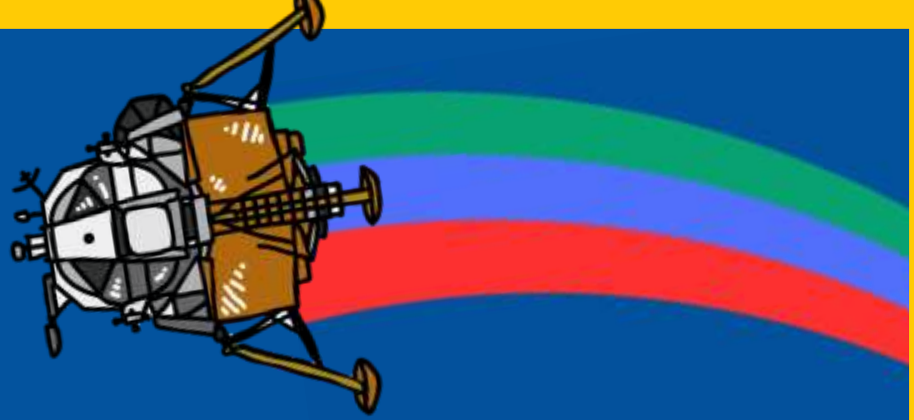
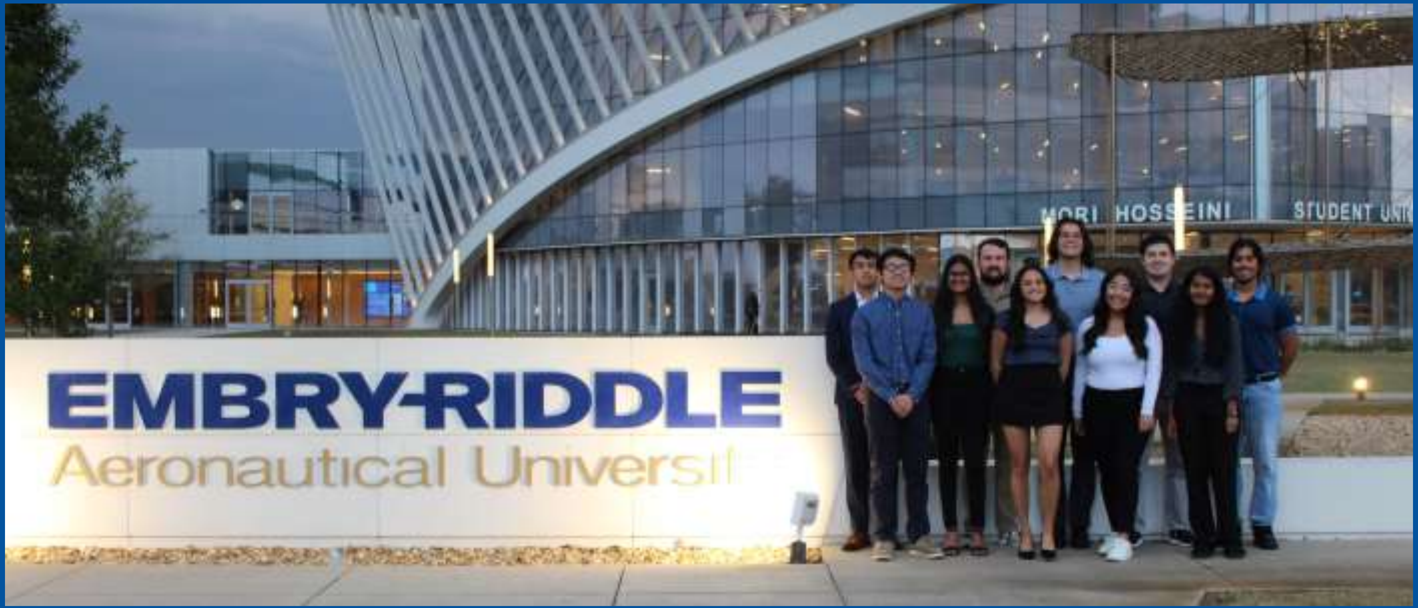


C.R.A.T.E.R.

Ceramic Research Advancement Technology at Embry-Riddle

Team Introduction



EMBRY-RIDDLE
Aeronautical University

- Avi Waghray (Secretary)
- Luizandrei Galanida
- Zeba Momin
- Caleb Thompson (Sub-Team Lead)
- Miquela Smith (Team Lead)
- Maximus Mendez (Financial Team Lead)
- Tristian Ahuna
- Joanna Fnu (Testing Coordinator)
- Justin Astacio (Sub-Team Lead)
- Dr. Seetha Raghavan (Advisor)

Table of Contents

Problem Statement & Solution

Problem Statement & Background

NASA Challenge Proposal Category:

- Liberated regolith during PSI or ejecta impacts can lead to a loss of instrumentation performance, landing visibility, and damage to lander/surrounding structure.

Background:

- Lunar regolith has been problematic since the Apollo missions, causing false readings in instruments, clogging mechanisms, and damaging thermal control systems.
- Effective strategies for mitigating lunar regolith are crucial to ensure the safety and integrity of HLS assets.

Our Assumptions:

- Mission Time: 1 Week (Artemis III – NASA).
- Lunar Landers: SpaceX Starship HLS, Blue Origin Blue Moon Mark 2.
- Substrate Materials: Al-6061, A-286 stainless steel.
- Temperature: 50K-225 K.
- Landing Site: Lunar South Pole.
- UV/Solar Radiation Exposure: 7 mSv.
- UV/Solar Irradiance: 1361 W/m^2.

Problem Statement & Background

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

Proposed Solution

Passive Lunar Regolith Damage Mitigation via Surface Coatings

Cold Spray & Laser Texturing

- Enhance preexisting surface characteristics with tungsten carbide cobalt (WC-Co).
  - Improved abrasion and impact resistance
- Effectively works on various materials (ceramics, metals, polymeric materials).
- Manipulate cold spray surface with laser ablation
- Etch biomimetic patterns in a subtractive. manufacturing process to promote adhesion and abrasion resistance.

Potential Benefit: Improve impact and abrasion resistance of preexisting surfaces with minimal mass and cost addition.

Ceramic 3D Printing

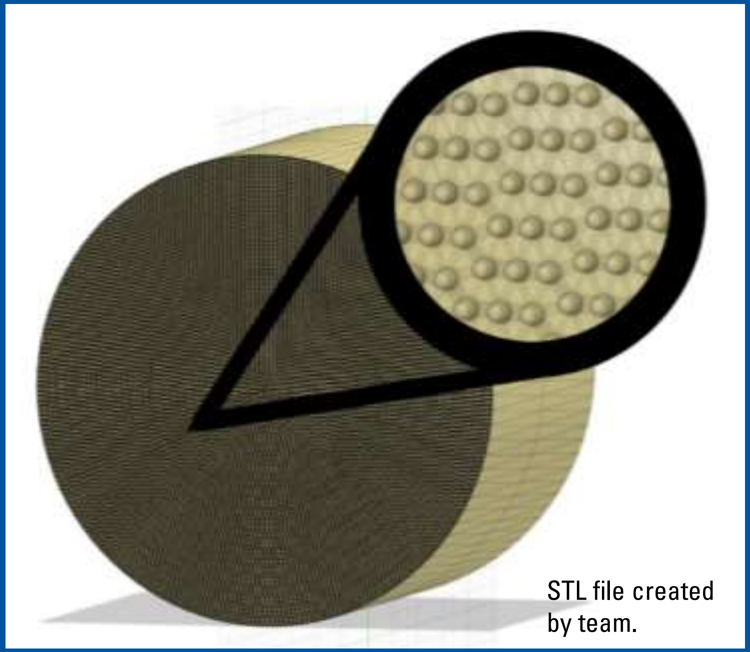
- Additively manufacture ceramics such as alumina (Al_2O_3) with microscale features for improved abrasion resistance.
- The integration of highly detailed biomimetic patterns in the print promotes adhesion resistance while providing ease of manufacturing.
- 3D printing offers versatility in pattern and materials design.

Potential Benefit: Produce highly detailed tiles with biomimetic patterns using ceramics. capable of creating transparent ceramics for windows and lenses.

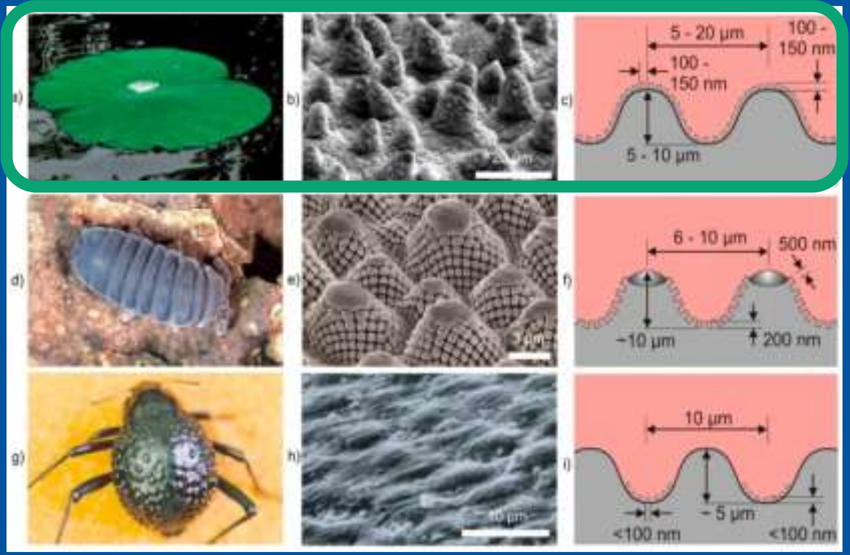
Technological Approach

Lotus Leaf Pattern

- The utilization of the Lotus Leaf pattern:
  - Purpose:
    - The shape of the microstructure increases the surface energy of any adhered material (Lotus Effect).
  - Challenges:
    - The nano pillars on the microstructure present on lotus leaves further increases this effect but is not possible to reproduce with current manufacturing methods.
    - Creating accurate models of the microstructure for manufacturing is very hardware intensive.
- Our goal is to create the Lotus Leaf microstructure using WC-Co:
  - Purpose:
    - The WC-Co provides a high resistance to surface deformation due to its hardness.
  - Challenge:
    - Due to this hardness, it is difficult to create patterns on its surface through subtractive methods.



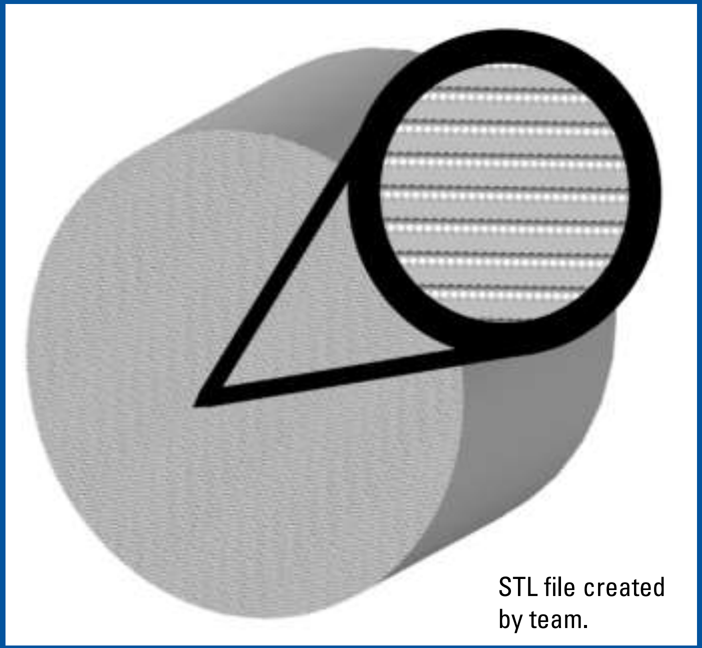
STL file created by team.



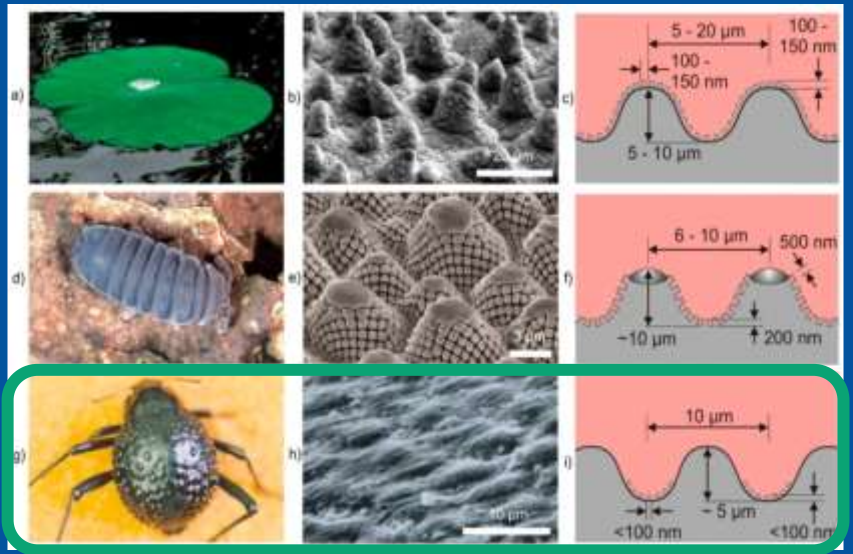
Müller FA, Kunz C, Gräf S. Bio-Inspired Functional Surfaces Based on Laser-Induced Periodic Surface Structures. Materials (Basel, Switzerland). 2016 Jun;9(6):E476. DOI: 10.3390/ma9060476. PMID: 28773596; PMCID: PMC5456748.

Desert Beetle Pattern

- The utilization of the Desert Beetle pattern:
  - Purpose:
    - The microstructure creates hydrophobic regions that help minimize wear.
  - Challenge:
    - Creating accurate models of the microstructure for manufacturing is very hardware intensive.
- Our goal is to create the Desert Beetle microstructure using WC-Co:
  - Purpose:
    - The WC-Co provides a high resistance to surface deformation due to its hardness.
  - Challenge:
    - Due to this hardness, it is difficult to create patterns on its surface through subtractive methods.



STL file created by team.



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Materials & Manufacturing Methods

Tungsten Carbide-Cobalt:
Hardness: Vickers 2,600.
Melting Point: 5,200 °F.
Young's Modulus: 530 GPa.
Density: 15.6 g/cm^3.

Alumina:
Hardness: Vickers 780.4.
Melting Point: 3,762 ° F.
Young's Modulus: 413 GPa.
Density: 3.68 g/cm^3.

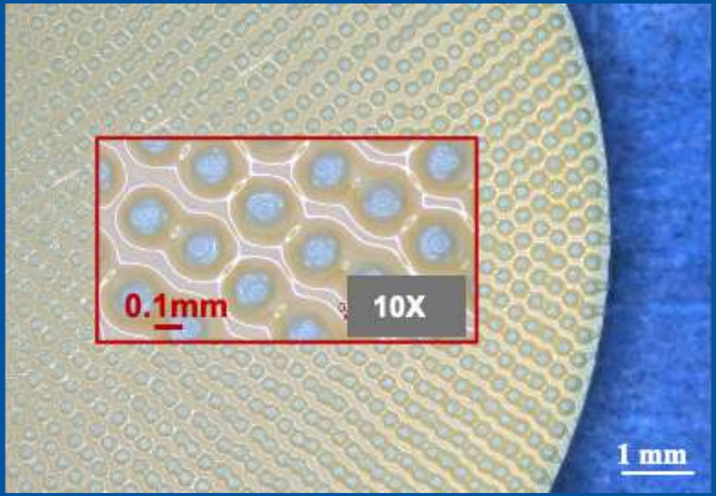
Subtractive Manufacture Approach:

- Cold spray WC-Co to be etched via laser ablation.
  - Utilized a high-pressure carrier gas to accelerate heated metal powders through a supersonic nozzle.
  - Laser patterning through Keyence UV Laser Marker.

Additive Manufacturing Approach:

- 3D Printed ceramic tiles using a typical ceramic, alumina.
- 2 pattern thicknesses: 25 micron (tested) and 10 micron.
- 12.7 mm diameter and 1 mm thickness.

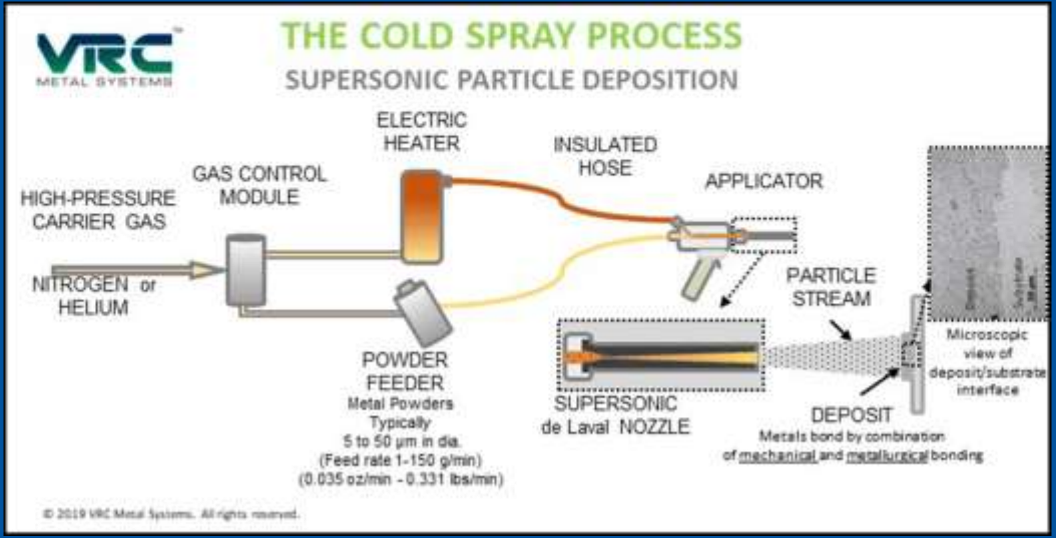
WC-Co Cold Sprayed sample.



SEM image of our 3D printed sample courtesy of Lithoz America LLC.

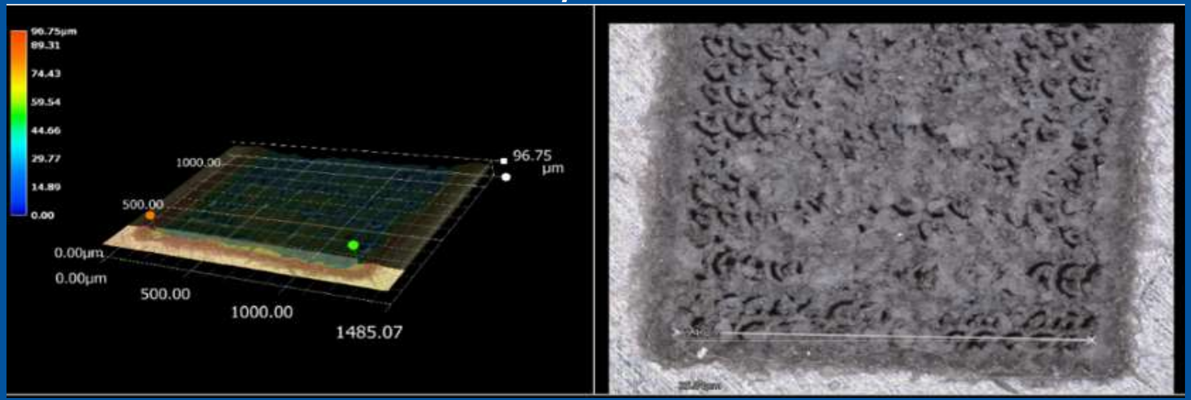
Cold Spray and Laser Patterning

- Cold-spray is a solid-state material deposition process.
- Capable of producing a thin layer of about ~254 µm coating of WC-Co.
- Samples were coated for abrasion testing.



What is Cold Spray?, VRC Metal Systems, https://vrcmetalsystems.com/what-is-cold-spray/

- Laser patterning utilized to augment the surface of the coating with micro-scale patterns.
- Keyence 3 Axis UV Laser Marker run at 2W power was found to be insufficient for patterning WC-Co, a much higher-powered nano pulsed laser is required.
- A trial run was done on bare Al-6061 sample and showed material removal resulted in debris which recrystallized.

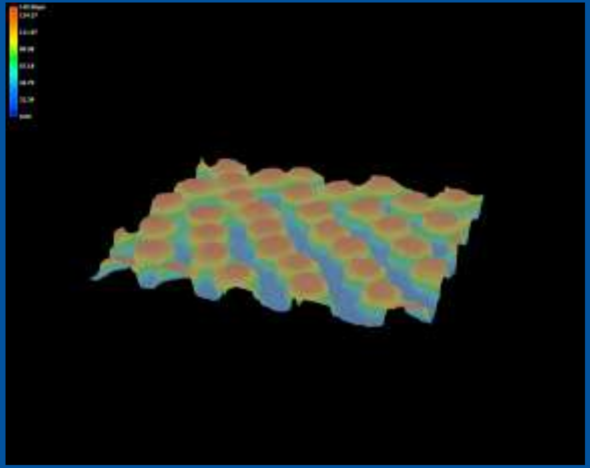


Trial Laser marking on Al6061 demonstrated debris formation affected patterning.

Ceramic 3D Printing

- Lithography-based ceramic manufacturing (LCM) supported by Lithoz:
  - Uses organic binder and ceramic powder to be printed and photocured.
  - Next step was to then sinter to make final product.
- Samples were chosen to be made using a typical ceramic, Alumina (Al_2O_3).
- 2 sintering methods: one step direct (D) and two step debind & sinter (D&S):
  - Direct:
    - Rapidly heat to 1650 °C, hold for 2 hours, then let air cool.
  - Debind and Sinter:
    - Slow heat to 1100 °C, then to room temperature to remove binder.
    - Rapidly heat to 1650 °C, hold for 2 hours, then let air cool.

Lithoz GmbH. (n.d.). CeraFab Multi 2M30. Retrieved June 17, 2024, from https://lithoz.com/en/3d-printer/cerafab-multi/



3D Imaging Scan of Lotus Leaf Patterning of our 3D Printed Ceramic taken with VHX microscope.

Testing

Testing Overview

- Lunar Simulant
  - LSP-1D
- Adhesion Testing
  - Tap-Tap Test
- Impact and Abrasion Testing
  - Grit Blaster Test

LSP-1D Lunar Simulant

- LSP-1D was chosen over LMS-1D and LHS-1D for having the closest minerology and chemical composition to the regolith found on the Lunar South Pole.
  - LSP-1D maintains the same particle size range of 0.04 µm – 30 µm as LMS-1D and LHS-1D with a mean particle size of 5.82 um.
  - LSP-1D has the closest anorthosite and glass-rich basalt weight percentages to South Pole regolith.
  - LSP-1D best aligns to most of South Pole regolith's major and minor oxides.

Bulk Chemistry				
Oxide	LSP-1D (Wt%)	LHS-1D (Wt%)	LMS-1D (Wt%)	South Pole Regolith (Wt%)
SiO2	47.13	51.20	46.90	45.00
TiO2	0.16	0.60	3.60	0.50
Al2O3	27.96	26.60	12.40	28.00
FeO	1.24	2.70	8.60	2.00
MnO	0.02	0.10	0.20	0.03
MgO	0.71	1.60	16.80	0.70
CaO	17.50	12.80	7.00	18.00
Na2O	4.02	2.90	1.70	4.00
K2O	0.42	0.50	0.70	0.45
P2O5	0.83	0.10	0.20	0.90
Total	~100	~100	~100	~100

Minerology				
Component	LSP-1D (Wt%)	LHS-1D (Wt%)	LMS-1D (Wt%)	South Pole Regolith (Wt%)
Anorthosite	90	74.4	19.8	85
Glass-rich Basalt	10	24.7	32	15

Lunar simulants' data obtained from Exolith Lab fact sheets. South Pole regolith data sourced from NASA research.

Adhesion: Tap-Tap Test Method

The NASA publication 'Low-cost Testing in Representative Lunar Regolith Environment' served as a model for this experiment. (Microsoft Word - 20220016406PROPOSEDFINALTOAUTHORS.docx (nasa.gov))

- Purpose:
  - This experiment helps in evaluating the adhesion level of the various surface modification.
- Variables:
  - Independent: Surface modifications (none, Lotus Leaf, Desert Beetle).
  - Dependent: Mass change, surface roughness.
  - Control: Simulant amount, uniform simulant application, tapping frequency, testing environment.
- Procedure:
  - Use the VHX digital microscope to conduct imaging scans.
  - Use of a weighing scale with a precision of 0.1mg.
  - 5 g of regolith was determined to be used in each trial. It was also made sure that the regolith covered the mesh completely.
  - Uniform distribution of the regolith with the help of sieves whose mesh sizes include 0.074mm, 0.18mm, and 2mm.
  - Sample is vertically placed and tapped twice.
  - The samples are then again weighed and imaged to assess the adhesion level.

Testing setup in vacuum hood.

Impact and Abrasion: Grit Blaster Test Method

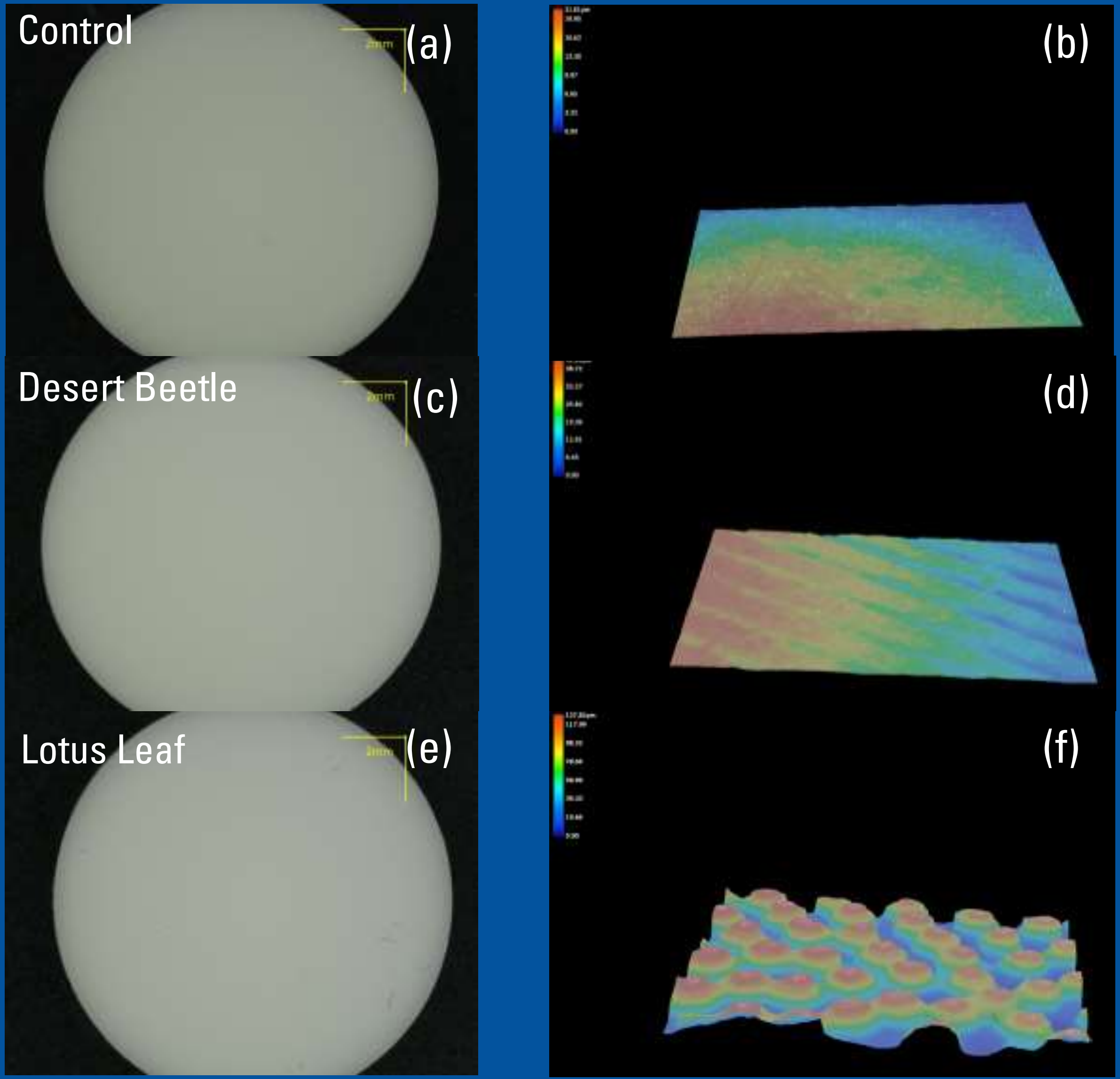
- Variables:
  - Independent: Surface material (WC-Co cold sprayed coating).
  - Dependent: Mass change, surface roughness.
  - Control: Simulant amount, brushing procedure, testing environment.
- Procedure:
  - Weigh sample using precision scale.
  - Capture high-resolution images with VHX microscope.
  - Blast the 1-inch diameter, cold-sprayed sample with 50g simulant using the MicroLux Grit Blaster and Stinger 2.5 L wet/dry vacuum.
  - Brush off the coated-side of the sample 3 times and its sides and bottom surfaces until no visible simulant.
  - Weigh blasted sample.
  - Capture same high-resolution images.
  - Repeat for a total of three cycles.

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

Testing setup of the grit blaster modified with a vacuum and LSP-1D feed with 3D-printed support.

Results & Analysis

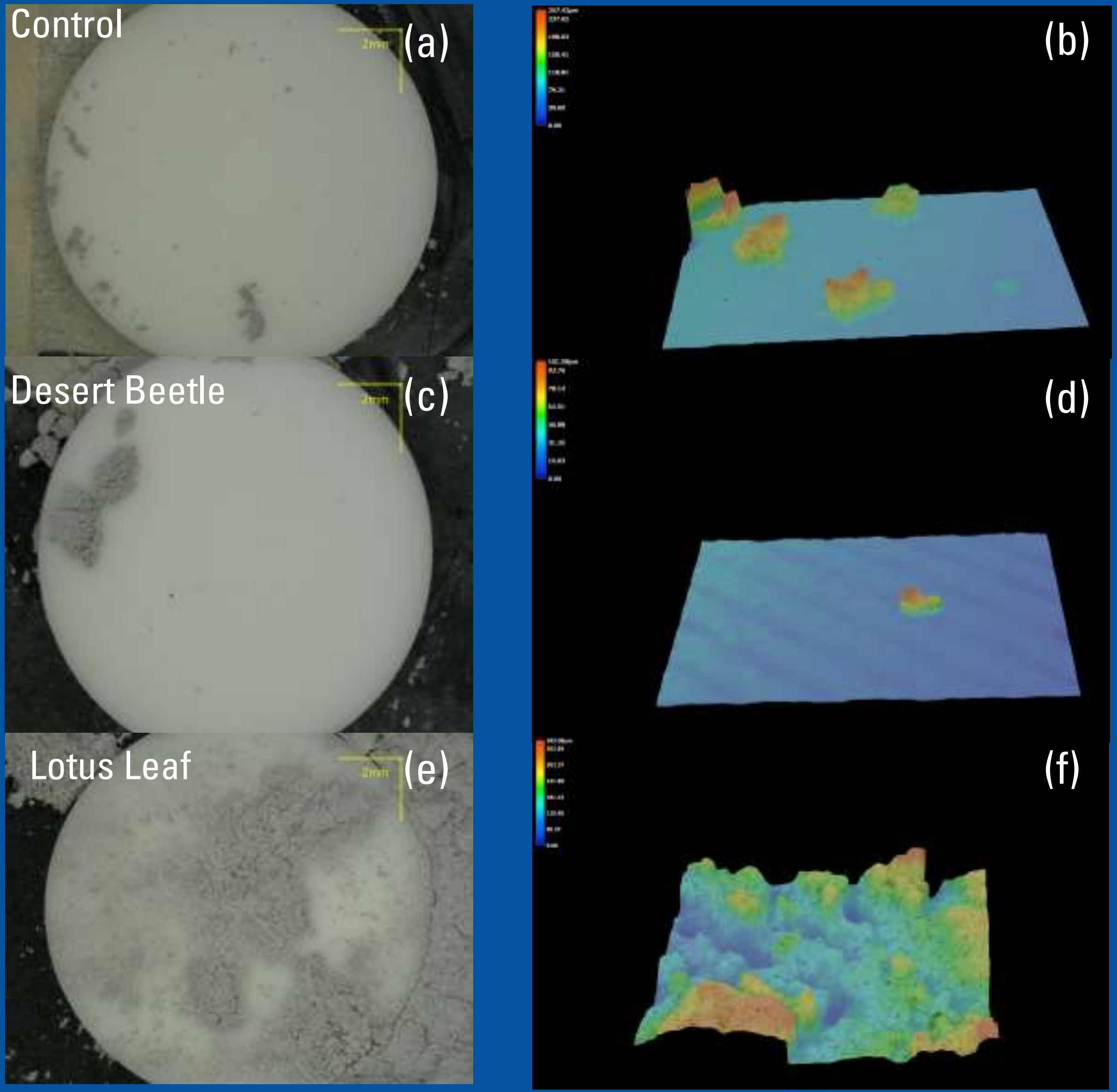
Pre-Tap test Microscope Analysis for Adhesion



- Images taken using a Keyence VHX7000 microscope.
- Samples show pristine surfaces with small height gradient.
  - Does not affect relative height difference in local areas.
- Lotus Leaf more pronounced than Beetle.
  - May be effect of sintering process.
- Lotus Leaf peaks appear slightly flattened more representative of mounds.
  - May be effect of printing.
  - Profilometer measurements in future.

Legend (all debind sintered Images captured by VHX Microscope):
(a) 20X, 2D image of Control.
(b) 200X, 3D color map image of Control.
(c) 20X, 2D image of Desert Beetle Pattern.
(d) 200X, 3D color map image of Desert Beetle.
(e) 20X, 2D image of Lotus Leaf Pattern.
(f) 200X, 3D color map image of Lotus Leaf Pattern.

Post-Tap Test Microscope Analysis for Adhesion

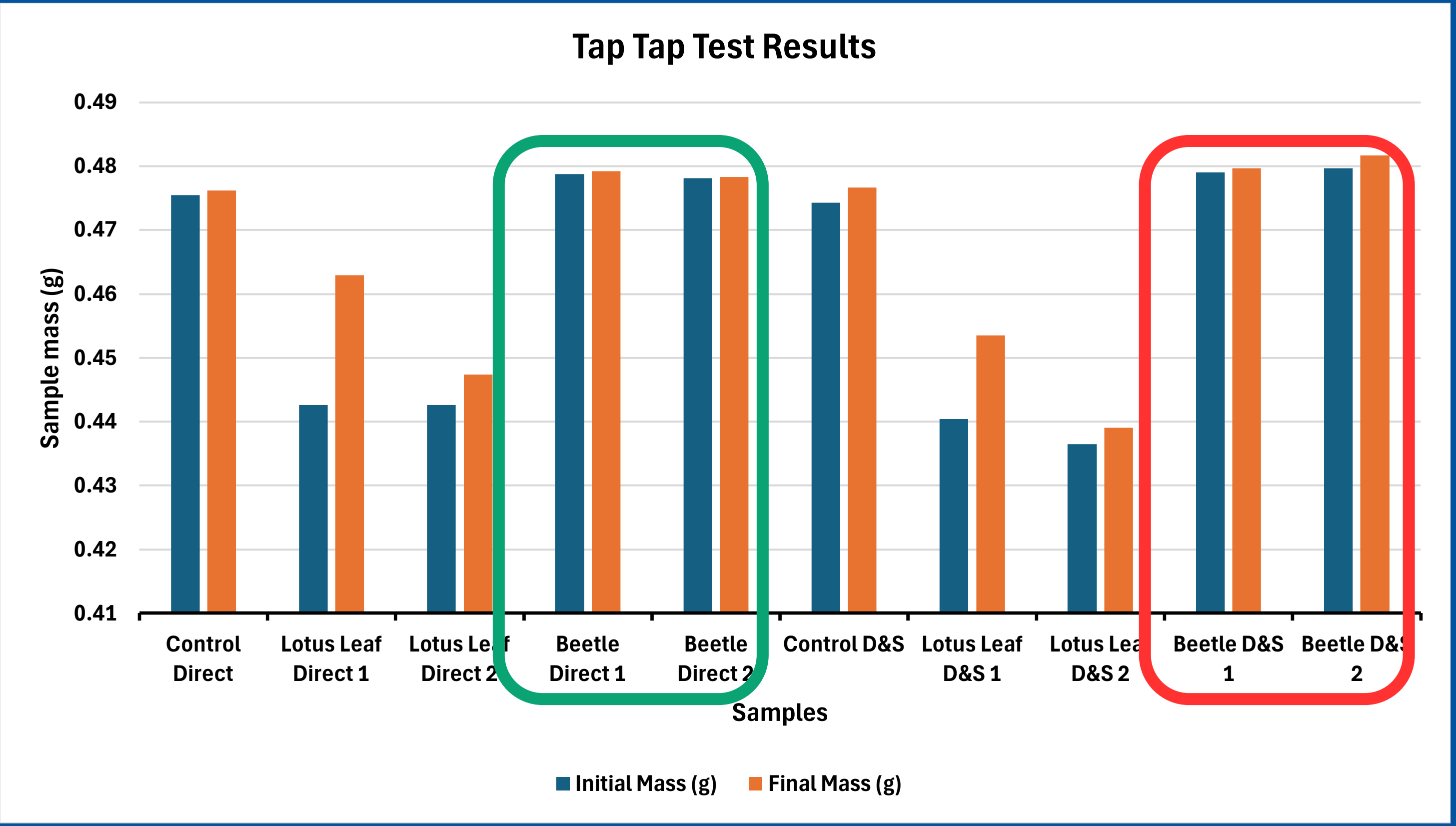


- All samples have some level of adhesion; however, clumps were formed due to cohesion of regolith.
- Control sample and Beetle sample had low adhesion compared to other images.
- Simulant particles may have been too large to get stuck in Beetle pattern.
- Lotus Leaf has highest level of visible adhesion mainly attributed to particles getting stuck between pillars.
  - Decrease in distance between pillars may allow for better future results.
  - Lack of nano pillars, spacing and height of micro pillars and increased cohesion are main contributing factors of outcome.

Legend (all debind sintered Images by VHX Microscope):
(a) 20X, 2D image of Control.
(b) 200X, 3D color map image of Control.
(c) 20X, 2D image of Desert Beetle Pattern.
(d) 200X, 3D color map image of Desert Beetle.
(e) 20X, 2D image of Lotus Leaf Pattern.
(f) 200X, 3D color map image of Lotus Leaf Pattern.

Tap-Tap Test: Mass Measurements for Adhesion

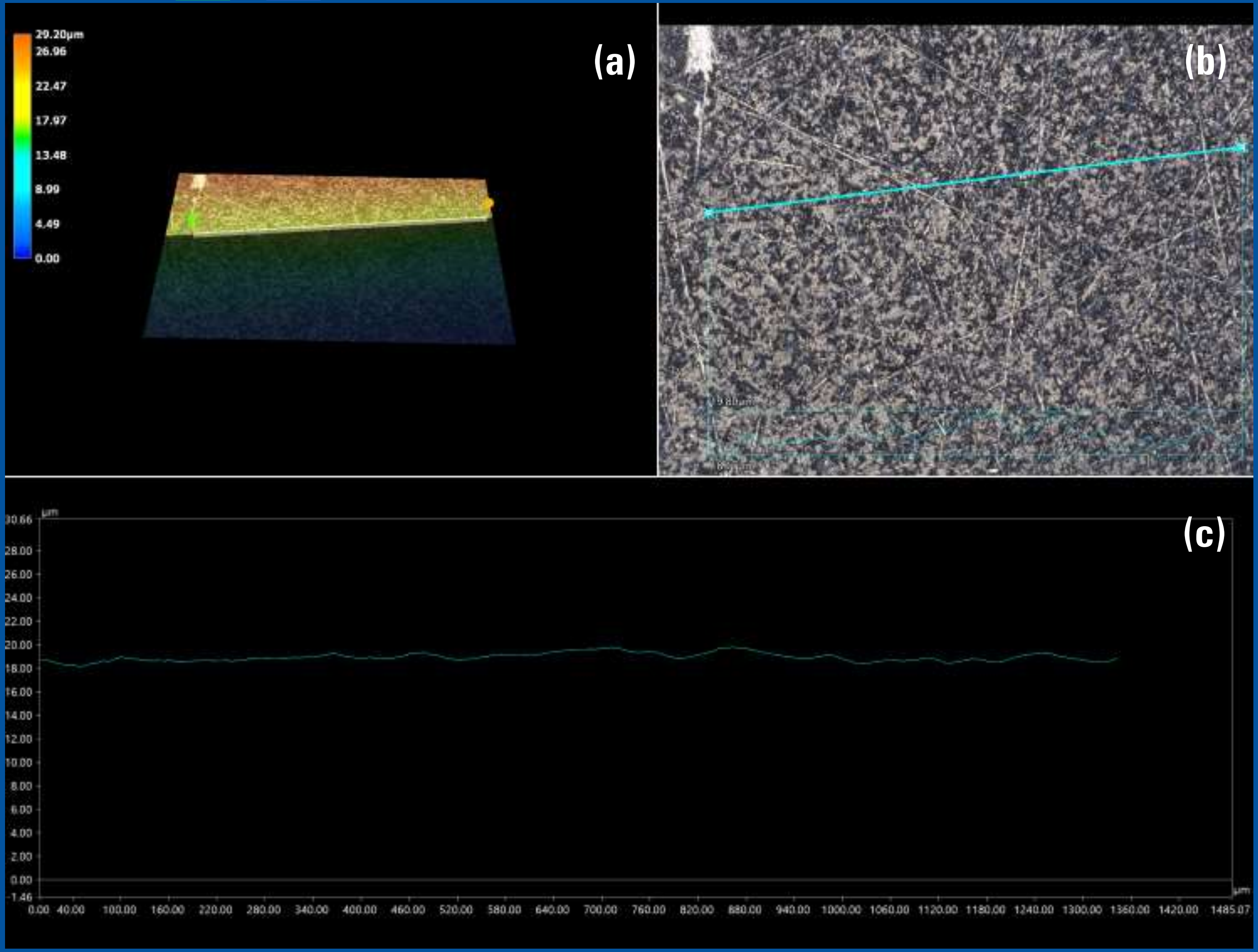
- The control sample added mass was less than 0.003 g.
- Lotus Leaf pattern added mass ranged from 0.05 to 0.02 g.
- The Desert Beetle (Beetle) pattern added mass was less than 0.003 g.
- Beetle pattern and control performed better than Lotus Leaf pattern.
- Minimal mass difference between direct and debind sintering suggests direct sinter is sufficient for large-scale production.



Mass measurements indicated inconsistent variations in mass addition between the two patterning samples which is likely due to the inconsistency of the Tap-Tap test. The high mass of regolith added led to cohesion effects being more present than adhesion. A more advanced and accurate test is needed for adhesion assessment.

Grit Blaster Results: Pre-Blast Depth Composition

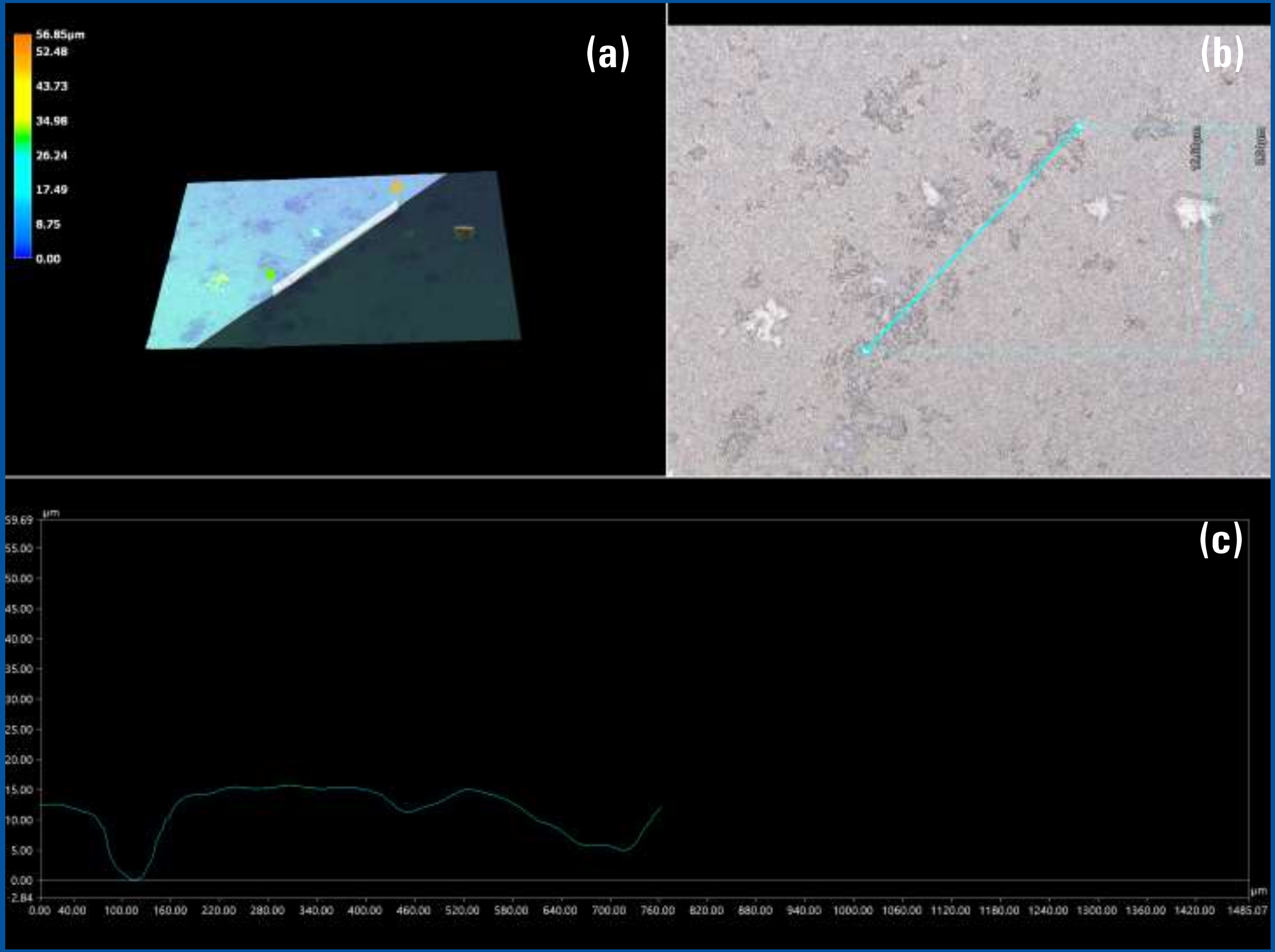
- As coated samples measured from the surface of the coating, there exist a relatively smooth surface with an average surface roughness of ~19 µm across the entire cross section.



Legend (applies to all depth composition images):
(a) 200x, 3D color map image highlighting the lighted and shadowed sides separated by a cross-sectional line.
(b) 200x, 2D image of the coated surface featuring an imaginary line indicating the depth profile for the cross-section; Shows the highest and lowest surface elevations for that cross-section.
(c) Illustrates the surface contour and elevation variations.

Grit Blaster Results: Post-Cycle 1 Depth Composition

- After Cycle 1, measured from the surface of the coating, there exists initial signs of surface roughness and wear.
- Pits near 0 µm indicate heavy areas of abrasion close to the baseline surface level.
- Even surface around 15 µm suggests areas retaining some of the coating's texture pre-abrasion.

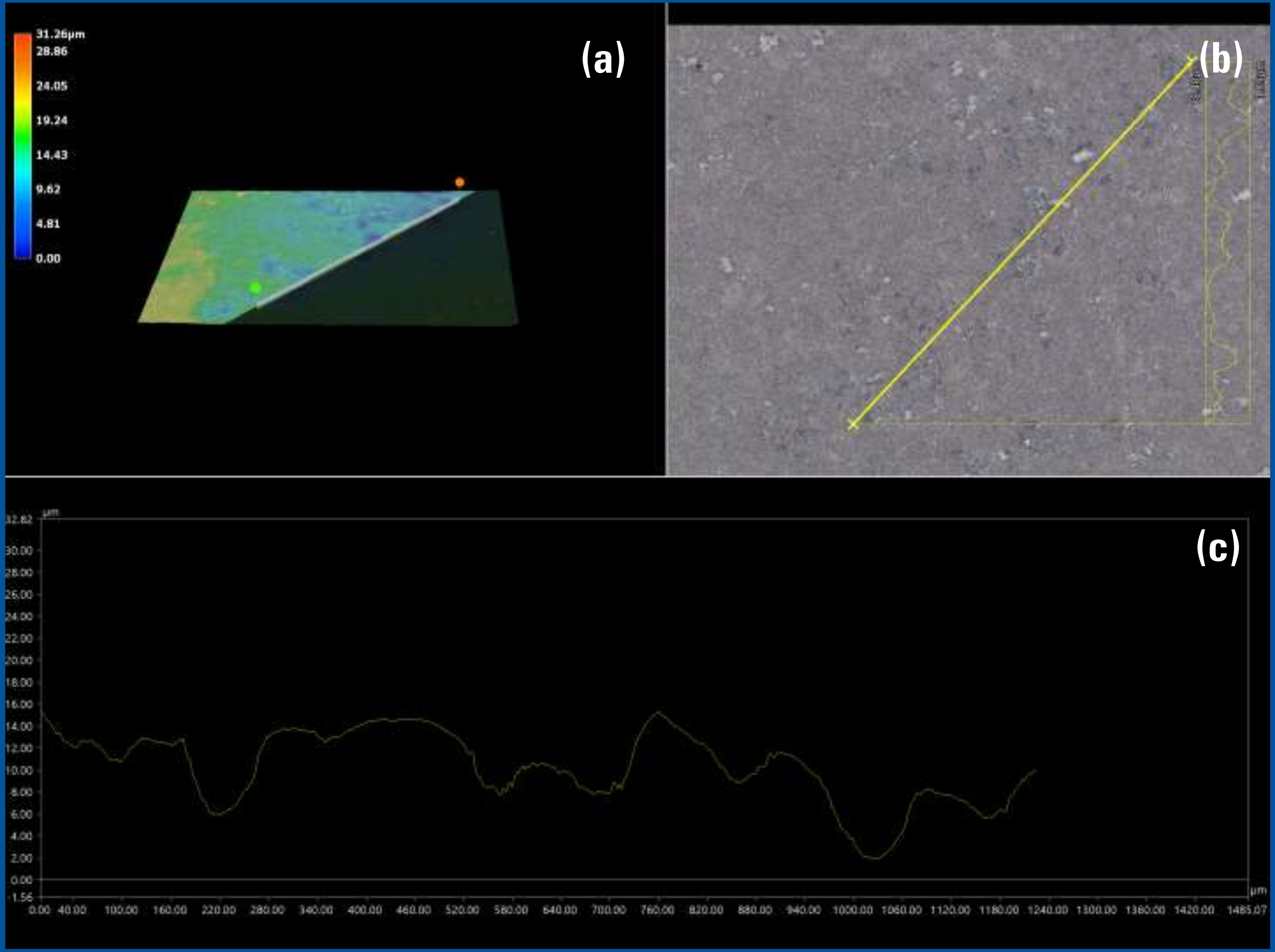


Grit Blaster Results: Post-Cycle 2 Depth Composition

- After Cycle 2, measured from the surface of the coating, there exists increased surface irregularities and deeper pits.

- Pits near 0 μm indicate heavy areas of abrasion.

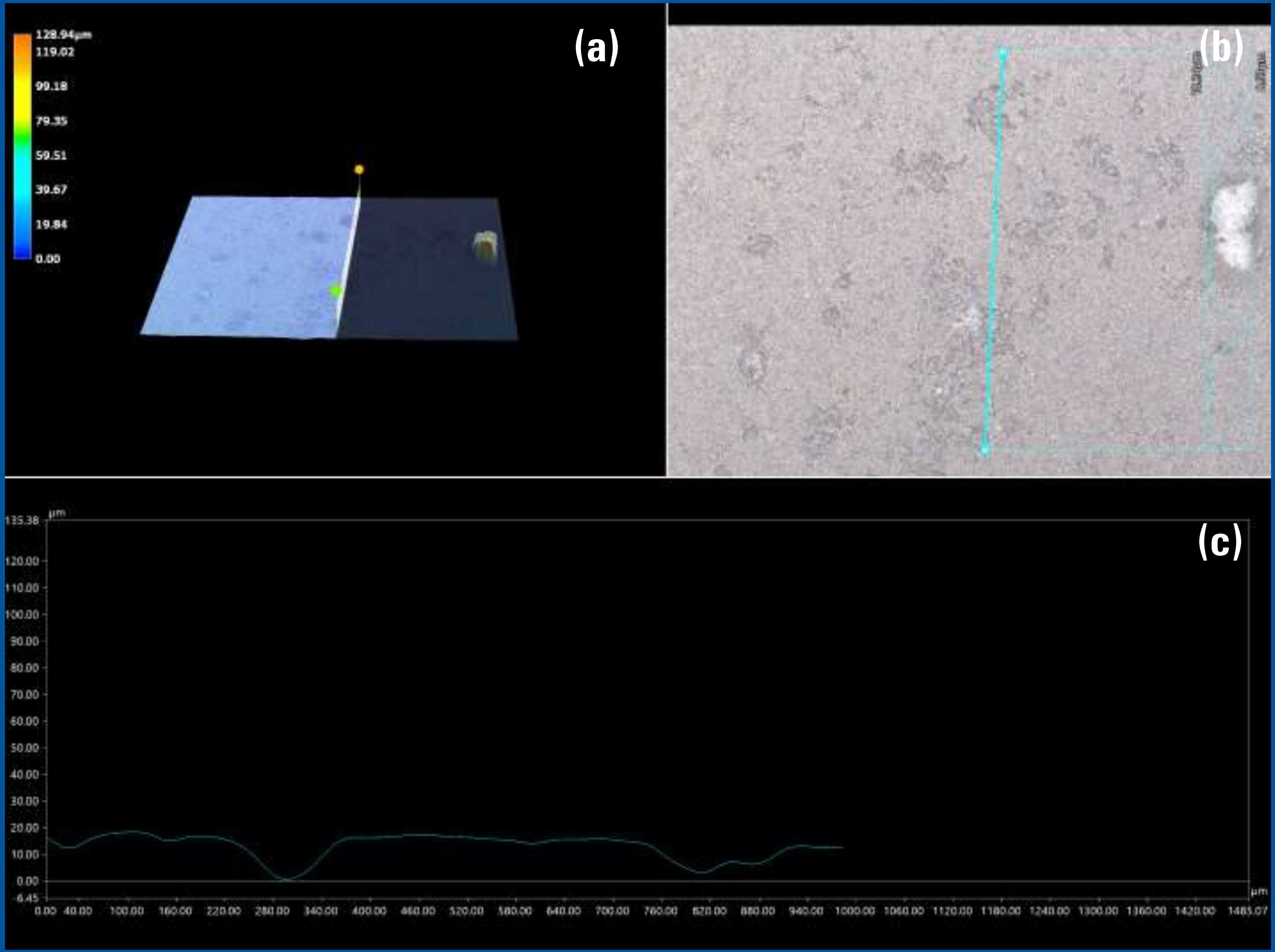
- Relatively even surface, of around 14 μm suggests areas retaining some of the coating's post-cycle 1 texture.



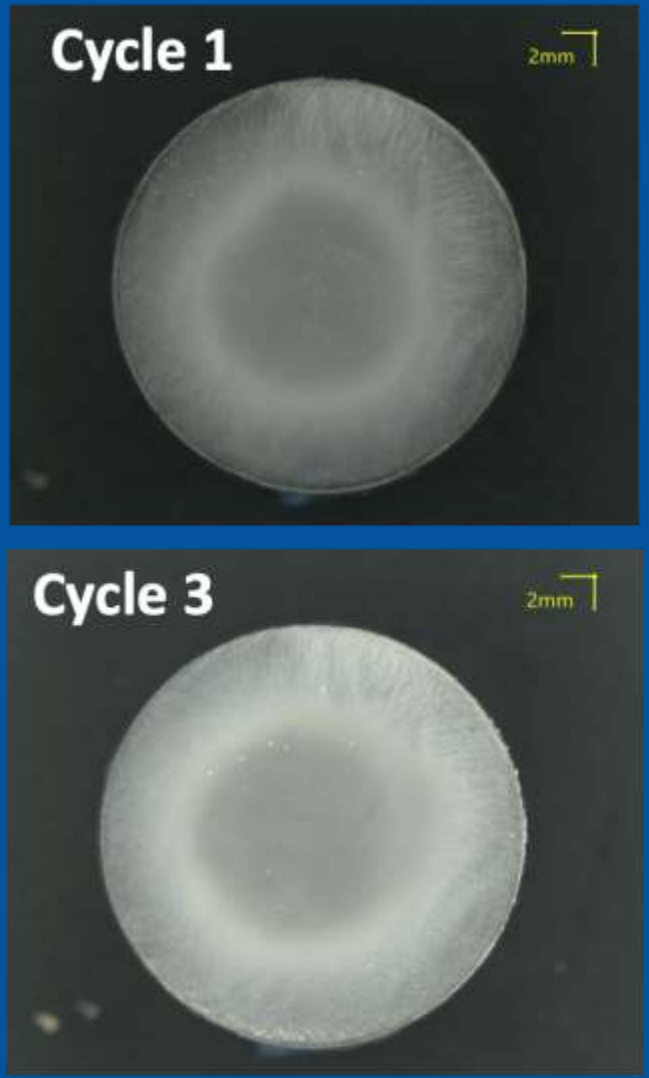
Grit Blaster Results: Post-Cycle 3 Depth Composition

- Measured from the surface of the coating, the surface continues to show surface degradation, however, with minimal additional wear.
- Depth profile indicates a relatively stabilized degradation, albeit, with depth variations up to 128.94 µm.
- Pits near 0 um indicate heavy areas of abrasion.
- Relatively even surface of around 15 µm suggests areas retaining some of the coating's post-cycle 2 texture.

Images showed surface roughness through ongoing abrasive action.



Grit Blaster Results: Image Comparison



Post abrasion cold sprayed WC-Co sample images after each of the 3 cycles of testing showing progressive degradation of coating.

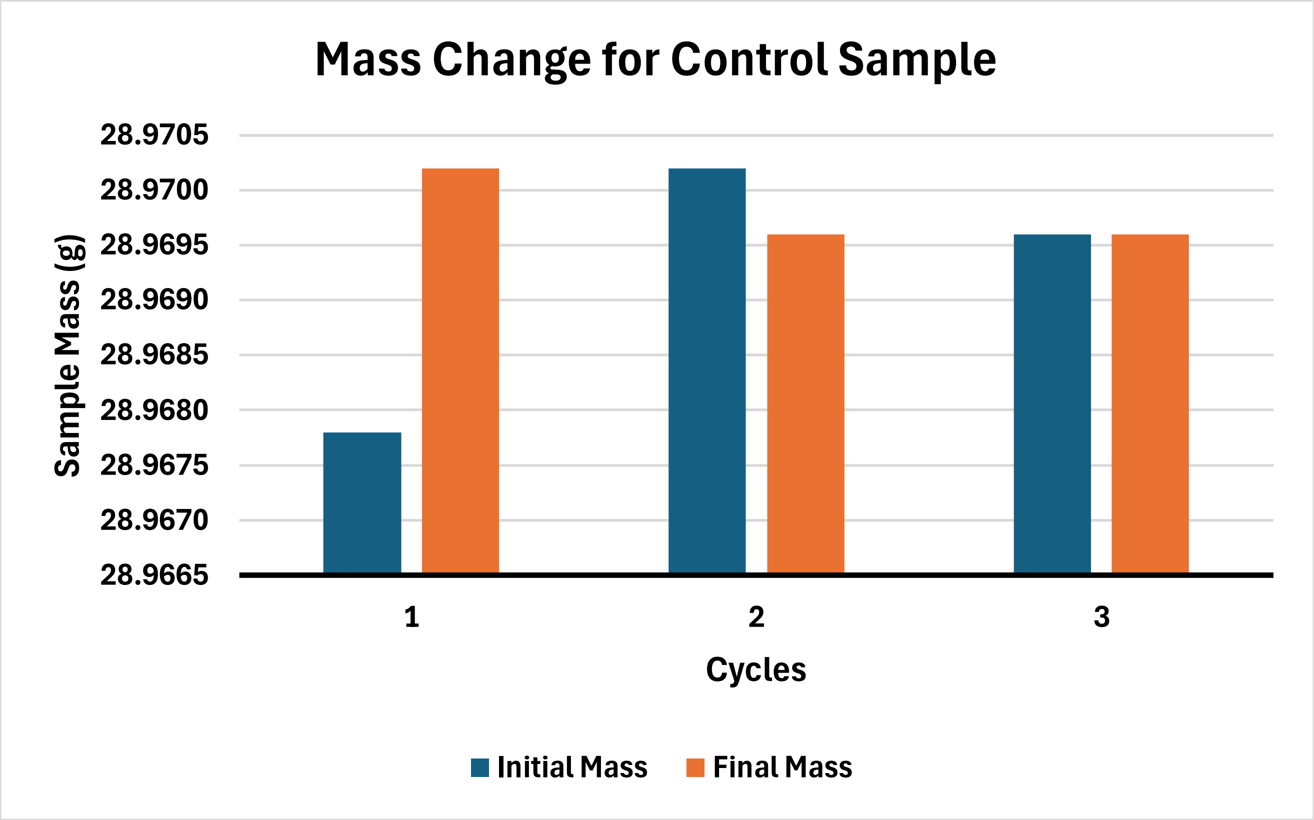
- VHX7000 microscope was used to image the overall coating surface after each abrasion cycle.
- Images indicated increasing surface roughness and material displacement.
- However, the coating was intact and did not delaminate.

Grit Blaster Results: Mass Change

- Cycle 1:
  - Mass increase of 0.0024 g.
  - Possibly due to some simulant adhering on to the surface.

- Cycle 2:
  - Mass loss of 0.0006 g.
  - Loss of material from adhered simulant and/or WC-Co coating.

- Cycle 3:
  - No significant mass change.
  - Possible material redistribution.



Mass measurements indicated some initial material gain from simulant adhesion and material loss from abrasion.

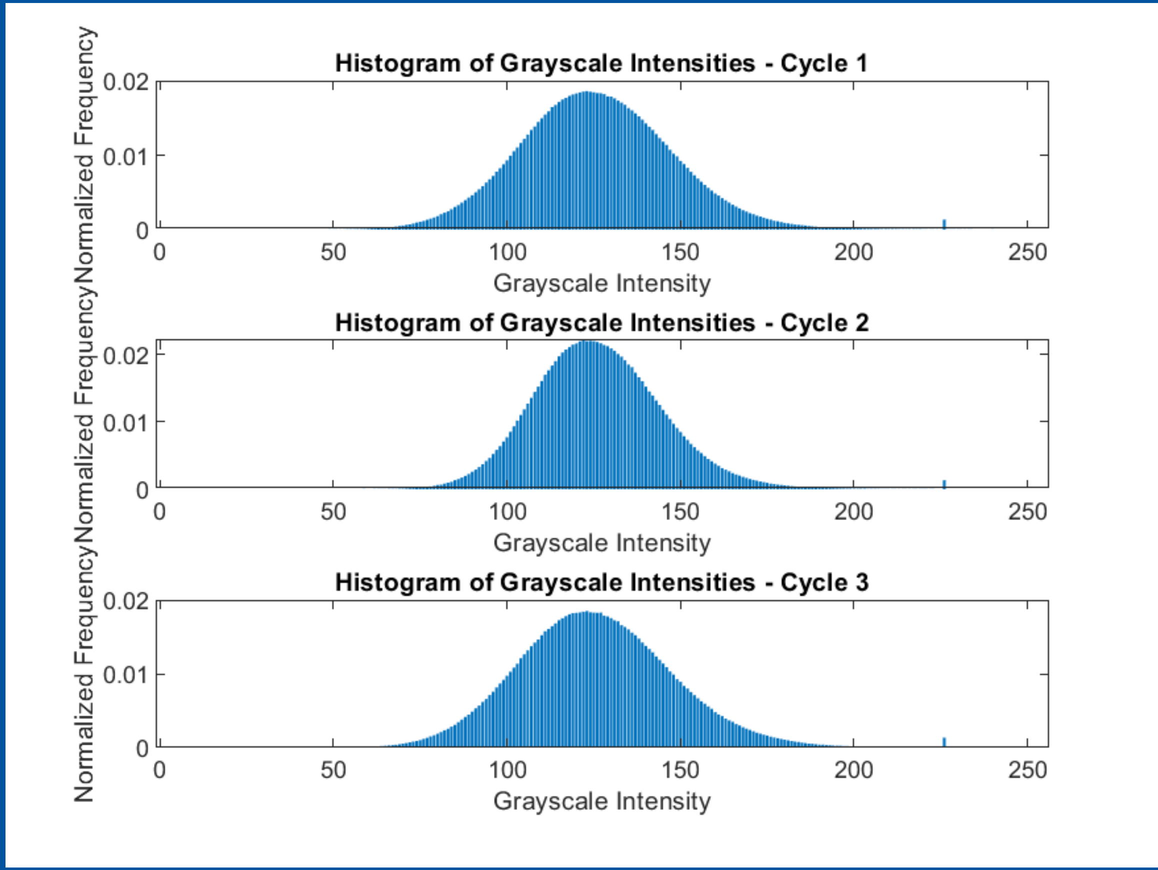
Grit Blaster Results: Pixel Color Intensity

- Cycle 1:
  - Mean intensity of 125.84.
  - Standard deviation of 22.12.
  - Shows initial surface irregularities.

- Cycle 2:
  - Mean intensity of 126.49.
  - Standard deviation of 18.84.
  - Shows surface irregularities to a lesser degree possibly due to surface material redistribution.

- Cycle 3:
  - Mean intensity of 125.63.
  - Standard deviation of 22.36.
  - Increased surface irregularities.

Color intensity analysis revealed changes in surface texture.



Shows the distribution of pixel brightness levels in our sample images, helps in determining the surface roughness after each grit blast cycle.

Overall Summary and Future Testing

- Overall Summary:
  - Concept : Passive method that enhances adhesion, abrasion and impact resistance with ceramics and bio-inspired textures.
  - Manufacturing: Used cold spray & laser texturing to add patterns to surfaces. This was not possible on WC-Co. The 3D printing process provided ease of manufacturing and is applicable to multiple materials.
  - Adhesion Results: Tap-Tap Test: Beetle pattern had the least adhesion, and the Lotus Leaf had the most due to regolith trapping between micro-pillars.
  - Abrasion Results: Grit Blaster Test: Changes in color intensity align with mass data and visual degradation, highlighting ongoing abrasive damage and the need for surface modifications.
  - Ceramics are promising with more work to improve manufacturing and testing methods.

Overall Summary and Future Testing

Future Testing:

- Centrifuge Testing:
  - Additional adhesion test to be conducted.
- Taber Abrader:
  - Additional wear resistance test to be conducted.
- Chemical Exposure Testing
- Heat Resistance Testing
- Cryogenic Resistance Testing

Images:

- (a) Centrifuge to be used for testing.
- (b) Taber Abraser to be used for testing.

Prospects of Ceramic Coatings

Thermal Protection Systems:

- Thin tiles of variable emissivity ceramics have successfully been used on satellites.
  - Reimi and Hayabusa satellites from the Japan Aerospace Exploratory Agency (JAXA).
- Combined with MLI (multi-layer insulation) blankets, ceramic coatings can reduce solar absorptivity.

Transparent Ceramics:

- Several transparent ceramics have been created that could be used to coat sensors and exterior windows.
  - Combining these ceramics with the proposed patterns could improve the reliability of sensors and windows.
- These patterns could impair the functionality of sensors utilizing small wavelengths.

Cost Assessment

- Based on Apollo Lunar Module (LM) dimensions and VRC's quote for cold-sprayed WC-Co sample.
  - Apollo LM used due to well-documented dimensions & successful design in similar lunar conditions.
  - VRC quote used due to its realistic basis from actual coated samples.
    - This is inaccurate based on bulk manufacturing prices
- Costs scaled up for the lander legs and windows.
- Assumptions:
  - Cylindrical legs.
  - Windows - based on Apollo 11 ascent stage windows.
  - Limited to initial application.

Description	Value
Target Thickness	0.010 in
Surface Area of One Sample	0.7854 in^2
Cost per Square Inch	$ 265.27 per in^2
Area of Window	350 in^2
Surface Area of Primary Strut	916.3 in^2
Total Surface Area of Secondary Struts	9076.2 in^2
Total Surface Area of Legs	9992.5 in^2
Estimated Total Cost:	$ 11,051,314.40

Cost Analysis Breakdown

Technological Readiness

- Laser ablation technology is not readily available for high hardness coatings.
  - USPL (Ultra Short Pulse Laser) ablation at high power (200W).
- Cold spray is already being used in industry.
  - Has been used on submarines and aircraft.
- Lithography-based Ceramic Manufacturing has currently limited scale size and material selection but accelerates prototyping.
- Lotus Leaf and Desert Beetle patterns need further iterations to achieve the best possible design.

Full Concept Timeline

Year 1:

January – March:

- Researching cold spray deposition method, bio-inspired surface modifications, laser ablation, and etc.
- Preliminary literature review, budgeting, and objectives.

April – December:

- Developing coatings.
- Contacting manufacturing companies.

October – December:

- Preliminary testing.
- Basic adhesion and abrasion testing of initial designs.

Year 2:

January – December:

- Iterative testing of coatings.
- Refining coatings through detailed tests.

May – August:

- Enhanced coating development.
- Develop new coating batches based on results.

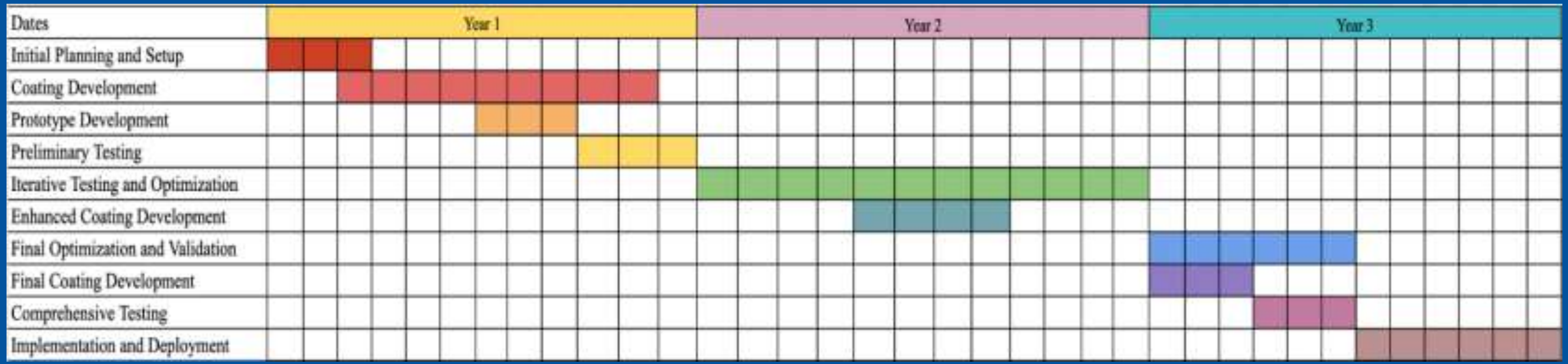
Year 3:

January – June:

- Final coating development.
- Comprehensive Testing.

July – December:

- Implementation and deployment.
- Application of the coating to lunar landers, and post-deployment results.



Gantt Chart of Full Concept Timeline

Acknowledgements

Florida Space Grant Consortium for providing funding to support additional advanced testing.

Lithoz America LLC – Beth Bornick, Ryan Fordham, and Shawn Allen for discussions on ceramic lithography and working with our design and STL files to support sample development.

VRC Metal System – Quentin Golay and Nick Case for discussions on cold spray technology and working with our tungsten carbide – cobalt coating designs to support sample development.

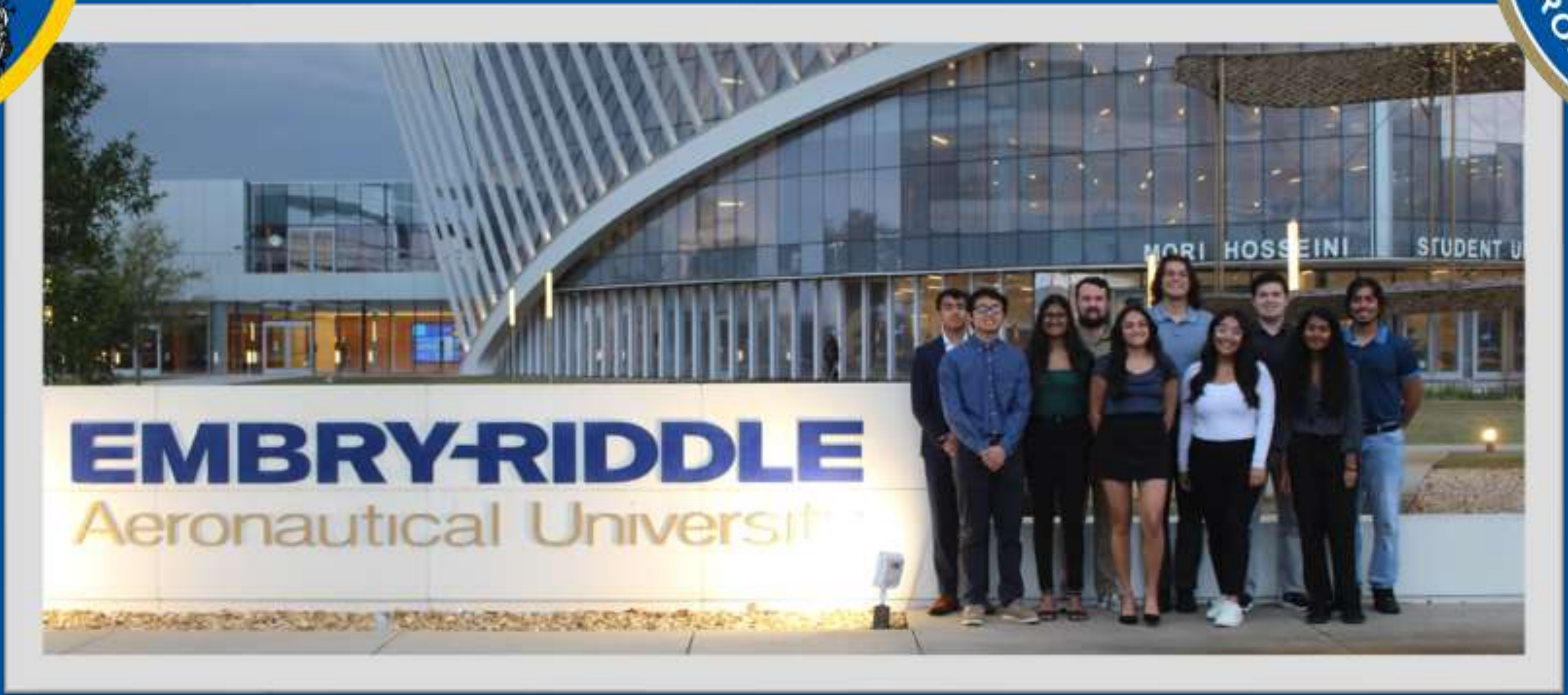
Keyence Corp of America – Michael Romund for working with us to laser mark our designs.

Zachary Stien, PhD student and NASA MSTAR Fellow for guiding additional advanced testing at NASA Langley.

Dr. Valerie Weisner for providing support and guidance on bio-mimetic surfaces.

NASA Langley Research Center for supporting our additional advanced testing.

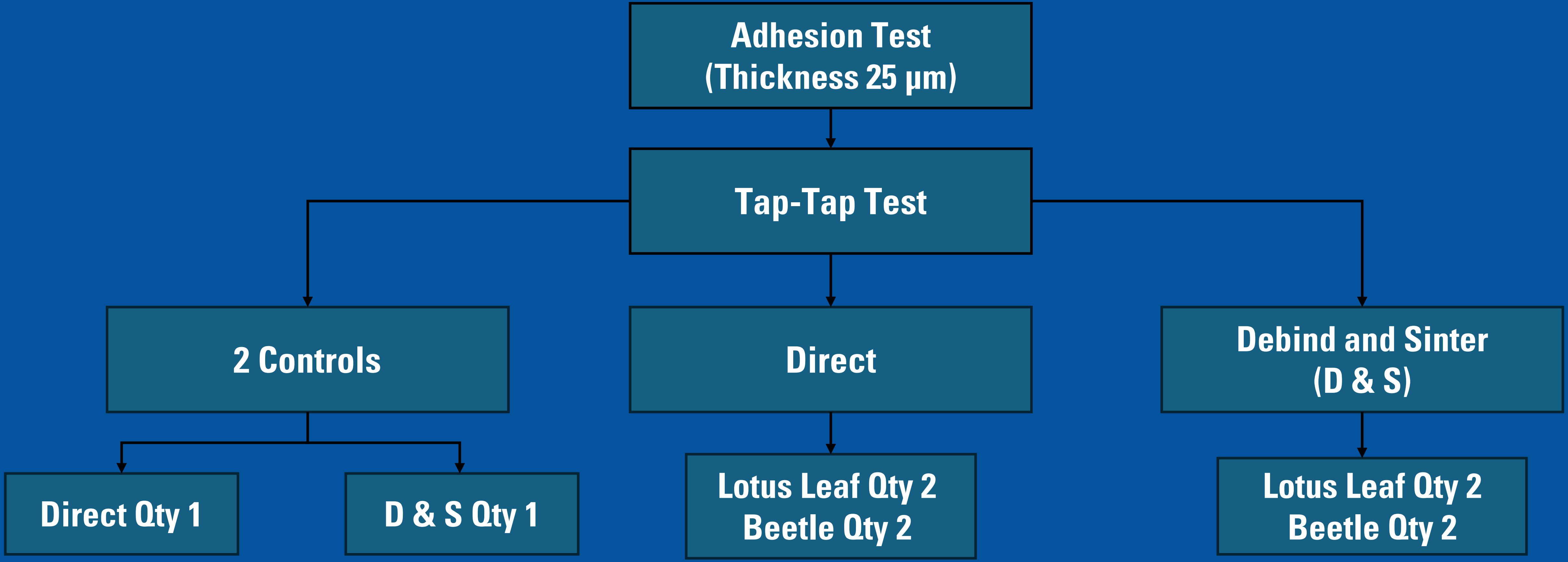
Thank You!



Any Questions?

Supplemental Information

Types of Tests



Adhesion Testing Chart

Lunar Lander References

Blue Moon Mark 2 Human Lunar Lander

Blue Origin. (2023, October 26). Blue Moon | Blue Origin.
https://www.blueorigin.com/blue-moon

Starship Human Lander System

Human landing Systems - NASA. (n.d.). NASA.
https://www.nasa.gov/reference/human-landing-systems/

Other Lotus Leaf Manufacturing Method

Wood, J., Superhydrophobic polymers cast from lotus leaves: Fabrication & processing, Materials Today, Volume 8, Issue 10, 2005, Page 15, ISSN 1369-7021

- Lotus Leaf pattern has been made for softer materials.
- Mostly done through Soft-Lithographic Duplication.
  - Form mold by pouring Polydimethylsiloxane (PDMS) onto Lotus pattern.
  - Print material into mold.

Risk Analysis

Likelihood \ Impact	Minor	Moderate	Significant	Severe
Very High	Medium	Medium	High	High
High	Low	Medium	Medium	High
Medium	Low	Medium	Medium	Medium
Low	Low	Low	Medium	Medium

Risk Matrix Criteria

Name of Risk	Likelihood	Impact
Thermal Mismatch	High	Severe
Micrometeoroid/Debris Impact	Very High	Moderate
Chemical Degradation	Low	Moderate
Mechanical Stress	Low - Medium	Low-Moderate
Manufacturing Defects	Medium	Moderate
Adhesion Failure	Medium	Moderate

Ceramic Coating Risk Matrix

External Trade Study

Table 2
Trade study results for Coatings & Finishings.

Concept	Type	Mass (2x)	Complexity (1x)	TRL (1x)	Manufacturability (0.5x)	Durability (1.5x)	Temperature Sensitivity (1x)	Efficacy (1x)	Score
Lotus Leaf Coating	Coating	4	2	2	1	3	3	3	**18**
Laser Texturing	Finishing	2	3	2	0.5	4.5	3	2	**17**
ESD Coating	Coating	4	1	2	1	1.5	2	2	**13.5**
Peel Away Coating	Coating	2	1	1	0.5	1.5	1	2	**9**

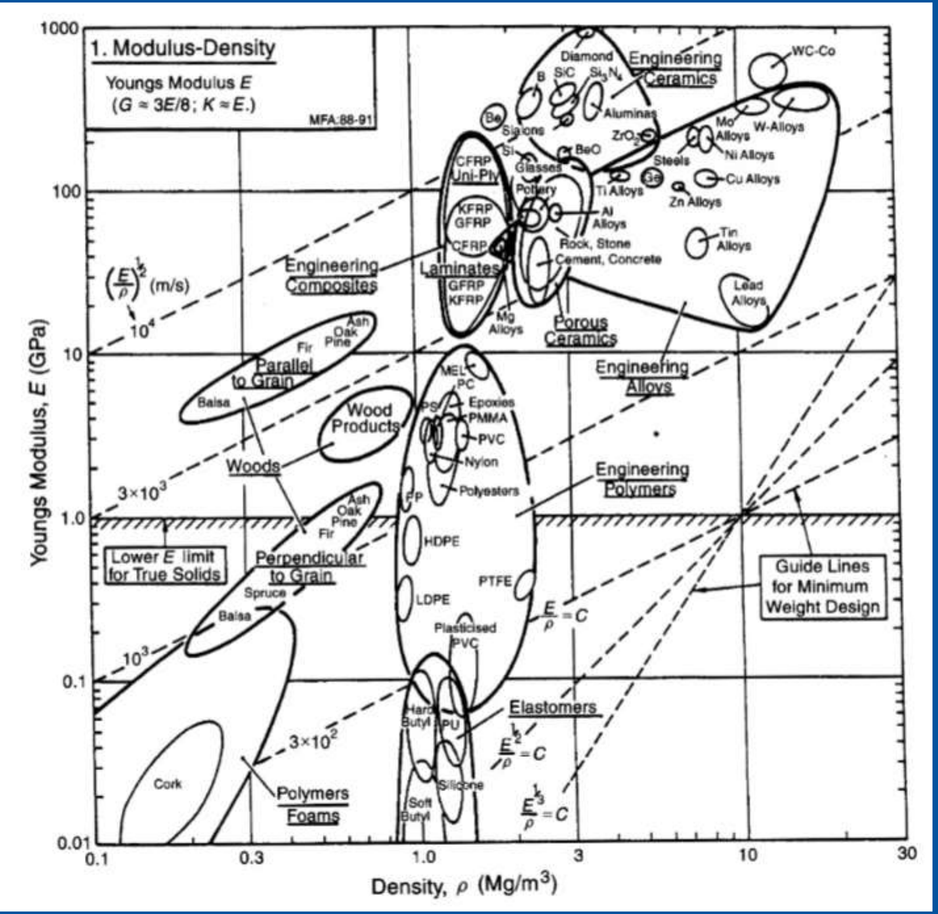
Table 7
Trade study results for Active Dust Mitigation.

Concept	Type	Mass (2x)	Complexity (1x)	TRL (1x)	Manufacturability (0.5x)	Durability (1.5x)	Temperature Sensitivity (1x)	Efficacy (1x)	Score
Electrodynamic Dust Shield (EDS)	Electrodynamic	6	3	3	1	4.5	2	3	22.5
Nylon/Fiberglass Brush	Mechanical	4	3	2	1.5	1.5	3	3	18
Pressurized Gas	Fluidal	4	3	1	1	3	1	3	16
Vibration	Mechanical	2	2	1	1	4.5	3	2	15.5
Electron Gun	Electrodynamic	2	1	1	1	3	3	2	13
Magnetic Roller	Electrodynamic	2	1	1	0.5	1.5	3	1	10

External Trade Studies on Coatings & Finishings, and Active Dust Mitigation

K. M. Cannon, C. B. Dreyer, G. F. Sowers, J. Schmit, T. Nguyen, K. Sanny, J. Schertz, "Working with lunar surface materials: Review and analysis of dust mitigation and regolith conveyance technologies," *Acta Astronautica*, vol. 196, 2022, pp. 259-274. https://doi.org/10.1016/j.actaastro.2022.04.037.

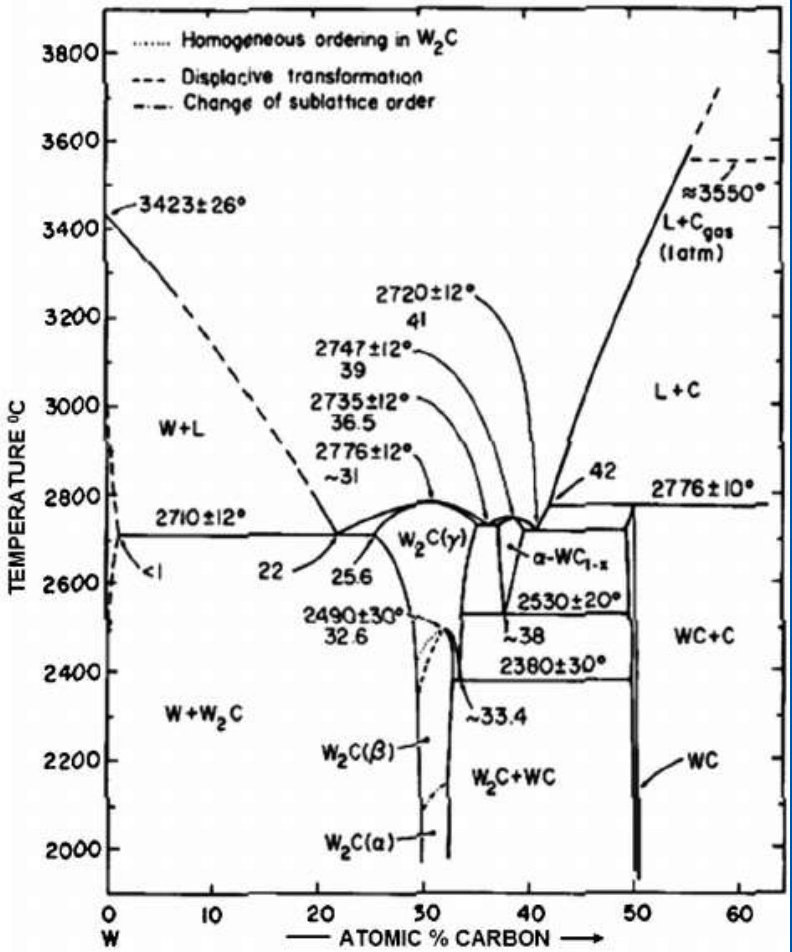
Material Selection Chart



Material Selection Chart

M.F. Ashby, Materials Selection in Mechanical Design, Second Edition, Elsevier, Oxford (1999)

Phase Diagram Chart



W-C Phase Diagram

Dash, Tapan & Nayak, Bijan & Abhangi, Mitul & Makwana, Rajnikant & Vala, Sudhirsinh & Jakhar, Shrichand & Rao, Chandan Venkata & Basu, T.K.. (2014). Preparation and Neutronic Studies of Tungsten Carbide Composite. Fusion Science and Technology. 65. 241-247. 10.13182/FST13-663.

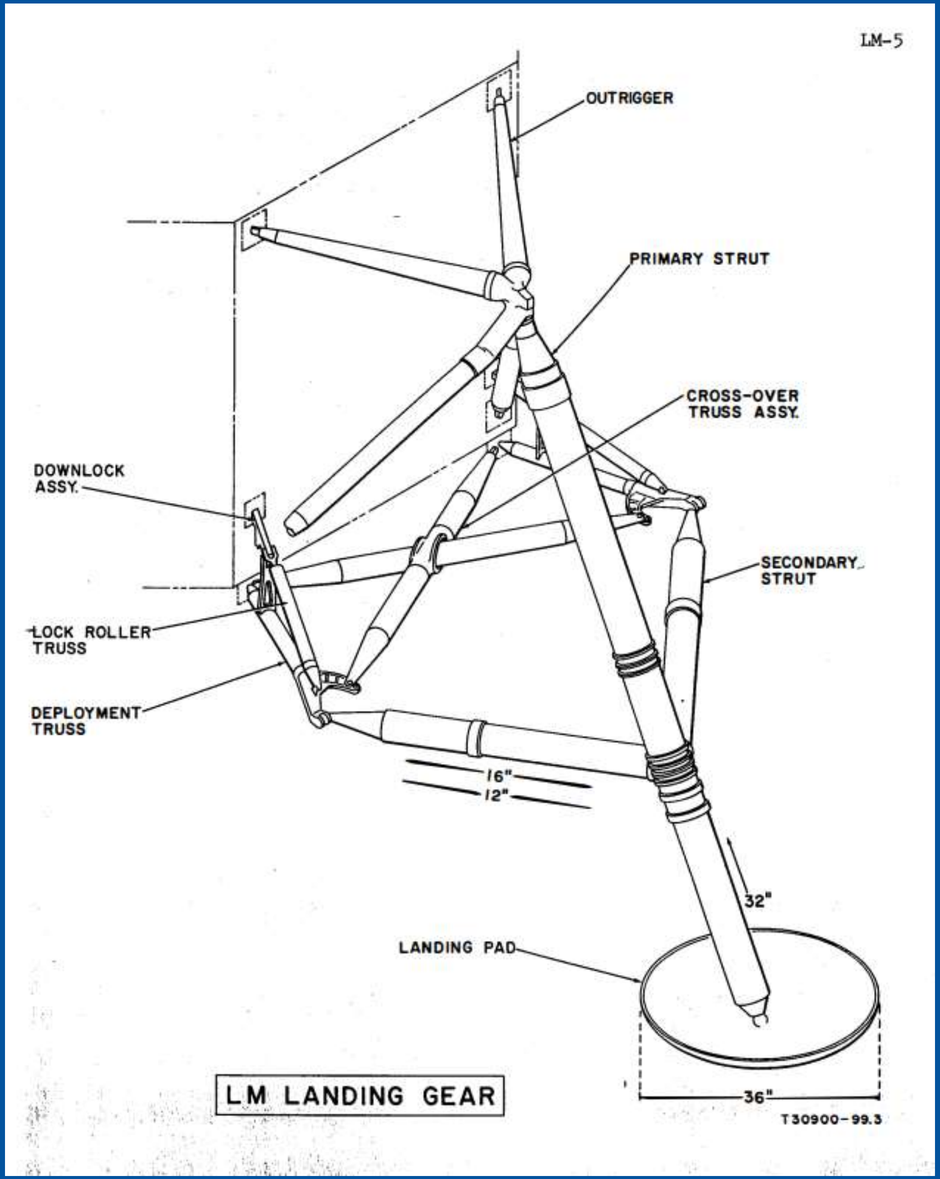
Mass Cost Calculations

$$m = \rho V = \rho l A = (14.9\ g/cm^3)(0.025\ cm)(1\ cm^2) = 0.3725\ g$$

Mass Cost Calculations for Applying WC Coating per square centimeter

Cost Assessment: Dimensions

- WC-Co Sample:
  - 1 inch diameter.
  - 0.010 inches thick.
- Primary Strut:
  - 4.5 inches diameter.
  - 64 inches length.
- Secondary Struts (14 pieces):
  - 3.5 inches diameter.
  - 58 inches length.
- Windows (Based on Apollo 11 ascent windows):
  - 25 inches length.
  - 28 inches height.



Lunar Lander Reference Image

Singer, J. L. a. P. (2017, January 24). *To get a man on the moon, China's program takes cues from the Apollo lunar lander*. Popular Science. https://www.popsci.com/china-lunar-lander-moon/https://www.popsci.com/china-lunar-lander-moon/

Calculations of Estimated Cost

Part 1

Geometric Calculation:

- Sample Calculation

  Diameter: 1 inch
  Target thickness: 0.010 inch
  Surface Area of One Sample = $\pi r^2 = \pi (0.5)^2 = 0.7854 \text{ in}^2$

- Legs Calculation

  Primary Strut
  Diameter: 4.5 inches
  Length: 64 inches
  Surface Area of Cylinder = $2\pi rh + 2\pi r^2 = (2\pi)(2.25)(64) + (2\pi)(2.25)^2 = 916.3 \text{ in}^2$

Secondary Strut (14 pieces)
Diameter: 3.5 inches
Length: 58 inches
Surface Area of One Secondary Strut = $2\pi rh + 2\pi r^2 = (2\pi)(1.75)(58) + (2\pi)(1.75)^2 = 648.3 \text{ in}^2$
Total Surface Area of Secondary Struts = $(14)(648.3) = 9076.2 \text{ in}^2$

Total Surface Area of Legs
Total Surface = Surface Area of Primary Strut + Total Surface Area of Secondary Struts = $916.3 + 9076.2 = 9992.5 \text{ in}^2$

Surface Area Calculations for Cost Estimate

Calculations of Estimated Cost

Part 2

Cost Estimation:

- Using the cost from the sample quote, the cost per square inch for the coating process was estimated. Per Square Inch Cost (assuming the coating will have the desired thickness of 0.010 inch)

  Net Unit Price = \$4,375.00 / 21 = \$ 208.34

  Surface Area of one sample = 0.7854 in^2

  Cost Per Square Inch = Net Unit Price / Surface Area of One Sample = (\$ 208.34)/(0.7854 in^2) = \$ 265.27

- Legs Cost (All four legs)

  Total Leg Surface Area = 9992.5 in^2
  Cost Per Square Inch = \$ 265.27
  Window total area = (350)(5) = 1750 in^2
  Window cost = (1750 in^2)(\$ 265.27 per in^2) = \$ 464,222.50
  Legs Cost = (4)(Total Leg Surface Area)(Cost Per Square Inch) = (4)(9992.5 in^2)(\$ 265.27 per in^2) = \$10,602,841.90

  Total Estimated Cost for Lander Leg and Window Application = \$ 11,067,064.40

Cost Estimate for Applying Cold Spray to Lander Legs and Window

Taber Abraser Test Setup

- Purpose: Evaluates the wear resistance of the WC-Co coating and analyze its wear characteristics over an extended number of cycles.
- Variables:
  - Independent: WC-Co and surface modifications.
  - Dependent: Mass change, eddy current thickness.
  - Control: Number of cycles, pressure applied, cleaning procedure, testing environment.
- Procedure:
  - H-18 wheels with 500g load used for abrasion.
  - Run for 3,000 total cycles stopping every 100 cycles to clean wheels, dust sample, weigh, and measure thickness using eddy current.

Centrifuge Test Setup

- Purpose: Evaluate adhesion effects of aerosolized lunar simulant on WC-Co coated samples.
- Variables:
  - Independent: WC-Coating and surface modifications.
  - Dependent: Mass change, surface adhesion.
  - Control: RPM levels, cleaning method, testing conditions.
- Procedure:
  - Aerosolizing lunar simulant to achieve a thin layer coating on top of the samples to prevent adhesion.
  - Samples spin at varying levels of 500-4000 RPM.
  - Weigh sample's mass before/after dust application and after rotation.
  - Clean samples and reapply dust.

WC-HVOF Coating Abrasion Testing

Table 4. Abrasive wears weight loss

Abrasive wear (Taber abraser)									
Cycles	Tungsten carbide			Accelerated hard chromium			Conventional hard chromium		
(*N*)	Total mg	mg/1000	Depth (μm)	Total mg	mg/1000	Depth (μm)	Total mg	mg/1000	Depth (μm)
1000	2.20	2.20	1.57	8.30	8.30	11.67	2.83	2.83	3.97
2000	3.90	1.70	2.78	13.40	5.10	18.81	5.57	2.74	7.82
3000	4.70	0.80	3.56	16.50	3.10	23.16	8.33	2.76	11.70
4000	7.97	3.27	5.69	19.10	2.60	26.81	11.33	3.00	15.90
5000	10.80	2.83	7.72	21.00	1.90	29.47	14.83	3.50	20.81
6000	13.03	2.23	9.31	22.60	1.60	31.72	17.63	2.80	24.74
7000	14.20	1.17	10.15	24.10	1.50	33.82	20.60	2.97	28.91
8000	15.80	1.60	11.29	25.30	1.20	35.51	22.93	2.33	32.20
9000	17.40	1.60	12.43	26.30	1.00	36.91	25.83	2.90	36.25
10000	18.87	1.47	13.48	27.10	0.80	38.80	29.13	3.30	40.80
Median		1.89 mg/1000 cycles		2.71 mg/1,000 cycles			2.91 mg/1000 cycles		
Standard deviation		0.75 mg/1000 cycles		2.34 mg/1000 cycles			0.88 mg/1000 cycles		

Marcelino P Nascimento et al., "Effects of tungsten carbide thermal spray coating by HP/HVOF and hard chromium electroplating on AISI 4340 high strength steel," *Surface and Coatings Technology*, vol. 138, no. 2-3, 2001, pp. 113-124. DOI: 10.1016/S0257-8972(00)01148-8.

MATLAB CODE

Part 1

Note: Must have Image Processing Toolbox

```
% Load images for each cycle
img_cycle1_2D = imread('SAMPLE3_CYCLE1_2D(200X).tif');
img_cycle2_2D = imread('SAMPLE3_CYCLE2_2D(200X).tif');
img_cycle3_2D = imread('SAMPLE3_CYCLE3_2D(200X).tif');
% Convert images to grayscale for intensity analysis
gray_cycle1 = rgb2gray(img_cycle1_2D);
gray_cycle2 = rgb2gray(img_cycle2_2D);
gray_cycle3 = rgb2gray(img_cycle3_2D);
% Calculate histogram of grayscale intensities
[counts1, binLocations1] = imhist(gray_cycle1);
[counts2, binLocations2] = imhist(gray_cycle2);
[counts3, binLocations3] = imhist(gray_cycle3);
% Normalize histograms
counts1 = counts1 / sum(counts1);
counts2 = counts2 / sum(counts2);
counts3 = counts3 / sum(counts3);
% Calculate statistical measures
mean_intensity1 = mean(gray_cycle1(:));
mean_intensity2 = mean(gray_cycle2(:));
mean_intensity3 = mean(gray_cycle3(:));
std_intensity1 = std(double(gray_cycle1(:)));
std_intensity2 = std(double(gray_cycle2(:)));
std_intensity3 = std(double(gray_cycle3(:)));
```

MATLAB CODE

Part 2

```
% Display the results
fprintf('Cycle 1 - Mean Intensity: %.2f, Std Dev: %.2f\n', mean_intensity1, std_intensity1);
fprintf('Cycle 2 - Mean Intensity: %.2f, Std Dev: %.2f\n', mean_intensity2, std_intensity2);
fprintf('Cycle 3 - Mean Intensity: %.2f, Std Dev: %.2f\n', mean_intensity3, std_intensity3);
% Plot histograms
figure;
subplot(3, 1, 1);
bar(binLocations1, counts1);
title('Histogram of Grayscale Intensities - Cycle 1');
xlabel('Grayscale Intensity');
ylabel('Normalized Frequency');
subplot(3, 1, 2);
bar(binLocations2, counts2);
title('Histogram of Grayscale Intensities - Cycle 2');
xlabel('Grayscale Intensity');
ylabel('Normalized Frequency');
subplot(3, 1, 3);
bar(binLocations3, counts3);
title('Histogram of Grayscale Intensities - Cycle 3');
xlabel('Grayscale Intensity');
ylabel('Normalized Frequency');
% Save the plot
saveas(gcf, 'color_intensity_histogram_analysis.png');
```