we performed multiple linear regression analysis using the distance (d) travelled by the pin and relative ratios of the regoliths with different particle size ranges (PR_x). We found that the linear model using only d as an independent parameter provides fairly good result for all investigated tribo-pairs and regoliths. In most of the cases, R^2 is greater than 0.9 for the friction coefficient and for the wear as well. In the multiple linear regression model, we determined the most influencing regolith size categories (Table 5) and found that they were identical for wear and friction. The results indicate that the behaviour of stainless steel is influenced in different ways according to the pin type. For Lc and Pn,

the effect of smaller fractions of regolith was dominant, while for Ln and Pc the effect of the larger fractions was dominant.

Table 5. Calculated model equations for wear and coefficient of friction for the different pin materials.

Pin	Dominant Regolith Size	Model Equation	R ²	Standardized β Coefficient of d	Standardized β Coefficient of PR_x
Ln	PR_{1000}	wear = $-0.172 + 0.003d - 7.452 PR_{1000}$	0.974	0.779	−0.606
		COF = $0.187 + 0.00006d - 0.486 PR_{1000}$	0.128	0.138	0.33
Lc	PR_{100}	wear = $-0.852 + 0.005d + 3.108 PR_{100}$	0.782	0.983	0.492
		COF = $-0.016 + 0.00026d + 2.187 PR_{100}$	0.964	-	0.973
Pn	PR_{125}	wear = $-0.884 + 0.002d + 4.276 PR_{125}$	0.984	0.36	0.986
		COF = $0.7 - 1.07 PR_{125}$	0.873	-	−0.931
Pc	PR_{800}	wear = $0.697 - 0.002d - 7.266 PR_{800}$	0.881	−0.519	−0.898
		COF = $0.307 + 0.001d + 1.37 PR_{800}$	0.796	0.79	0.611

4. Conclusions

The sealing performance of four different sealants, including solid PTFE, a solid composite PTFE, a braided PTFE and a braided hybrid PTFE sealant, was investigated, as well as the abrasive effect of lunar simulant regoliths (LHS-1 and LMS-1) by pin-on-disc tests on the steel/pin material pairs. Although the investigated systems showed large variation in terms of tribological behaviour, depending on the type of simulants and the pin material, the most significant difference was observed between the solid (Ln, Lc) and braided (Pc, Pn) type of pins.

In the running-in section, the particles entered into the contact zone, and the three-body abrasion mechanism prevailed. The friction resistance in the steady friction stage is characterized by a μ value of 0.2–0.3 for the block pins and 0.4–0.5 for the braided pins. Frictional instabilities occurred in all systems, accompanied randomly by friction noise effects. The instabilities can be attributed to the dynamism of the three-body process taking place in the contact zone for the solid pins, while in the case of the braided pins, the disintegration of its structure and its interaction with regolith dust was the decisive phenomenon.

Similar to friction, a significant difference between the wear of solid and the braided pins was identified. Wear curves were correlated with the friction curves for the solid pins. At the end of the running-in section, an apparent negative wear value was typical due to the particles that could reach the contact zone and raise the pin holder head. Wear is characterized by how the three-body mechanism of the particles develops, how many particles remain in the contact zone and the intensity with which they transform the original surface of the steel and (composite) PTFE. Severe abrasion effects on the surface were exerted by the particles remaining embedded in the steel and PTFE. The extension of wearing and the affected areas of abrasion increased with abrasion time.

Conversely, in the case of the braided pin structure, a weak correlation was found between the wear curves and the friction curves. Since the vertical displacement of the pin holder head occurred due to the dynamic effects of the regolith powders in the contact zone, and due to disintegration of the pin specimens, realistic wear curves could not be interpreted. During the abrasion test, abrasive wear was slightly increased, mainly in the form of (1) scratches, (2) a couple of embedded particles and (3) fragments of the pin material. The overall wear, however, was found to be almost negligible.

Comparing the two different lunar simulant dusts, no significant difference was observed in their impact on the steel surface against any pin series. The extension of

wearing and the affected areas of abrasion gradually increase with abrasion time, up to 30 min. Taking into consideration all of the effects observed (friction, wear, surface change, embedment, layer formation and agglomerations), the LMS-1 Lunar regolith was found to be more harmful for abrasive sliding for the contacts examined.

The results suggest that while the braided pins have a lower abrasive effect on the metallic parts of the abrasive system, as compared to solid pins, the braided pins were prone to rapid disintegration, making their use as sealants less advantageous in the pin-on-disc system.

The measurement system is in accordance with DIN 50322 VI category measurement under soil laboratory conditions, which is the first accelerated comparative measurement and basic phenomena study system with the appropriate structural materials, load and speed conditions. The next step is the modelling of real machine elements, the results of which will be reported in a later article. This will be followed by the consideration of vacuum and temperature conditions.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/lubricants13020043/s1>: Figure S1: Coefficients of friction of the steel-PTFE material pair in the presence of the LHS-1 lunar regolith simulant dust as a function of distance travelled during different test times.; Figure S2: Coefficients of friction of the steel-PTFE material pair in the presence of the LMS-1 lunar regolith simulant dust as a function of distance travelled during different test times; Figure S3: Coefficients of friction of the steel-composite PTFE material pair in the presence of the LHS-1 lunar regolith simulant dust as a function of distance travelled during different test times; Figure S4: Coefficients of friction of the steel-composite PTFE material pair in the presence of the LMS-1 lunar regolith simulant dust as a function of distance travelled during different test times; Figure S5: Coefficients of friction of the steel-PTFE packing pin material pair in the presence of the LHS-1 lunar regolith simulant dust as a function of distance travelled during different test times; Figure S6: Coefficients of friction of the steel-PTFE packing pin material pair in the presence of the LMS-1 lunar regolith simulant dust as a function of distance travelled during different test times; Figure S7: Coefficients of friction of the steel-composite PTFE packing pin material pair in the presence of the LHS-1 lunar regolith simulant dust as a function of distance travelled during different test times; Figure S8: Coefficients of friction of the steel-composite PTFE packing pin material pair in the presence of the LMS-1 lunar regolith simulant dust as a function of distance travelled during different test times; Figure S9: Effect of travelled distance on the wear behaviour the LHS-1 lunar regolith during different test times for steel- PTFE material pair; Figure S10: Effect of travelled distance on the wear behaviour the LMS-1 lunar regolith during different test times for steel- PTFE material pair; Figure S11: Effect of travelled distance on the wear behaviour the LHS-1 lunar regolith during different test times for steel-composite PTFE material pair; Figure S12: Effect of travelled distance on the wear behaviour the LMS-1 lunar regolith during different test times for steel- composite PTFE material pair; Figure S13: Effect of travelled distance on the wear behaviour the LHS-1 lunar regolith during different test times for steel-braided PTFE material pair; Figure S14: Effect of travelled distance on the wear behaviour the LMS-1 lunar regolith during different test times for steel- braided PTFE material pair; Figure S15: Effect of travelled distance on the wear behaviour the LHS-1 lunar regolith during different test times for steel-braided composite PTFE material pair; Figure S16: Effect of travelled distance on the wear behaviour the LMS-1 lunar regolith during different test times for steel- braided composite PTFE material pair.

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