Investigating Durability of 8YSZ via Wear and Erosion Testing for Lunar Applications

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Abstract: As the number of missions to land on the Moon with and without crew continues to increase, there are a plethora of factors to consider that could affect aerospace materials. Lunar dust, or lunar regolith, composed of small rock fragments, glass beads, and minerals, is quite corrosive, abrasive, reactive, and adhesive, necessitating effective mitigation strategies. Ceramics have emerged as a promising material selection in the aerospace industry for structural protection due to their high strength, excellent thermal properties, and resistance to degradation. Among these ceramics, zirconia (ZrO_2) is a promising material, exhibiting exceptional mechanical and thermal properties. This study evaluates the resilience of an 8-mol% yttria-stabilized zirconia (8YSZ) ceramic coating, tested against wear and erosion, to characterize its degradation over time. The results of 8YSZ testing demonstrated its high tailorability and potential as a ceramic coating for wear and abrasion resistance.

Introduction: Lunar Dust and Its Challenges

Lunar Dust and Regolith

Enabling a sustainable human presence on the Moon requires technologies capable of withstanding the harsh lunar environment[1-3]:

- Lunar dust:
  - Mixture of crystalline and amorphous
  - Abrasive, jagged morphology
  - Electrically charged
  - Varying composition from lunar region to region
- Wide range of particle sizes: sub-micron to millimeters

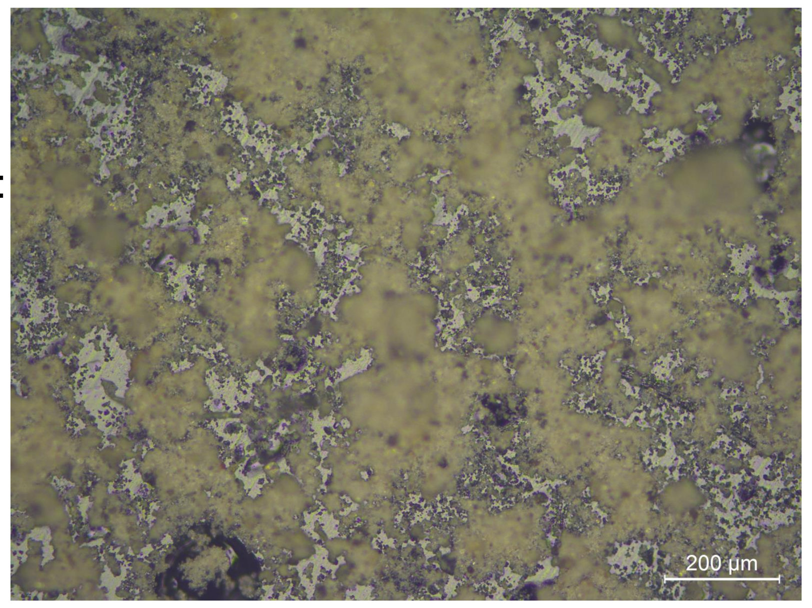
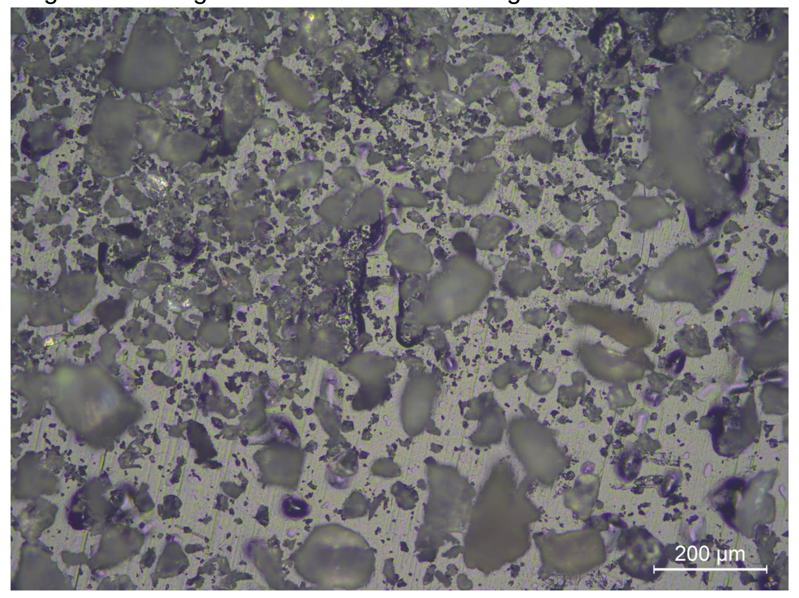


Fig. 1 Lunar mare simulant at 10x magnification.

Fig. 2 Lunar highland simulant at 10x magnification.



Challenge

- Dust threatens long-term durability of mechanisms operating on lunar and Martian surfaces
- Lunar dust physical qualities, electrostatic charge, and velocities result in severe abrasion and degradation of materials and structures
- More resilient materials are sought out to withstand the wear and abrasion against lunar dust

A Promising Passive Solution: Ceramic Coatings Ceramic coatings are thin, durable layers of ceramic material applied to metals to provide protection against:

- Wear, impact and corrosion
- Lightweight (in layers)
- Exceptional hardness

- Ceramics like alumina and zirconia offer additional advantages such as: thermal stability and transformation toughening (for crack resistance)

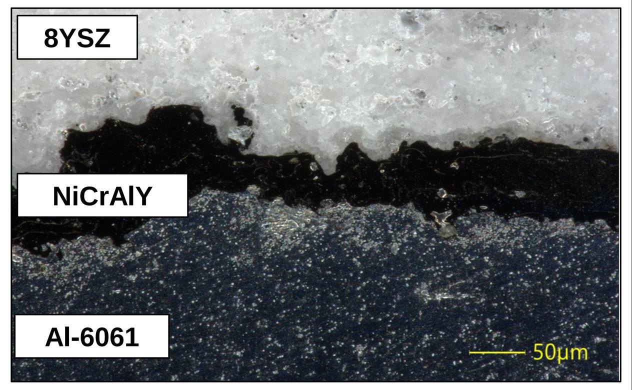
Wear Resistant Ceramic Coating

8 Mol-% Yttria-Stabilized-Zirconia was identified as a suitable ceramic coating solution, because it is:

- Extremely tailorable
- Exists in 3 phases: monoclinic, tetragonal, and cubic
- Through the air plasma spray (APS) deposition method, a t' phase is acquired, exhibiting the highest fracture strength and toughness due to ferro-elasticity
  - Ferro-elastic toughening: absorption of energy, withstanding stresses and strains, hindering further crack growth

Motivation: Employing ceramic coatings is crucial to extending the durability and resilience of materials on the lunar surface, prolonging mission lifespan.

a)



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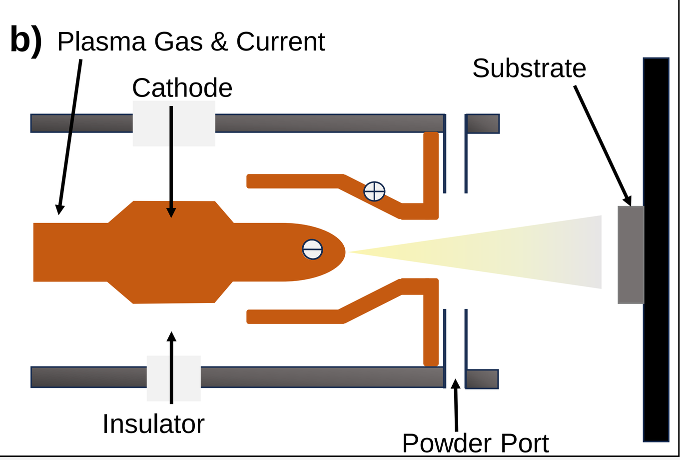

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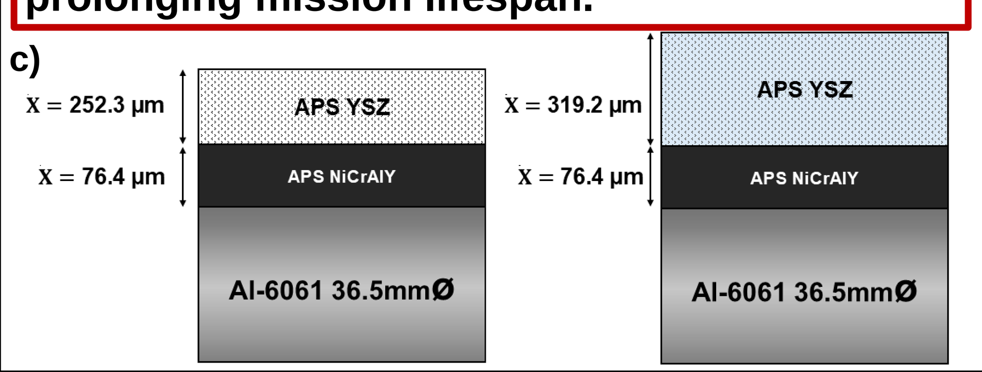


Fig. 3 (a) Cross-sectional view of specimens. (b) Air plasma spray schematics for deposition. (c) Specimen batches of distinct thicknesses.[5]

Experiment

Objective Investigate the effect of thickness (250 µm vs. 320 µm) through wear of 8 mol-% yttria-stabilized-zirconia (8YSZ) ceramic on aluminum 6061 substrates with an intermediate layer of nickel, chromium, aluminum, yttrium (NiCrAlY) through abrasion testing.

Abrasion Mechanism

- **Abrasion Medium:** CS-17 Wheels (Taber Industries ®)
  - Composition: Resilient binder and silicon carbide particles
  - Hardness: 95 Shore A
- **ASTM D4060-19**

Procedure

1) Weight measurement, 2) Thickness measurements, 3) Roughness scans, 4) Optical Images, 5) Abrade, and 6) Repeat for 0, 400, 800, 1200, and 5000 cycles

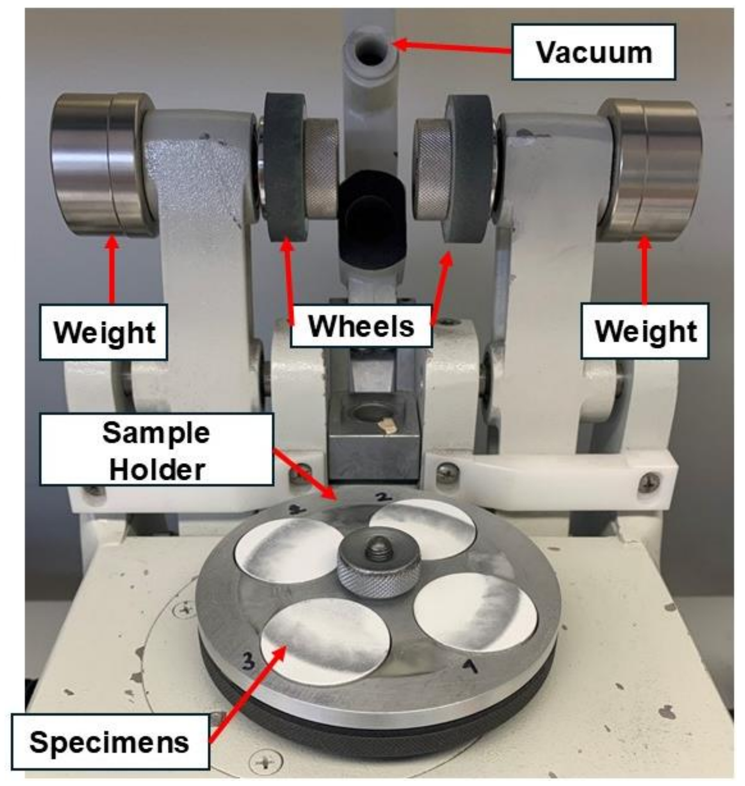


Fig. 4 Sample batches with distinct thicknesses were tested in abrasion mechanism with the parameters above.[5]

Raman Spectroscopy

Objective Investigate the 8YSZ coating's stress and phase transformation prior/post abrasion testing through the non-destructive evaluation method of Raman Spectroscopy.

Raman spectroscopy allows for the investigation of the coating's composition through peak shifts. These peak shifts allow for identifying stress indicators and phase changes through these behavioral peak shifts.

- The peaks obtained from Raman scans represent individual Raman bands of the molecular structure and their photon response to laser excitation
- Each Raman peak has a distinct response depending on its excitation response properties

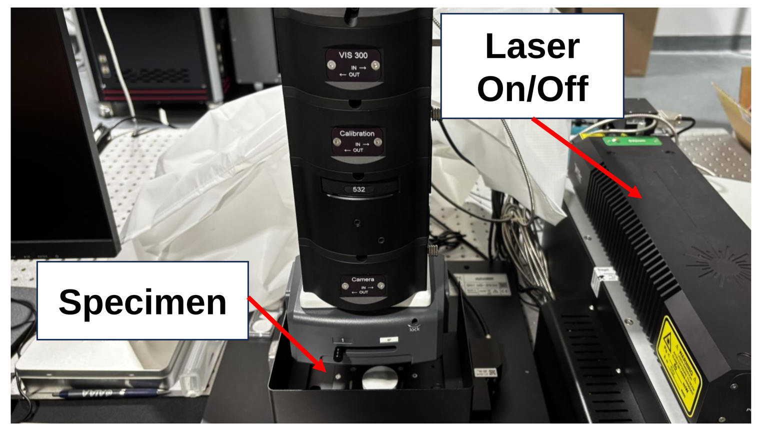


Fig. 5 WiTec Raman system set-up at Embry Riddle Aeronautical University, Daytona Beach.[5]

Raman Spectroscopy Results

Results of Raman Spectroscopy

- Decrease in intensity post-abrasion testing
- Presence of both tensile and compressive stress -> heterogeneous stress distribution post-abrasion
- Mixed profile means coating has anisotropic response to the abrasion process
  - Tensile -> could lead to crack propagation
  - Compressive -> helps close and resist microcracks

Peak	Peak Shift	$\Pi_{Hydrostatic}$	$\Delta\sigma$
cm^{-1}	cm^{-1}	cm^{-1}/GPa	GPa
148.49	-0.38	-0.53	0.71
248.23	-0.53	1.07	-0.49
470.59	0.27	-2.13	-0.13
635.47	0.68	-1.07	-0.64

Table 1. Stress calculations for the 4 prominent peaks.[5]

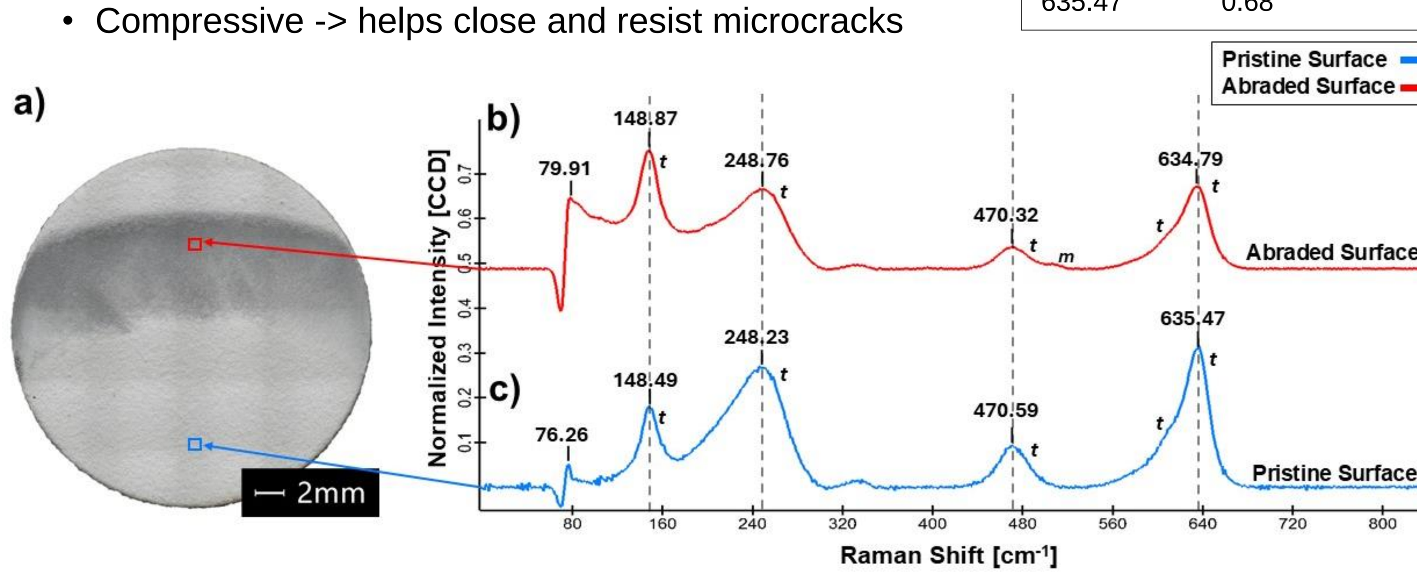


Fig. 6 (a) Specimen used for Raman scans. Raman spectra of (c) pristine and (b) abraded area and the respective stresses in.[5]

Abrasion Results

Mass Percent Loss

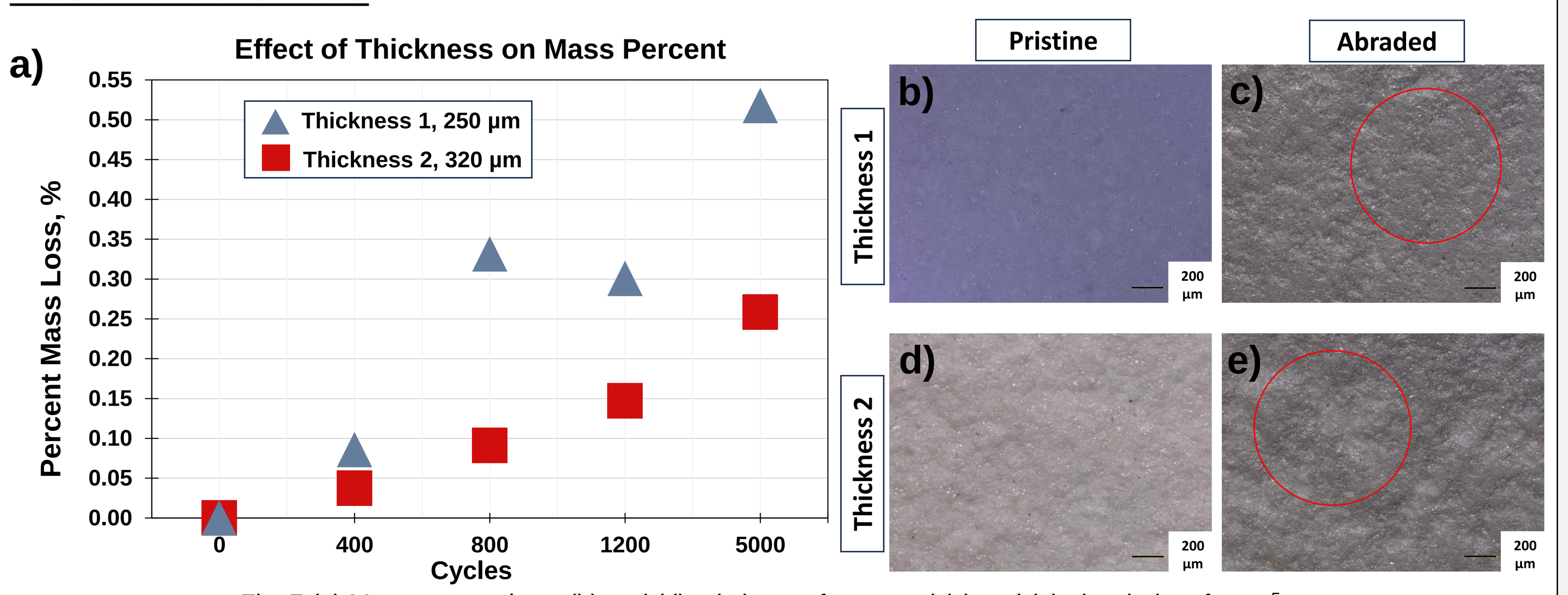


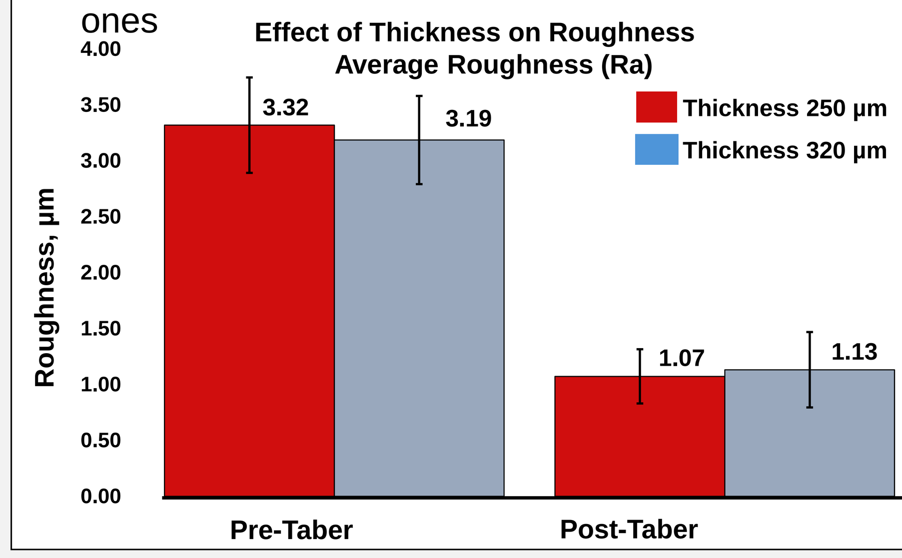
Fig. 7 (a) Mass percent loss, (b) and (d) pristine surfaces, and (c) and (e) abraded surfaces.[5]

- The 250 µm thickness coating lost 2x more mass than the 320 µm thickness coating after 1200 cycles and optical imaging appears to depict smoothening of the abraded regions for both specimen batches
- Both thicknesses per specimen experienced a significant decrease in roughness post-abrasion, however, 320 µm specimens demonstrated that post-5000 cycles, the roughness was higher (less polished) than the 250 µm specimens

While the thicker coated specimens exhibited superior mass loss compared to 250 µm, the roughness must also be considered. When considering dust adhesion due to mechanical forces, a surface with lower roughness parameters may potentially offer a reduction of particle adhesion due to the lack of features for particles to mechanically anchor. A rougher surface could possibly result in more dust particle adhesion.

Roughness Scans

- 320 µm coatings exhibited less mass loss, with almost two times less than that of the 250 µm specimens. Additionally, the roughness parameters of the coatings with thickness of 250 µm experienced a total thickness loss of 32.77 µm post-abrasion, with a final roughness of 1.07 µm compared to a total thickness loss of 27.12 µm and a final roughness of 1.13 µm for the thicker ones



The lower mass retention of thicker coatings suggests their suitability for environments requiring extended wear life, while the lower roughness of thinner coatings may reduce particle adhesion, however, are favorable to reduce weight addition to aerospace cargo.

Fig.8 Average roughness scan values prior to and post abrasion.[5]

Summary and Continuing Efforts

- Thicker-coated specimens exhibited better wear over time and less mass loss.
- Specimens achieved lower roughness values post-abrasion testing.
  - 250 µm specimens optically looked to smoothen more evenly, as opposed to the 320 µm, which exhibited a more valley/cratered abraded surface.
- While thicker coatings are less suitable for dust adhesion applications, they demonstrate a better wear rate over time.
- Predominately compressive stress (favorable)->resists cracking, closes microcracks. Intensity decrease could be a result of the concentration of 8YSZ coating post-abrasion.

Next Steps: Test various yttria mol % with zirconia, along with incorporation of silicon carbide additives->Incorporate the use of new abrasive media: Regolith simulant->Distinct manufacturing method for YSZ ceramic: Lithography-based printing.

References: Noble, S. K., "The lunar regolith," Lunar Regolith Simulant Workshop, 2009.; [2] Mark Hyatt, J. F., "Lunar dust: characterization and mitigation," 9th International Conference on the Exploration and Utilization of the Moon/International Lunar Exploration Working Group, 2007.; Benaroya, H., "Lunar habitats: A brief overview of issues and concepts," REACH, Vol. 7-8, 2017, pp. 14–33. https://doi.org/https: //doi.org/10.1016/j.reach.2018.08.002, URL https://www.sciencedirect.com/science/article/pii/S2352309318300014.; [4]Zachary Stein et. al, Residual stress effects of CMAS infiltration in high-temperature jet engine ceramic coatings captured non-destructively with confocal Raman-based 3D rendering, 2023;[5] Ashley Tirado Pujols et. al, Investigating the Resilience of 8 mol-% Yttria-Stabilized Zirconia Coatings for Lunar Environments, 2024. **Acknowledgments:** This material is based upon work supported by the National Aeronautics and Space Administration under Grant No. 80NSSC21M0309 issued through the NASA Office of STEM Engagement. This work was supported by a NASA Space Technology Graduate Research Opportunity 2024, under Grant No. 80NSSC24K1368.