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Measuring Wear and Abrasive Resistance of Air Plasma Sprayed Aluminum Oxide Coatings for Lunar Exploration

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Abstract

Lunar regolith, especially finer dust particles traveling at high velocities, can cause significant wear and abrasive damage to structural components that ensure a prolongated presence on the surface of the Moon. With the absence of an atmosphere and lower gravity than on Earth, regolith particles maintain high velocities at large distances from where they were generated, for example next to lunar landers. Wear-resistant ceramic and ceramic composite materials can improve the durability of spacecraft components during long missions on the Moon's surface. Aluminum oxide coatings are lightweight, have multifunctional properties, and have high strength including high hardness and wear resistance. These properties can help improve the durability of structures used in space exploration. Air plasma sprayed (APS) aluminum oxide coatings have demonstrated the potential to protect critical structures. This study investigated the abrasive wear resistance of APS aluminum oxide coatings via Taber abrasion experiments. Taber abrasion offers the advantage of quantifying the abrasive wear behavior of particles with different shapes on a surface. In this work, an abrasive wheel made of silicon carbide was utilized to evaluate wear properties of specimens progressively over 5000 cycles. This experiment focused on testing two series of specimens to determine whether a bond coat composed of nickel, chromium, aluminum, and yttrium (NiCrAlY) improved the protective behavior of the APS aluminum oxide coating. The specimens varied in topcoat thickness and were made with and without an approximately 100 µm bond coat layer. The mass of the specimens was measured at 400 cycles, 800 cycles, 3800 cycles, and 5000 cycles. Increasing thickness was found to result in higher wear for samples with and without a bond coat. Increased mass loss in samples with a bond coat was observed indicating a need for further studies on the overall impact of the use of a bond coat on the protective behavior of the coatings. To continue designing wear resistant coatings for structural protection in space missions, the multifunctional properties of the APS aluminum oxide coating will be studied. Future experiments will determine whether the APS aluminum oxide coating can protect the structures from other aspects of the harsh space environment, such as extreme temperature variations and ionizing radiation.

Keywords: Lunar Exploration, Wear Resistance, Lunar Regolith, APS Alumina

Acronyms/Abbreviations

Air Plasma Spray (APS)
Nickel, Chromium, Aluminum, and Yttrium (NiCrAlY)
micrometers (µm)
millimeter (mm)

1. Introduction

Previous lunar missions have demonstrated that lunar regolith is a constraint for humans to return to the lunar surface. Lunar missions, such as during the Apollo program, found that lunar regolith causes wear damage to components used for space exploration. Factors such as the absence of an atmosphere or any form of erosion or fluid motion allow the particles to maintain their abrasive properties, affecting the integrity of the components used for lunar exploration during their activity [1]. Additionally, the lunar regolith is electrically charged and enhances the adhesive properties of the regolith particles at the surface of the components [2].

During the Apollo missions, observations regarding the effects of the lunar regolith were performed. It was observed that the lunar dust became elevated during landing, walking, and by the rover vehicle [3]. When the regolith is kicked up, it covers exposed areas, leading to increased friction at mechanical surfaces resulting in abrasive wear and tear effects, limiting the lifetime of surface equipment [4]. Previous studies have demonstrated that damage caused by lunar regolith projectiles during different landing stages is expected, considering the plume dynamics and its interaction with the lunar surface [4]. Other studies have shown that during the landing trajectory, damage on the hardware can happen due to the high velocity ejecta particles [5].

Aluminum 6061 is a lightweight alloy that has medium to high strength [6]. Studies have shown that aluminum composite reinforcements may improve the mechanical properties and wear resistance of the material. However, they have also shown that the addition of a coating improves the wettability and offers better interface bonding between the matrix and reinforcement [7]. Ceramic coatings have been used to protect the integrity of components from different damage mechanisms, such as wear and abrasion, in applications on Earth. In our previous work, the mechanical properties of air plasma spray (APS) alumina have been studied through Rockwell hardness and piezospectroscopy [8, 9]. The results demonstrated that the distance between each indent made during Rockwell hardness testing affected each other exhibiting an increase of stress at the indented region and lower stress values around the indents. The results also demonstrated that more indents applied to the coating decreased its hardness [8, 9].

Ceramic materials, such as aluminum oxide, have demonstrated high strength, wear resistance, and abrasion resistance. Understanding the properties of ceramic coatings for use as coatings for lunar applications has recently begun to determine their suitability as protective coatings that could minimize wear and abrasion caused by lunar regolith [10]. In the present study, the wear behavior of different layer thicknesses of APS aluminum oxide and the presence of a bond coat has been investigated through Taber abrasive experiments and analyzed by profilometry and goniometry measurements. These findings will be correlated with properties relevant to applications for future lunar exploration to increase the durability of the components used in identified applications.

2. Experiment and Sample Preparation

Aluminum 6061 disks with a diameter of 36.45 mm were plasma sprayed with aluminum oxide particles (Praxair*, ALO-101, median particle size d_{50} = 45 μm). In this study, the specimens were divided into two groups with Group A consisting of two sets of specimens (three specimens per set) with different layer thicknesses and without a bond coat layer. Group B had three sets of specimens (three specimens per set) with different layer thicknesses and a bond coat layer. The bond coat composition was nickel, chromium, aluminum, and yttrium (NiCrAlY) (Praxair, NI164-211, -106/+45 μm). The average layer thicknesses and the bond coat thickness, where present, are listed in Table 1.

Table 1. APS alumina coating bond coat and topcoat layer thickness in μm. Group A, specimens do not have a bond coat. Group B, specimens have a bond coat.

Sample Type	Estimated Bond Coat Thickness (μm)	Average Thickness (μm)
Group A-1	0	228.3 ± 11.7
Group A-2	0	461.3 ± 21.9
Group B-1	100	146.2 ± 11.6
Group B-2	100	581.4 ± 20.7
Group B-3	100	938.6 ± 16.6

A Taber Abraser (Qualitest GT-7012-T, Taber Industries) was used to create a wear path on the surface of the coating as shown in Fig. 1. The ASTM D4060 standard for abrasion resistance of organic coatings by the Taber Abraser was used in this study. The mass and layer thickness of each specimen was recorded with a weight balance (Analytical Balance ML204T/00) prior to performing the wear test. Abrasive wheels (CS-17 Calibrase wheels, Taber Industries) composed of a resilient binder and silicon carbide abrasive particles were used during the wear experiment. Each wheel had a load of operation of 4.9 Newton (N). A total of 5000 cycles was performed to compare with previous experiments performed at NASA Langley Research Center [10], and the mass of the specimens were measured at 400 cycles, 800 cycles, 3800 cycles, and 5000 cycles. The abrasive wheels were refaced with a diamond tool to allow for continuous wear.

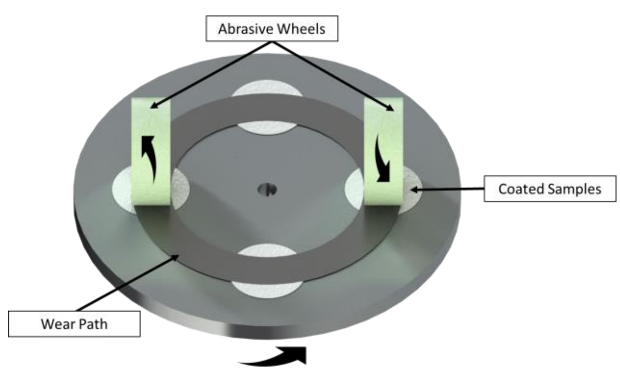

Fig. 1. Schematic of Taber Abraser test showing the specimens location and wear path.

The surface energy and roughness of the coating was measured before and after 5000 cycles of wear were completed. The surface energy measurement was performed with a contact angle goniometer (First Ten

* Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the analytical tools used. The use of vendor and manufacturer names does not imply an endorsement by the authors nor does it imply that the specified equipment is the best available.

Angstroms Goniometer-FTA1000). One droplet of water was deposited at three different locations on the specimen, as shown in Fig. 2. The stage rotated to a maximum of 60° at a rate of 2°/sec. The droplet had a desired volume of 8 µL. The roughness of the coating was measured with an optical profilometer (FRT Microprof 100 Profilometer) with an area of 20 mm x 20 mm, 1000 points/line, and 250 lines per scan. The scanned area allowed collection of data from the regions where the wear path would be created.

3. Theory and Calculation

The roughness and surface energy of the coating was demonstrated to play a role in the protection of the substrate from wear and abrasive damage. These two characteristics also play a role in the adhesive properties of the lunar regolith on the surface of the components [11]. For this study, the surface roughness and the surface energy were analyzed before and after completing 5000 cycles of Taber testing.

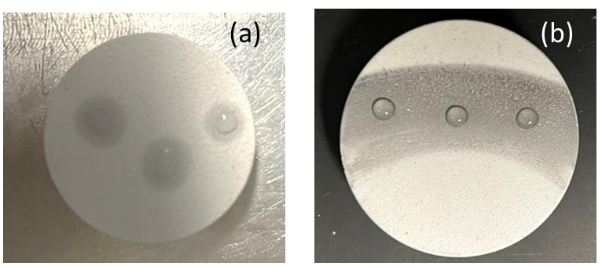

Fig. 2. APS alumina coated specimen for the contact angle goniometry measurement with the water droplets performed at different surface regions (a) before wear testing and (b) after wear testing.

3.1 Surface Roughness

The roughness of each sample was measured with an optical profilometer and averaging the surface roughness of the specimen. The average roughness of the coating was calculated with the FRT Mark III software using equation 1, where R_a is the mean roughness value, l_m, represents the measuring distance, and y is the peak height:

$$R_a = \frac{1}{\mathrm{I}_m}\int_0^{I_m} |y| dx \quad (1)$$

3.2 Surface Energy

Contact angle goniometry allows determination of wettability of a surface and calculation of the surface energy. The surface energy of the coating was calculated using equation 2. Where γ_S is the surface energy of the coating, γ_L is the surface energy of the liquid, and θ is the advancing contact angle measured with the contact angle goniometer:

$$\gamma_s = \frac{0.5\gamma_L(1 + cos\theta)^2}{\gamma_L} \quad (2)$$

4. Results

Results were analyzed using a MATLAB program to quantify the surface roughness of the coatings with different topcoat thicknesses with and without bond coats from Group A and Group B. The surface roughness was also studied and compared with the surface energy of the coating taking into account its potential effect on enhancing the adhesion force between the lunar regolith and the surface of the APS alumina coating.

4.1 Mass loss

Due to minimal mass loss at lower cycle numbers and to compare with results from previous work [10], the mass loss of each specimen was determined after 5000 cycles of abrasion and presented in Fig. 3. The mass of the specimens decreased by 0.10% and 0.13% for specimens from Group A with average thickness of 228.3 µm and 461.3 µm and 0.12%, 0.13%, and 0.21% for specimens from Group B with average layer thicknesses of 146.2 µm, 581.4 µm, and 938.6 µm, respectively. Regardless of group, the results demonstrated that the specimens with greater layer thickness had greater mass loss than the specimens with a smaller thickness. The specimens with a bond coat had comparable mass loss as the specimens without a bond coat for specimens with averaged layer thicknesses of 581.4 µm and 461.3 µm, as shown in Fig. 3, whereas the specimen with bond coat and thickness of 938.6 µm appeared to exhibit the highest amount of mass loss of all specimens investigated. Further investigation into the impact of bond coat on mass loss is underway. A higher mass loss was observed in the specimen with bond coat and thinnest topcoat of 146.2 µm compared to the specimen with thinnest topcoat of 228.3 µm and without bond coat was observed.

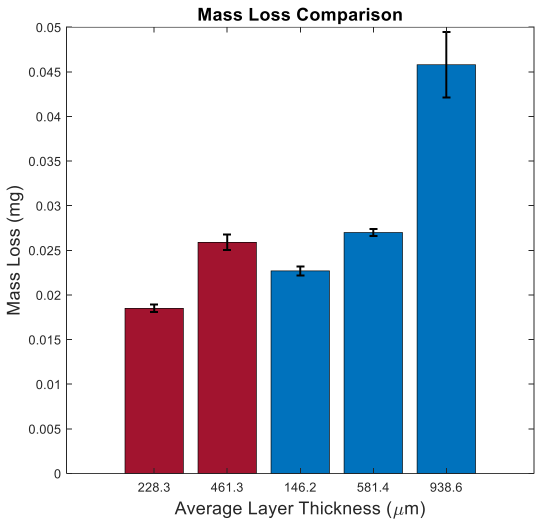

Fig. 3. Average mass loss of the APS alumina coating with different layer thicknesses and without (red) and with (blue) bond coat layers.

4.2 Surface Roughness

The relationship between surface roughness and layer thickness is shown in Fig. 4. The roughness of the coating increased with the layer thickness due to the solidification of the alumina particles during the spraying process. Smaller roughness values were obtained for larger layer thickness for both groups, as shown in Fig. 4. The specimens with a bond coat had higher roughness values due to the expected high roughness of the bond coat to improve the interlocking within the topcoat, alumina. Further analysis needs to be performed to determine the effect of its composition and the roughness values.

As shown in Fig. 5, coating roughness decreased to a range of ~ 0.6 µm to ~ 1.5 µm after 5000 cycles of Taber abrasion testing. The specimens from Group A with averaged layer thicknesses of 228.3 µm and 461.3 µm had a roughness decrement range of 0.496 µm to 1.095 µm and 0.392 µm to 0.548 µm, respectively. The specimens from Group B with averaged layer thicknesses of 146.2 µm, 581.4 µm, and 938.6 µm had a roughness decrement range of 3.146 µm to 1.229 µm, 2.514 µm to 1.381 µm, and 2.065 µm to 1.642 µm, respectively. The specimens from Group B had higher roughness values prior to the wear testing. This finding suggested that the thicker coatings in this study possessed a lower degree of starting roughness (Fig. 4).

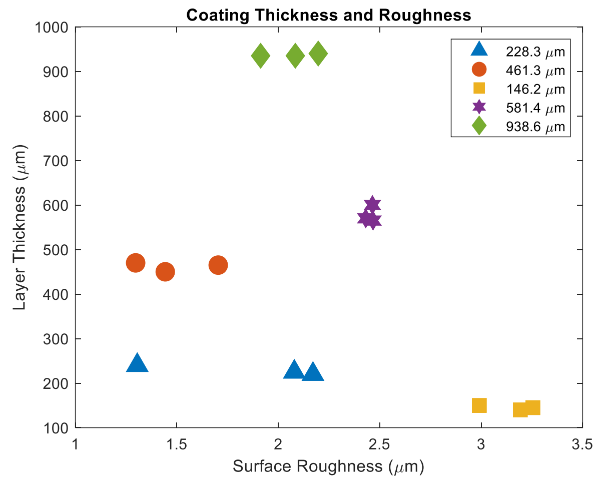

Fig. 4. Comparison between surface roughness and total layer thickness of the APS alumina coating before the wear and abrasive experiment.

4.3 Surface Energy

Contact angle goniometry measurements were performed before and after 5000 cycles of wear testing to investigate the adhesion properties of the APS alumina coatings. Prior to performing the wear test, the APS alumina samples were determined to be hydrophilic, since the contact angles were smaller than 90º, with a range of < 5º to 60.95º. Surface energy values for individual specimens before and after wear testing are shown in Fig. 5. After wear testing, the bond coat samples seemed to have greater surface energy values compared with samples without bond coats, though one specimen was observed in the sample set with thickness of 146.2 µm to be lower by approximately 15 mN/m. Additionally, for Group A specimens without a bond coat, one specimen for each thickness of 228.3 µm and 461.3 µm appeared to have a surface energy lower by about 12 mN/m and 25 mN/m, respectively, than the specimen from the same sample set with next lowest surface energy. Further study is ongoing to understand the discrepancies in surface energy measurements. Overall, a higher surface energy observed in the bond coat samples was expected due to the higher roughness values, since factors, such as roughness and porosity, might have contributed to the surface energy of the APS alumina. After the 5000 cycles of wear testing were performed, the contact angles had a range of 72.44º to 97.38º. As shown in Fig. 5, the surface energy of the coating appeared to decrease with the roughness reduction after the wear test was performed on every specimen, though further work will focus on understanding this apparent trend. In general, the results also suggested that the specimens with higher roughness may have experienced a greater surface energy reduction.

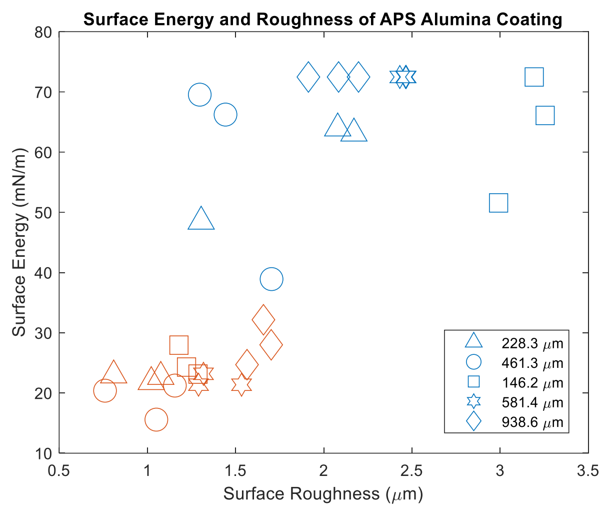

Fig. 5. Comparison between surface energy and surface roughness of the APS alumina coating before (blue) and after (red) the abrasive wear experiment.

5. Discussion

APS alumina was demonstrated to be a potentially suitable coating material to protect components used for lunar exploration due to its durability observed during the abrasive wear experiment. The decrease of roughness values after 5000 cycles suggested a decrease in the surface energy of the coating. The advancing water contact angle in the goniometry experiment increased with lower roughness values, making the coating hydrophobic. This finding suggests that after the coatings are worn, the adhesive force between the regolith particles and the surface of the coating decreases.

The coating specimen mass loss results (Fig. 3) suggested that specimens with a bond coat and topcoat thickness > 146.2 μm had greater mass loss compared to the specimens with no bond coat. However, specimens with bond coats were observed to have higher roughness values than the specimens without a bond coat. Different layer thicknesses were considered in this study to determine the effect during wear and abrasive damage. The results demonstrated that the specimens with a larger layer thickness experienced greater mass loss for Group A and Group B. Although studies have demonstrated that bond coats are effectively used as interlayers to promote adhesion and oxidation resistance of ceramic topcoats to the substrate and improve the durability of the ceramic coating [11], further analysis must be performed to compare the benefit of improved delamination properties the bond coat provides against these results to understand the impact of the bond coat on the overall protective behavior of the APS alumina coating.

The surface energy of the coating decreased around 60% for all specimens after Taber abrasion testing. As previously mentioned, the surface energy of the material plays a role with the adhesion forces between the lunar regolith and the surface of the components. Studies have demonstrated the adhesion force is dominated by the formed multiscale roughness of the aluminum surface. The dust adhesion appeared to increase with increasing surface energy [12]. In all samples for this work, the reduction in surface energy, which may consequently reduce regolith adhesion [13], over cycles appears to be a benefit of the use of these coatings. Current results suggest that the APS alumina coating has the ability to protect the substrate. Future work is ongoing to determine if the APS alumina coating may enable more durable lunar dust technologies.

6. Conclusions

The results demonstrated that the APS alumina coating could be a good candidate to protect components from wear and abrasive damage caused by the lunar regolith. The competing wear properties and delamination benefits of the bond coat must be further investigated to establish its role in the protective behavior of APS alumina coatings. For all samples in Group A and Group B, larger layer thicknesses were also demonstrated to show greater mass loss during the wear test. The results quantify how surface energy and the roughness of the APS alumina coating play a role in the wear behavior. The specimens with the bond coat will be further studied to determine whether the bond coat enhanced the protective behavior of the APS alumina coating and the adhesion of the coating with the substrate. Further studies to investigate development of coatings with controlled surface properties, including polishing to improve the surface characteristics, will be performed and compared with the results collected from the original surface properties.

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The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government nor does *it imply that the specified equipment is the best available.*

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