Abrasive Effects of Lunar Regolith on Material Wear for Long-Term Lunar Application

Zachary Stein[1], Ashley Tirado-Pujols[1], Christopher Wohl[2], Valerie Wiesner[2], and Seetha Raghavan[1]*

[1]Embry-Riddle Aeronautical University, Daytona Beach, Florida, United States
[2]National Aeronautics and Space Administration (NASA) Langley Research Center, Hampton, Virginia, United States

* Corresponding Author: seetha.raghavan@erau.edu

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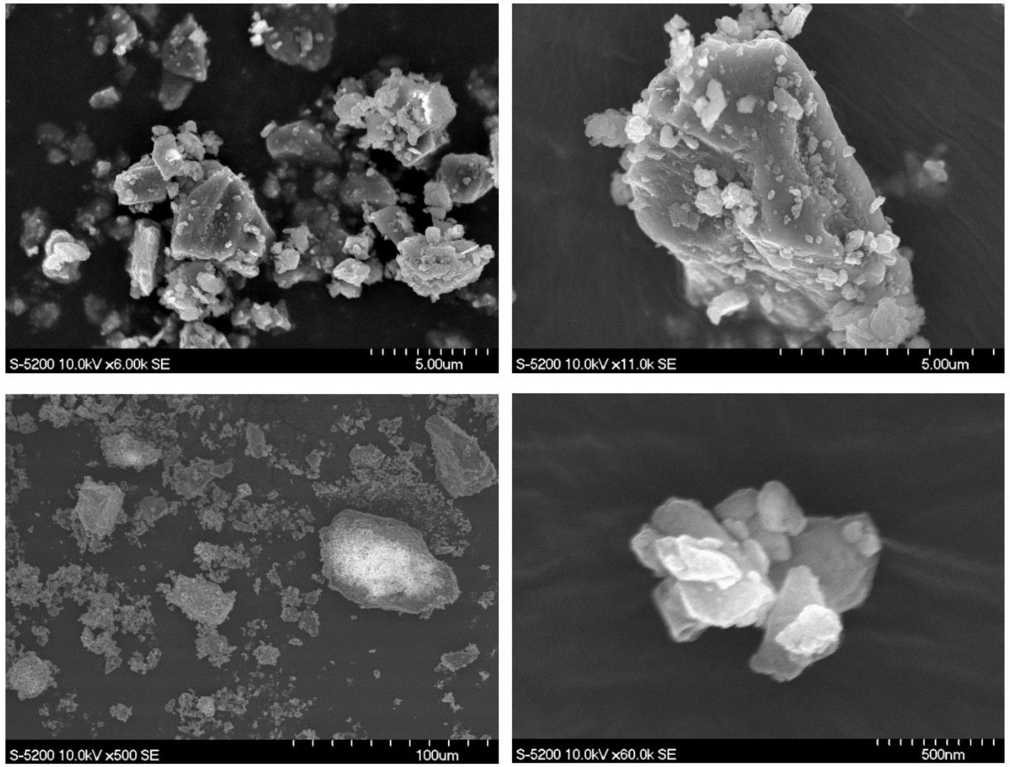
Resilient Materials for Wear Protection in Lunar Environments

- Increased interest in long-term lunar activities requires the design of wear resistant materials for protection of reusable lunar structures and vehicles
- Lunar dust is highly abrasive as a result of their fine-grained, sharp and jagged edges
- Alumina and zirconia-based ceramic coatings have demonstrated capabilities in wear protection for various applications
- But first current test methods need to be evaluated to better simulate and represent material degradation effects within the lunar environment



Scanning Electron Microscopy (SEM) images of lunar regolith simulants (taken by Zachary Stein)

Mishra, S. K., Prasad, K. D., Nath, P., Agarwal, D., Kumar, S. S., & Bhardwaj, A. (2022). Effect of lunar landing on its surface, surrounding environment and hardware: A numerical perspective. Planetary and Space Science, 211, 105398

Westergård, R., Axén, N., Wiklund, U., & Hogmark, S. (2000). An evaluation of plasma sprayed ceramic coatings by erosion, abrasion and bend testing. Wear, 246, 12–19

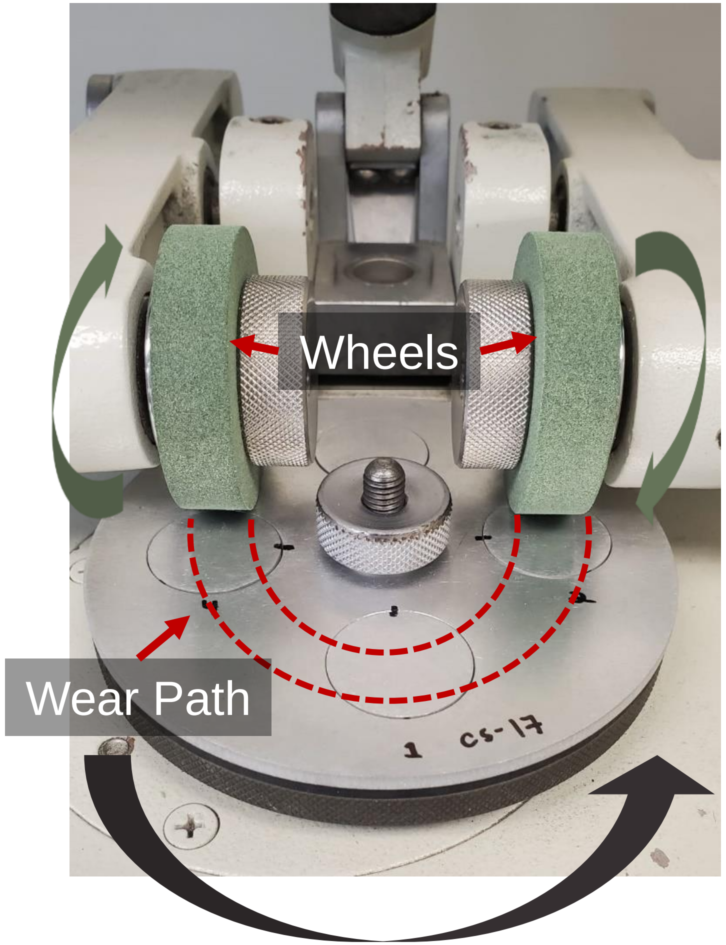
Motivation and Objectives

Provide a pathway for the **protection of lunar exploration systems** by exploring the **resilience of materials** to **withstand** the **abrasive lunar environment** with **test methods** that **accurately represent** and **capture the effects of abrasion and resulting wear.**

Objectives:

- Evaluate abrasion testing **with lunar regolith as wear media** in comparison to standard wear media
- Investigate the mature, **wear-resistant alumina and yttria-stabilized zirconia (YSZ) coatings** manufactured using air plasma spray (APS) for resilience to abrasion from lunar dust

Abrasion Testing Methodology



Picture of abrasion testing system with the components, wear path, and direction of movement labeled.

Mass Loss

Measurements for wear are based on mass loss after abrasion:

$\delta W = W_1 - W_2$

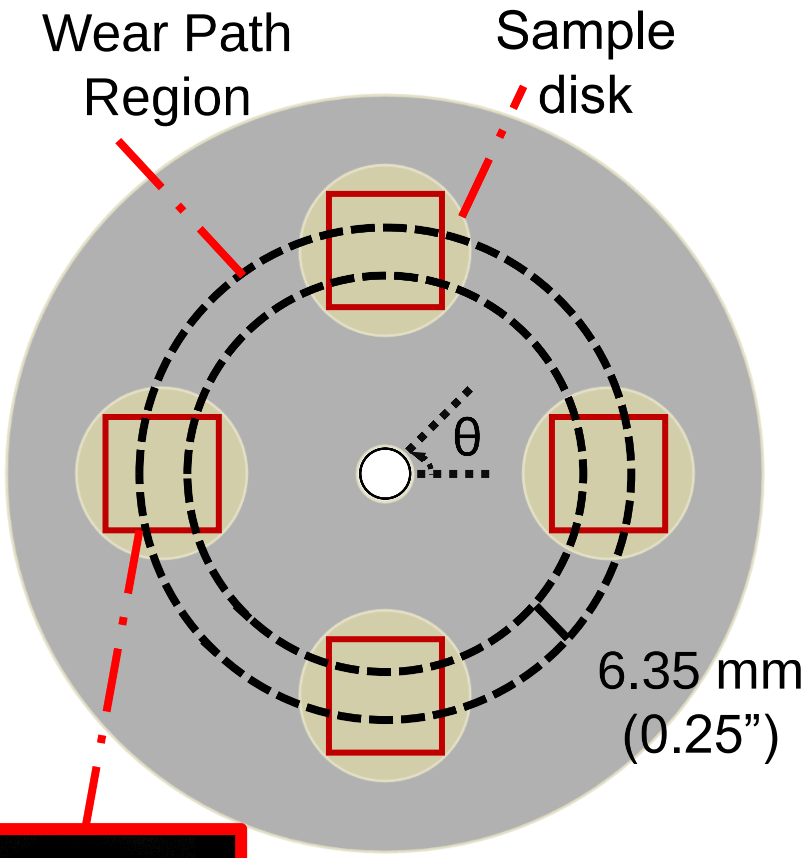
where δW represent this loss in milligrams (mg), W_1 corresponds to weight before abrasion in mg and W_2 is weight after abrasion in mg

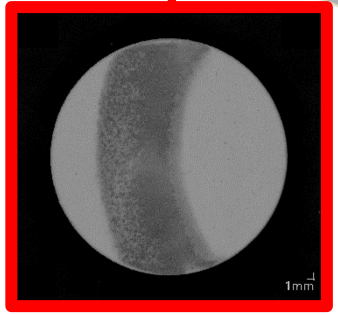
Wear Index

The wear index

$$I = \frac{1000 * (\delta w)}{c_T}$$

δW represents the mass loss, and C_T is the total number of abrasion cycles recorded

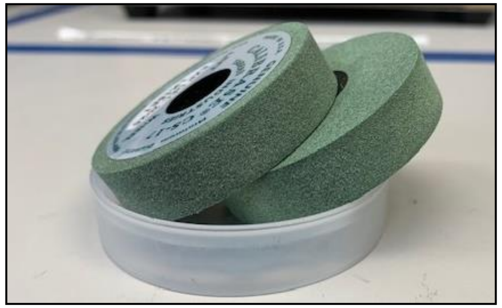




Alumina-coated sample wear path

ASTM D4060-19, "Test Method for Abrasion Resistance of Organic Coatings by the Taber Abraser," ASTM International, West Conshohocken, PA, 2019.

Regolith Simulant as Wear Media



CS-17

Mineralogy		Moh's Hardness
Component	**Wt. %**	**–**
Carborundum (SiC)	100.0*	9.0 – 9.5

*Excluding Resilient Binder

Regolith Wheels (LMS-1)

Mineralogy		Moh's Hardness
Component	**Wt. %**	**–**
Bronzite	32.8	5.5 – 6.5
Glass-rich Basalt	32.0	5.0 – 7.0
Anorthosite	19.8	6.0 – 6.5
Olivine	11.1	6.5 – 7.0
Ilmenite	4.3	5.5 – 6.0

Particle size range: 0-1 mm
Mean particle size (by volume): 63 μm

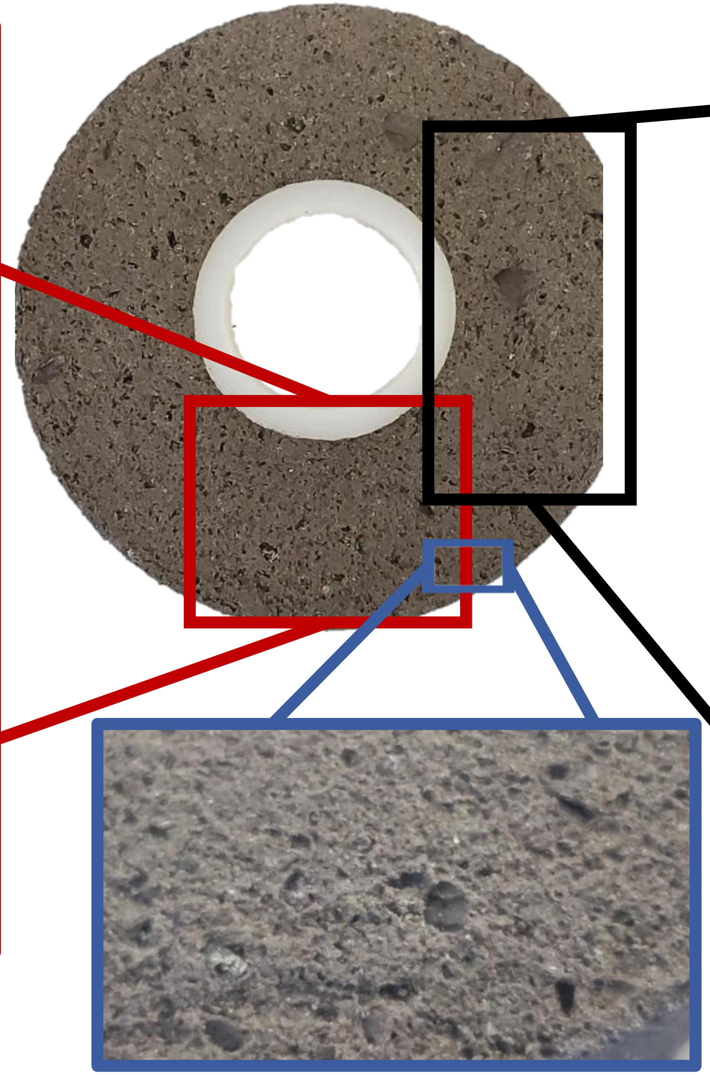
Shore A Hardness	
CS-17 Wheels	81 ± 5.0
LMS-1 Wheels	72 ± 3.0

Summary:

- Overall, the regolith wheels are similar relative to each other with the highest Moh's hardness constituent being around 7.0
- Both regolith wheels are softer than the CS-17 wheels (Moh's hardness between 9.0 – 9.5)

A. Madison, Z. Landsman, J. Long-Fox, A. Metke, K. Krol, P. Easter, C.Sipe, L. Weber, D. Britt, "Lunar Dust Simulants and Their Applications", Proceedings of Earth and Space 2022.

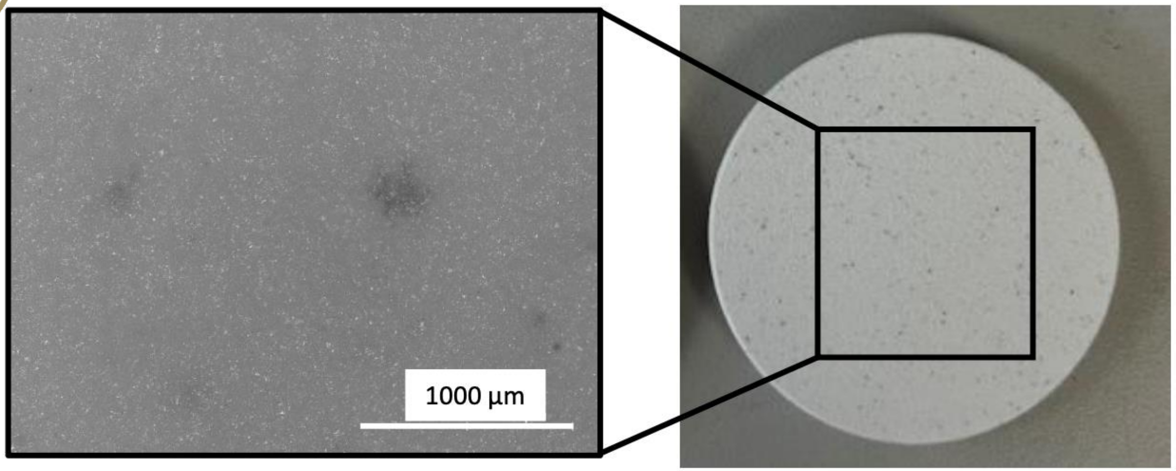
LMS-1 Regolith Wheels – Up Close



Assorted pictures of the LMS-1 Regolith Wheels

- Overall, slightly porous structure when paired with binder. Fine particle sizes can be observed

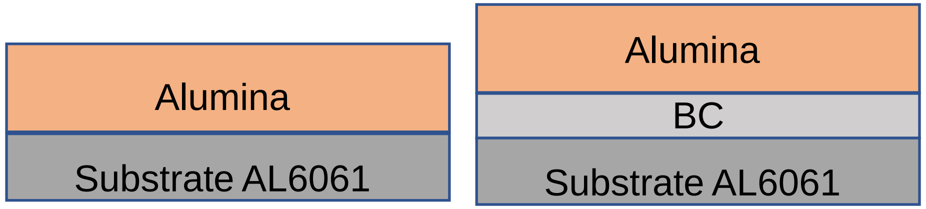
Air Plasma-Sprayed (APS) Alumina and 8YSZ Coatings



APS Alumina Coating before Abrasion test

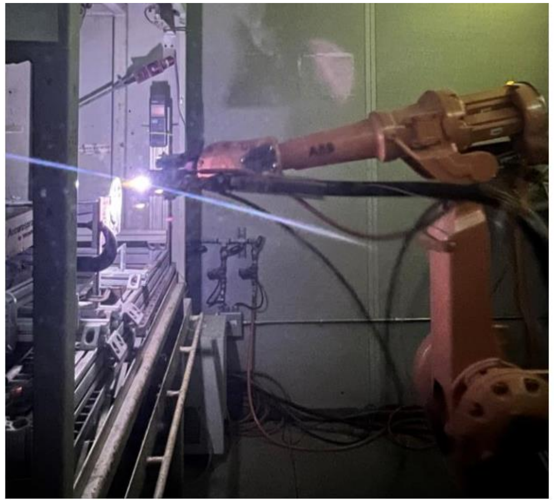
Table 1. Coating material parameters

Coating Layer	Al6061-T6	Alumina w/o BC	Alumina	8-YSZ
BC (µm)	-	-	100	123.8 ± 45.9
TC (µm)	-	461.3 ± 21.9	581.4 ± 20.7	358.8 ± 45.9



Top Coat (TC): Alumina or 8-YSZ
Bond Coat (BC): NiCrAlY (nickel, chromium, aluminum, yttrium)
Substrate: Al6061aluminum alloy, 6.35 mm thickness

Coating configurations tested (Not to scale)



Air Plasma Spray process with discharge plasma where droplets are accelerated towards substrate

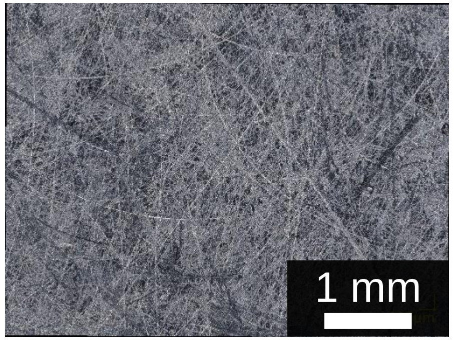
Latorre-Suarez, P. C, Fouliard, Q., Wohl, C., Wiesner, V., & Raghavan, S. (2023). Measuring Wear and Abrasive Resistance of Air Plasma Sprayed Aluminum Oxide Coatings for Lunar Exploration. International Astronautical Congress, Baku, 2023.

Results on Abrasion Testing and Wear Media

- Pristine Region
  - Untreated, as manufactured Al6061-T6
- Abraded Region
  - Cross-hatched wear pattern
  - CS-17 wheels provided fine and uniform wear
  - LMS-1 wheels provided rough uneven wear
  - Likely due to higher variation in grain sizes within LMS-1 composition

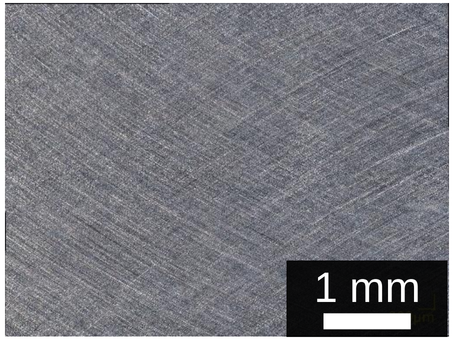
Al6061-T6

a)



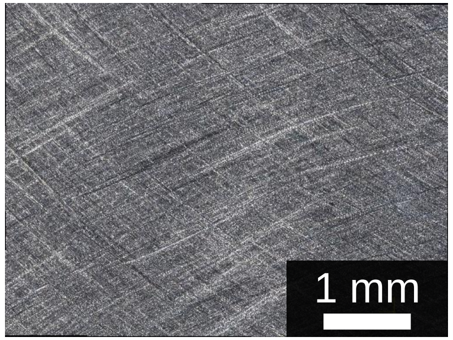
Pristine Region

b)



Abraded Region (CS-17)

c)



Abraded Region (LMS-1)

Results on Abrasion Testing and Wear Media

Table 2. Overall summary of results of Al606-T6 wear

Parameter	Al6061-T6 (CS-17 wheel)	Al6061-T6 (LMS-1 wheel)
Wear index (mg/1000 cycles)	3.29	3.64
Average surface roughness (Ra) (μm) Pristine	1.28 ± 0.04	1.83 ± 0.07
Average surface roughness (Ra) (μm) Abraded	0.68 ± 0.02	0.97 ± 0.03
Difference between Pristine and Abraded	0.60 ± 0.02	0.86 ± 0.04

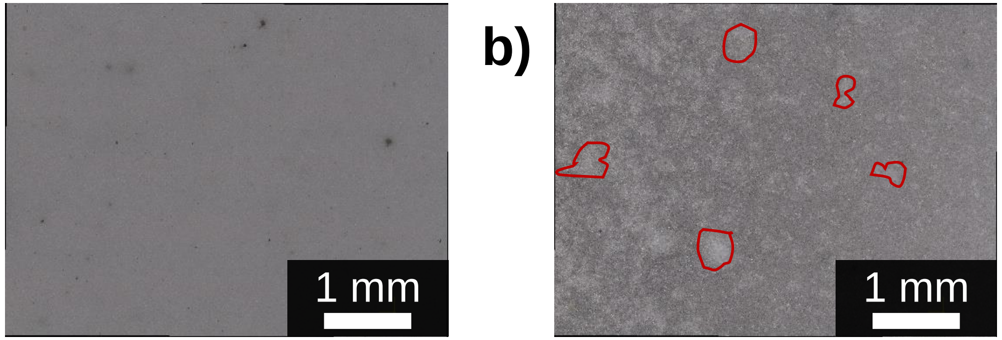
- LMS-1 wheels resulted in surfaces with a higher wear index by a difference of 0.35 mg mass loss per 1000 cycles
  - Potentially a result of a softer composition, meaning abrasion grains would wear at a faster rate, exposing newer grains faster during abrasion
- Average change in surface roughness was approximately 69% lower for the CS-17 wheels compared to the LMS-1 wheels

Results on Wear of APS Alumina Coatings

- Pristine Region
  - No discernible differences on the surface of the alumina coatings with or without BC
- Abraded Region
  - Speckled clusters of remaining alumina coating are outlined in red for both coatings with and without BC
  - Clusters are smaller and grainy in the alumina coating without a bond coat
  - Larger globules of remaining alumina on sample with bond coat are likely due to underlying microstructure and higher adhesion strength

Alumina Coating on a Al6061-T6 Substrate
No Bond Coat

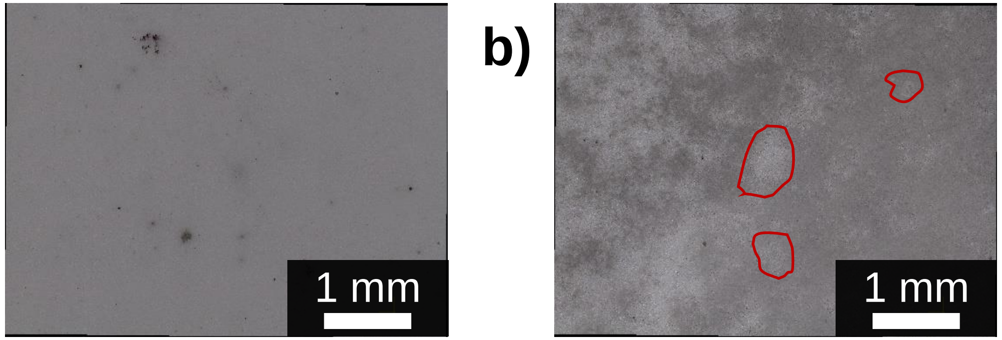
a) b)



Pristine Region — Abraded Region

Alumina Coating on a Al6061-T6 Substrate
With Bond Coat

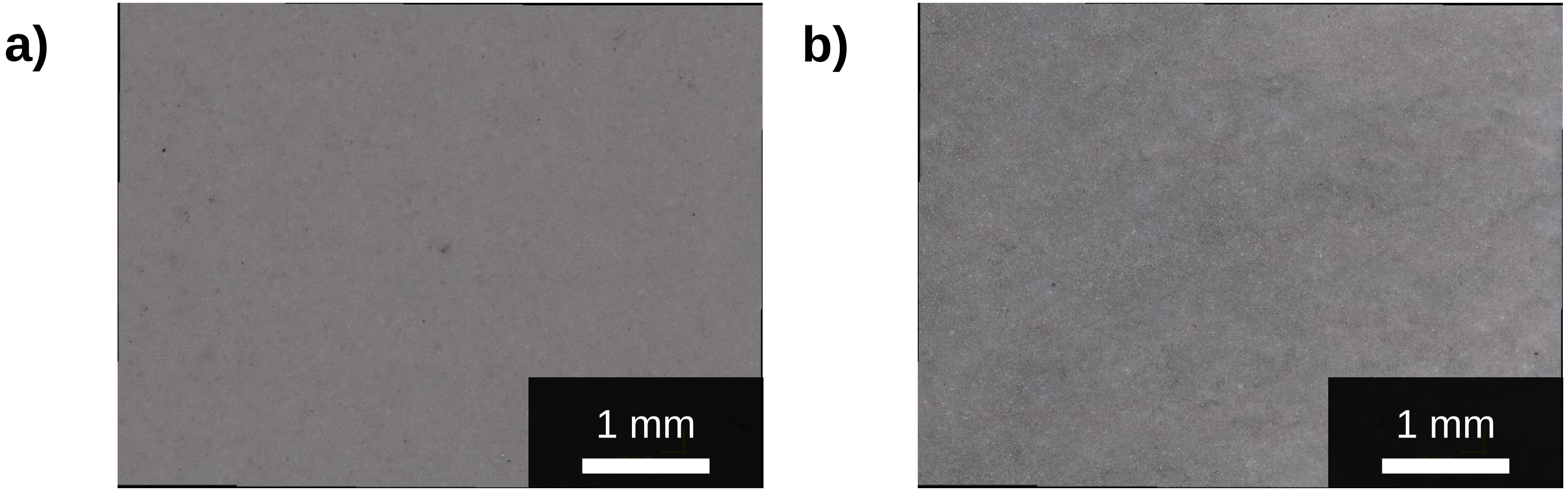
a) b)



Pristine Region — Abraded Region

Results on Wear of 8YSZ Coatings

8YSZ on a Al6061-T6 Substrate



Pristine Region

Abraded Region

- Pristine Region
  - Smooth and uniform surface
- Abraded Region
  - Some surface effects observed when comparing with pristine region
  - Changes are generally consistent over the entire surface

Comparing Wear Resistance of APS Ceramic Coatings

Table 3. Overall summary of results of APS coating wear

Parameter	Alumina w/o BC	Alumina w/ BC	8YSZ w/ BC
Wear index (mg/1000 cycles)	5.19	5.39	9.20
Average surface roughness (R_a) (µm) Pristine	3.70 ± 0.27	5.69 ± 0.27	8.72 ± 0.27
Average surface roughness (R_a) (µm) Abraded	2.79 ± 0.15	4.64 ± 0.17	4.11 ± 0.33
Difference between Pristine and Abraded	0.91 ± 0.12	1.05 ± 0.10	4.61 ± 0.06

- When comparing wear index, 8YSZ coating abrades nearly twice as much as the alumina coating samples
- In all cases, the average surface roughness decreased
- 8YSZ specimens had the highest change in roughness, followed by the alumina coating with BC, the alumina coating without BC, and finally, the Al6061-T6 control samples
- Data suggests a relationship between the average surface roughness prior to wear testing and the wear index

Conclusions & Moving Forward

Abrasion testing

- The results of wear from the standard CS-17 and LMS-1 wheels demonstrate a slightly higher wear index resulting from testing with the LMS-1 wheels. We captured the influence of wear media in the test process on the overall wear index and consequently abrasion performance of a material
- Future tests are planned with spectrum of lunar regolith wear media to capture the effects from various locations on the lunar surface that have different mineralogy compositions and particle sizes. This will be followed by a study on various coatings and their resistance towards lunar dust particle adhesion over their operational lunar lifetime

Wear resistance of Alumina and YSZ coatings

- Wear index is lower for alumina than 8YSZ suggesting that alumina possesses more wear resistance
- Nevertheless, the tailorability and versatility of 8YSZ makes it an attractive option to continue pursuing as protective coatings for varied lunar applications
- Future studies will aim to explore modifying the YSZ with additives to compensate for the lower wear resistance

Acknowledgements

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Thank you!
Questions?