Ceramic Research Advancement Technology at Embry-Riddle

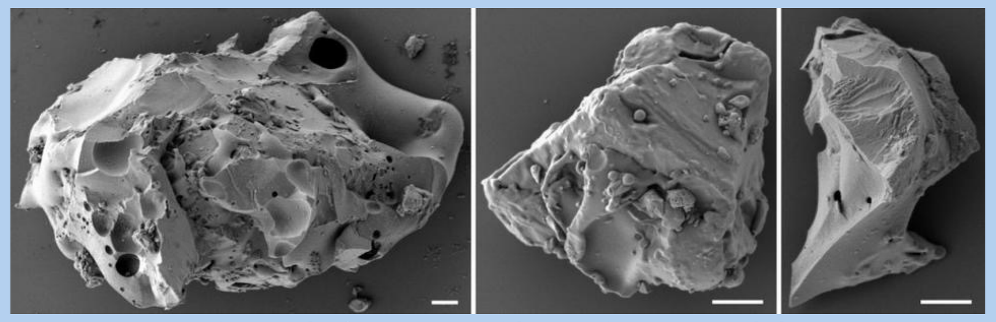
Avi Waghray [a], Caleb Thompson [a], Joanna Fnu [a], Justin Astacio [a], Luizandrei Galanida [a], Maximus Mendez [a], Miquela Smith [a], Tristan Ahuna [a], Zeba Momin [a], Seetha Raghavan [b]

a C.R.A.T.E.R. Team Member
b Faculty Advisor

Introduction

Lunar regolith has been problematic since the Apollo missions, causing false instrument readings, clogged mechanisms, and damaged thermal control systems. Many solutions have been proposed but have failed due to weight, cost, and effectiveness. Effective mitigation strategies are crucial for the safety and integrity of HLS assets, ensuring equipment durability and mission success on the lunar surface. Our focus is on developing lightweight, cost-effective solutions while providing reliable protection against the abrasive nature of lunar regolith. [1,2]

a.



a. Micrograph of Lunar Dust with one micrometer scale bar

Methods for Mitigating Effects of Lunar Regolith

Criteria\Method	Surface Coatings	Brushes and Seals	Self Cleaning Surfaces	Electrodynamic Dust Shield	Lunar Landing Pads
Surface Adhesion Resistance	Medium-High	Medium	High	Low-Medium	High
Impact Resistance	Medium	Low-Medium	Medium	Low	High
Abrasion Resistance	Medium-High	Medium-High	Medium	Low	High
Manufacture Difficulty	Medium	Medium	Medium	Medium-High	Medium-High
Cost	Medium	Medium	Medium-High	Low	Medium-High
Complexity	Medium	Low-Medium	Medium-High	High	Medium
Effectiveness	Medium	Medium	High	High	High

Priorities for Solution - Surface Coatings for Passive Mitigation
Surface Adhesion Resistance - Biomimetic Pattern
Impact & Abrasion Resistance – Engineered Ceramics

Motivation and Objective

Motivation

During HLS operation, lunar regolith presents several challenges:

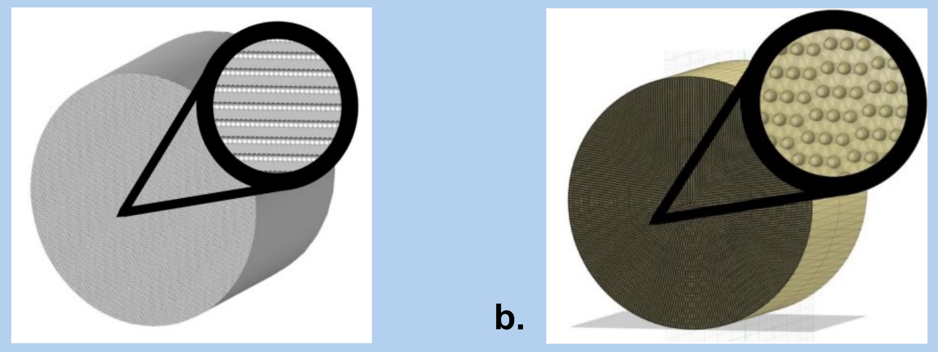
- Decreases the structural integrity of lander/nearby structures, and thermal control systems.
- Causes false readings on instrumentation.
- Inhibits visibility through windows and lenses.

Objective

- Determine the efficacy of ceramics to passively mitigate lunar regolith adhesion while promoting impact and abrasion resistance by manufacturing and testing bio-inspired patterns using ceramics.

Ceramic Coatings & Biomimetic Patterns

- Ceramics and ceramic coatings are highly resistant to abrasion and wear [3].
- Bio-inspired surface modifications can reduce regolith adhesion, enhance abrasion resistance, and reinforce durability. Some of these patterns are inspired by Lotus leaves and Desert Beetles [4,5].
- Utilizing laser ablation on cold sprayed ceramics coatings allows for bio-inspired patterns to be etched.
- Lithography-based manufacturing enables the additive manufacture of ceramic tiles integrated with these advanced patterns. There is potential for printing of transparent ceramics to meet application needs [6].



a. b.

a. C.R.A.T.E.R's CAD rendering of Beetle Pattern
b. C.R.A.T.E.R's CAD rendering of Lotus Leaf Pattern

Materials, Manufacturing and Experimental Setup

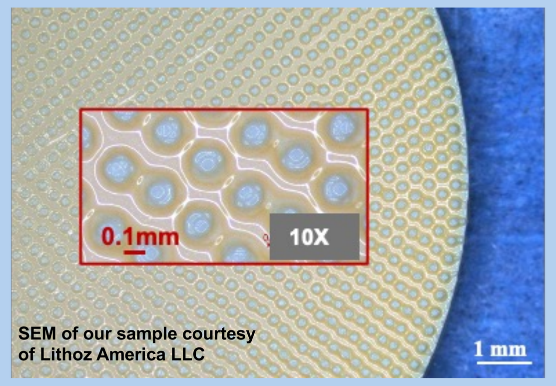
Lunar Regolith

Bulk Chemistry	
Oxide	LSP-1D (Wt%)
SiO2	47.13
TiO2	0.16
Al2O3	27.96
FeO	1.24
MnO	0.02
MgO	0.71
CaO	17.50
Na2O	4.02
K2O	0.42
P2O5	0.83
Total	~100

Minerology	
Component	LSP-1D (Wt%)
Anorthosite	90
Glass-rich Basalt	10

LSP-1D lunar south pole simulant were used for tests

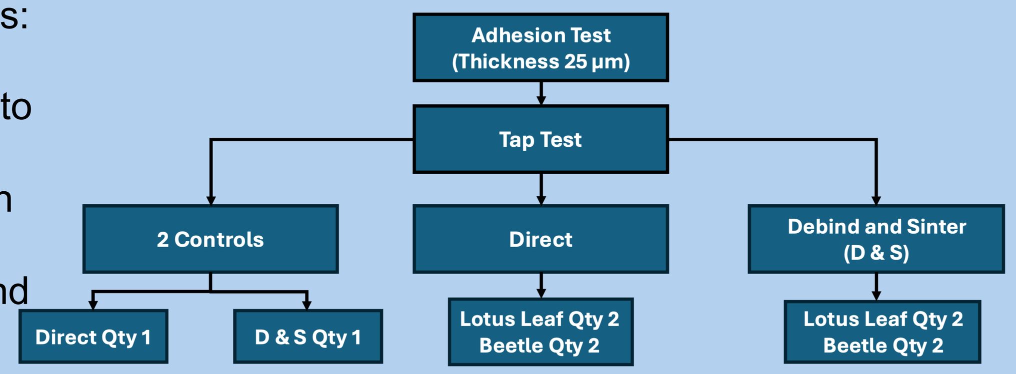
3D Printed Ceramic with integrated patterning



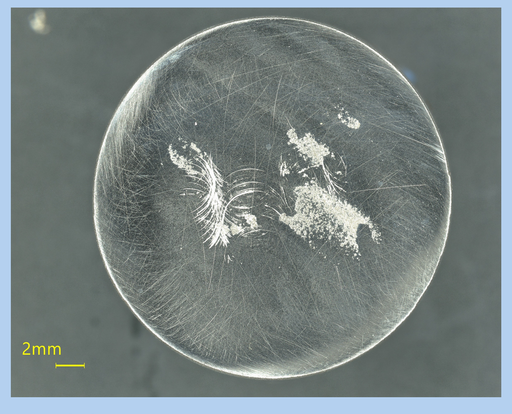
3D printed Lotus leaf pattern using Alumina

Samples were sintered in 2 ways:
1) **Debind and Sinter (D&S):** Initially slow heated and cooled to remove binder, then rapidly heated and held for 2 hours then air cooled
2) **Direct (D):** Rapidly heated and held for 2 hours then air cooled

Adhesion Tap Tap Test Sample Tree



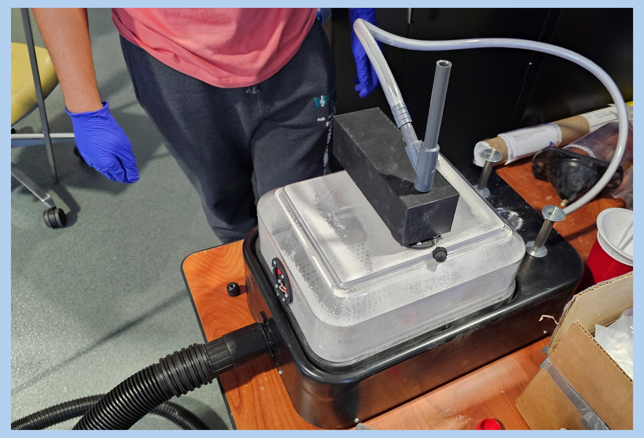
Cold Spray and Laser Patterning



Cold Sprayed WC-Co Sample

Cold Spray process utilizes a high-pressure carrier gas to accelerate heated metal powders through a supersonic nozzle to provide a thin layered coating. **Laser patterning** uses a pulsed laser of high power to etch the coating. The UV laser marker was unable to etch the pattern on the WC-Co coating due to low power.

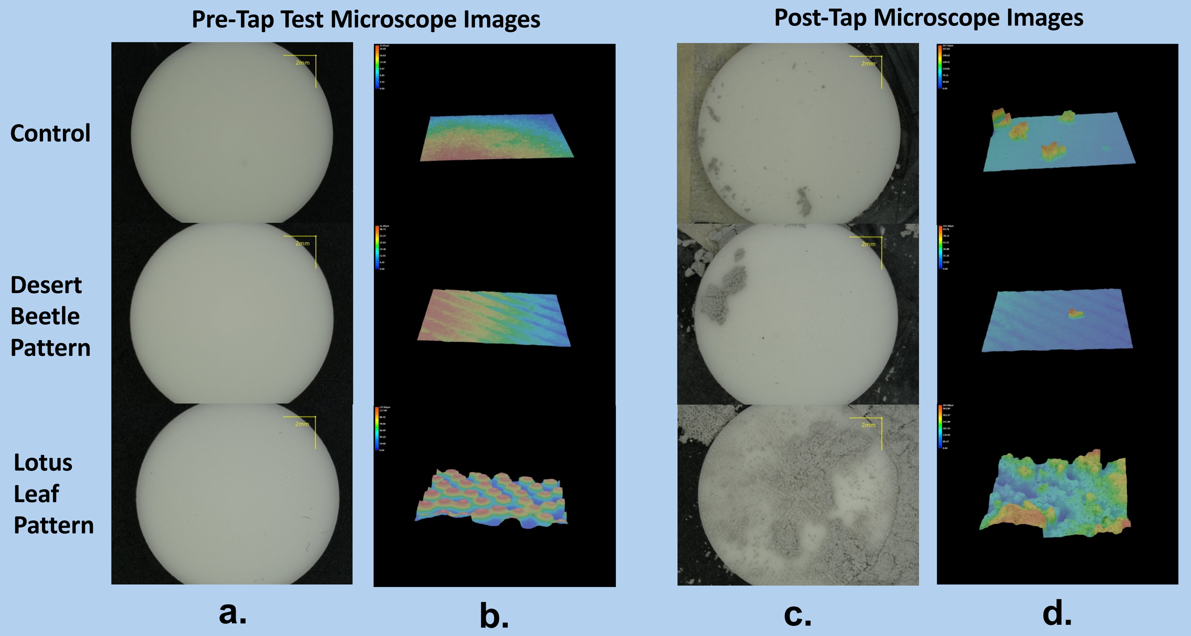
Impact and Abrasion Test Setup



The team modified a grit blaster with simulant feed to evaluate impact and abrasion resistance of WC-Co cold spray coating

Results of Adhesion, Impact and Abrasion Tests

Adhesion Test Results on 3D printed Alumina Samples



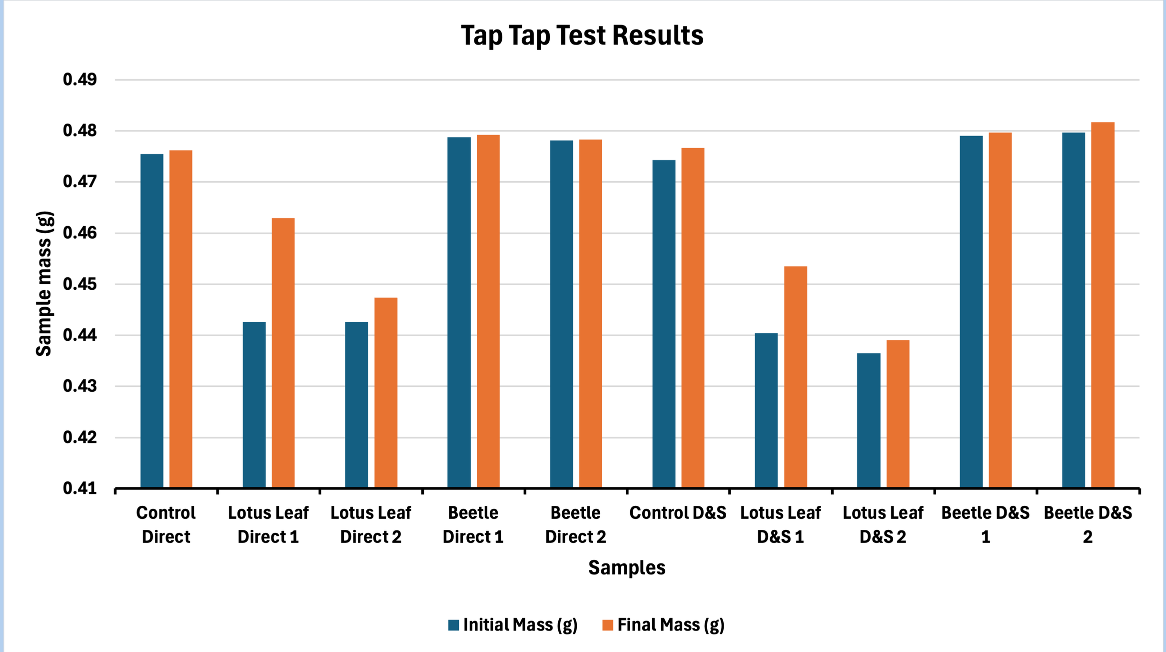
Columns a. & c. – 20 x Magnification, 2D image of samples (Control, Beetle, Lotus)

Columns b. & d. – 200 x Magnification, 3D images of samples (Control, Beetle, Lotus)

Pre-tap test pristine sample images **Post-tap test sample images**

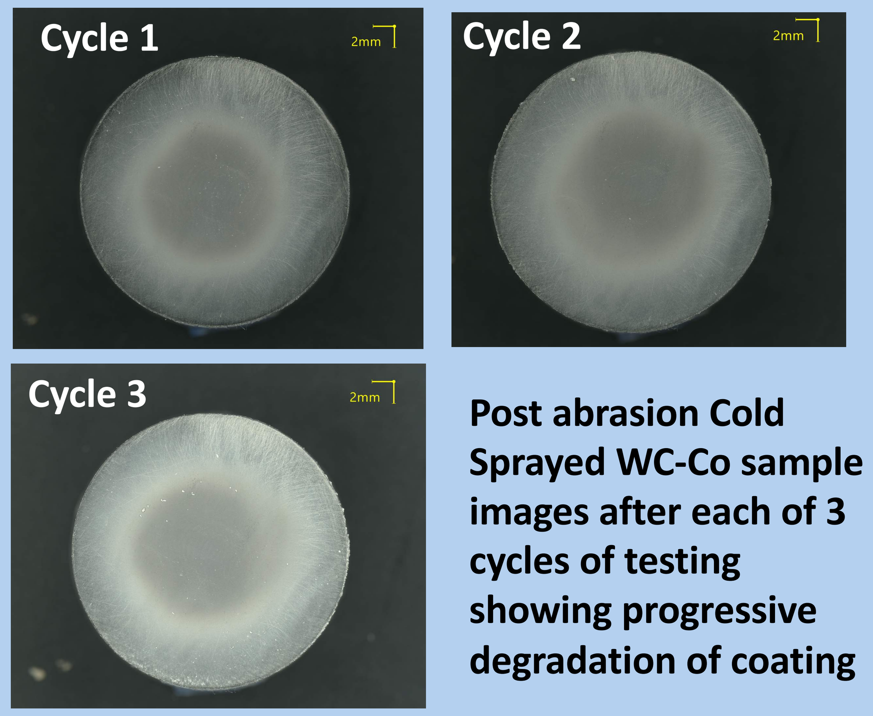
Results of Tap Tap Test

- Lotus Leaf trapped regolith particles between pillars leading to high adhesion rates
  - Lack of nano pillars, spacing of micro pillars and increased cohesion are main contributing factors of outcome
- Beetle and Control had much lower adhesion rates



Change in mass of 3D printed ceramic samples after Tap Tap Test

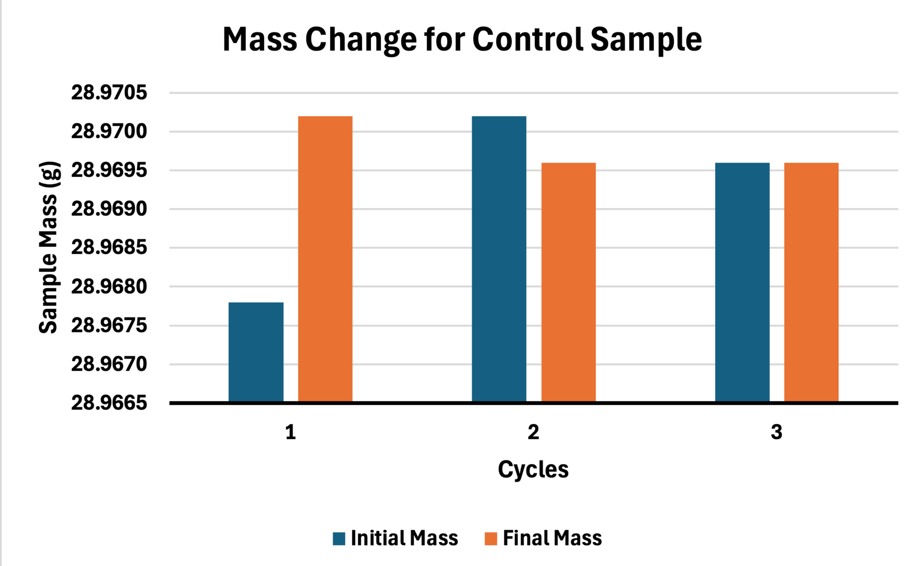
Impact and Abrasion Test Results on Cold Spray WC-Co Sample



Post abrasion Cold Sprayed WC-Co sample images after each of 3 cycles of testing showing progressive degradation of coating

Results of Grit Blaster Test

- Cycle 1: Mass increase of 0.0024 g due to simulant adhering to surface
- Cycle 2: Mass loss of 0.0006 g as mass of material abraded greater than simulant adhered
- Cycle 3: No significant change in mass as equal amounts of simulant adhered and mass abraded



Mass change after cycles of Abrasion

Conclusions

Adhesion Testing of 3D printed Bio-inspired patterns

- Desert Beetle Pattern had the lowest regolith adhesion.
- Lotus Leaf Pattern had the highest regolith adhesion due to micro pillar trapping and clumping.
- Test is not fully representative of real-world scenarios; more comprehensive adhesion testing is needed.
- Minimal mass difference between direct and debind sintering suggests direct sinter is sufficient for large-scale production.

Impact and Abrasion testing of Cold-sprayed WC-Co coatings

- Mass measurements showed material loss primarily in the first two cycles.
- Images indicated increasing surface roughness and material displacement.
- Color intensity analysis revealed changes in surface texture.
- Findings validate WC-Co coating's resistance to abrasion and highlight the necessity of surface modifications for enhanced durability.

Future Work

Taber Abraser Testing

- How a high number of abrasion cycles affects the surface integrity of the coating.

Centrifuge Adhesion Testing

- Determine the adhesion rate of the coating through and advanced testing using a centrifuge.

Temperature Testing

- Verify and validate temperature ranges the coating simulating the typical lunar environment.

Chemical Resistance Testing

- Verify and validate the chemical resistance of the coatings.

Acknowledgements & References

Acknowledgements:

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References:

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[6] Zhang, G., & Wu, Y. (2021). Three-dimensional printing of transparent ceramics bylithography-based digital projection. Additive Manufacturing, 47, 102271.