

Developing Abrasion Test Standards for Evaluating Lunar Construction Materials

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ABSTRACT

Operational issues encountered by Apollo astronauts relating to lunar dust were catalogued, including material abrasion that resulted in scratches and wear on spacesuit components, ultimately impacting visibility, joint mobility and pressure retention. Standard methods are being developed to measure abrasive wear on candidate construction materials to be used for spacesuits, spacecraft, and robotics. Calibration tests were conducted using a standard diamond stylus scratch tip on the common spacecraft structure aluminum, Al 6061-T6. Custom tips were fabricated from terrestrial counterparts of lunar minerals for scratching Al 6061-T6 and comparing to standard diamond scratches. Considerations are offered for how to apply standards when selecting materials and developing dust mitigation strategies for lunar architecture elements.

INTRODUCTION

The Vision for Space Exploration (VSE), announced in 2004, refocused NASA's direction to "undertake lunar exploration activities to enable sustained human and robotic exploration of Mars and more distant destinations in the solar system" [1]. The VSE then led to the NASA Authorization Act of 2005, calling for a "sustained human presence on the Moon". Before humankind returns to its nearest celestial body, however, research is needed to better understand many characteristics of the Moon, and in particular, lunar dust, which caused numerous problems for the crew and hardware on the six Apollo surface missions. While astronaut safety concerns are the top priority, dust mitigation will also be needed for

other surface elements of the lunar architecture, including the Lunar Lander *Altair*, Extravehicular Activity (EVA) Systems (EVAS), crew surface mobility aids and robotic systems. NASA's Global Exploration Strategy (GES) is the blueprint for implementing the VSE. Under the theme of Exploration Preparation, one of the highlighted objectives presented at AIAA's 2nd Space Exploration Conference (Houston, TX, 2006), was to "evaluate and employ dust mitigation techniques to protect crews, materials, and instruments during extended surface stays" [2]. As further explained by Tony Lavoie, this will be critical to test technical capabilities, and characterize critical environmental parameters and lunar resources. The GES also led to the announcement of the Lunar Architecture Team (LAT) who released two reports on defining lunar objectives. In the fall of 2007, the Constellation Architecture Team-Lunar (CxAT-Lunar) was formed to investigate the transportation elements of future missions [3]. Then, per the results and assessment of the Exploration Systems Architecture Study, the Dust Management Project (DMP) was created in NASA's Exploration Technology Development Program. Implementation of the DMP continues to be refined by the results of follow on NASA studies and technology needs assessments for the Constellation Program. The DMP has investigators spread across different centers, industries and universities, and is structured into four main branches including Engineering Design Environment, Technology Development, Technology Integration and Testing, and Education and Outreach. The abrasion work presented here falls under the first branch in the areas of Regolith Characterization and Simulant Development and Characterization.

BACKGROUND

A detailed characterization of the lunar environment and a review of abrasion theory were described in a paper presented at the International Astronautical Congress, 2008, Glasgow, UK [4]. Select information is summarized in this paper.

APOLLO ERA

Gaier [5] cataloged the specific effects of lunar dust on EVAS during the Apollo era and additionally noted that the severity of dust problems was consistently underestimated by ground tests. Points of concern for astronauts on lunar EVA included issues such as vision obscuration, false instrument readings, dust coating and contamination, loss of traction, clogging of mechanisms, abrasion, thermal control problems, seal failures, inhalation and irritation, excessive crew time being used to clean EVA suits and equipment, and electrical conductivity. Problems plagued the entire mission from before touchdown, when jet-blasted dust impeded vision and led to a landing that straddled a crater, to continuous eye irritation on the return trip to earth. Dust abrasion problems that are specific to this research included:

- Conrad and Bean's suits were worn through above the boot, including Micrometeoroid protection layer and several layers of Kapton® multi-layer thermal insulation were breached
- Wear noted on outer layer of Mylar® multi-layer insulation on boots
- Pressure integrity failures
- Gauge dials scratched (Lunar Roving Vehicle (LRV) unreadable on Apollo 16) and pitted
- Harrison Schmitt's visor sunshade so scratched he could not see in certain directions (Apollo 17)
- Apollo 17 astronaut glove covers were worn through after drilling cores on two (of three) EVA excursions

DUST IN THE LUNAR ENVIRONMENT

Understanding the dynamics of the lunar environment is essential to being able to characterize the forces and variables that can affect lunar dust transport and material abrasion. Lunar soil primarily results from innumerable micrometeorite impacts forming everything from spheres to highly angular and irregular shape silicate glass particles [6]. Pulverization of the lunar materials creates small particles or causes agglutinate formation to occur which forms large particles or conglomerates (or impact breccias). Pulverization can also completely melt the materials forming glass [7]. This process causes some mixing from region to region on the Moon, but in the absence of an atmosphere or any form of erosion or fluid motion, the particles are not sorted by size and they maintain their abrasive properties. Lunar dust less than 20 µm accounts for 10-

20% of the regolith's bulk mass [6]. NASA's Constellation program uses a definition of less than 10 µm for dust [8], while the DMP in NASA's Exploration Technology Development Project has heretofore been using 20 µm. Traditionally the Moon is categorized into two distinct regions: the basaltic-rich mare and the anorthositic highlands. The regolith is deeper in the older highlands than the maria. The maria contain dark basalts, while the lunar highlands have lighter-colored feldspar-rich rocks [9]. For abrasion considerations, the region where exploration will take place will dictate the type of dust particle interactions on hardware. Other environmental considerations for abrasion testing include:

- Relative micrometeorite bombardment (distributed approx. by power law, sizes ranging 30-150 µm in radius, masses of 10^{-10} to 10^{-8} kg, and impact at speeds averaging 7 km/s) [9], the "backside" of the Moon experiences a higher rate of micrometeorite impacts
- Earth-Moon orbital alignment with respect to the Sun
 - Temperature (40 Kelvin - 396 Kelvin) [10]
 - Electrostatic charging via photoelectric effects
 - Radiation
- Lunar gravity (mean equatorial force 1.62 m/s^2) [10]
- Near vacuum (approx. 10^{-14} torr)
- Absence of humidity
- Chemical reactivity (within exposed air systems) [11]

The properties and composition of dust particles of less than 20 µm are not well known, as this portion of returned lunar samples was not well preserved, partially because the dust grains in that range tended to adhere to the sample bags and were not removed for analysis. Relative density increases with regolith depth, suggesting that the regolith becomes more compact the further down it occurs [9]. Because of the properties of density, void ratio, cohesion, and friction angles, crater rims are expected to be less dense (less than 50%) than the surrounding lunar terrain [9]. This is important to note for exploration activity, as it may result in more dust leaving the surface as well as greater penetration of hardware into the soil. Regolith density from actual missions was found to be higher than predicted, and the increase with depth was suggested to be primarily due to self-weight. Density estimations and calculations suggest that the soil on slopes is considerably less stable [12].

ABRASION THEORY / HARDNESS

The lunar science community identified the abrasive nature of lunar dust as one of the top five physical properties of interest. Abrasion's importance was ranked as 'high' because it affects any material that moves or has a sealing surface. In the field of Tribology, abrasion is one of the four basic types of wear or physical mechanisms for material removal or displacement [13]

and is the most severe and most costly form of wear [14]. Wear is not a basic material property, but a system response of the material as a function of its use [13]. Abrasive wear occurs when a hard protuberance (asperity) on the surface of a material, or a hard, loose particle trapped between surfaces, plastically deforms, gouges or cuts the counter surface as a result of motion. The result is a series of grooves in soft material or surface fractures in brittle material. Additionally, with hard material this is often accompanied by the resulting formation of wear particles. Abrasion can be sub-categorized by degree of freedom into two tribosystems; two-body and three-body wear. Two-Body abrasive wear occurs when hard particles or protuberances, which produce the wear of one body, are fixed on the surface of the opposing body [15]. A simplified example would be sandpaper against a surface. Three-Body abrasive wear occurs when loose particles are introduced or generated between the contacting surfaces [15]. For example, this occurs when sand is continually poured between two plates rubbing against each other. Two-body fixed abrasives are typically used for testing plastics, metals, ceramics, and composites, while 3-body testing is used for all materials [14].

Degree of freedom influences the abrasiveness of a test, and generically two-body abrasion will produce significantly higher wear than three-body, because three-body particles have the ability to roll. This may make two-body measurement easier to obtain since the wear would be more sizeable. The wear on a material is fairly constant when the abrasive is much harder than the material. For this reason, the material property of hardness can be used as an estimate of how much abrasion is expected between a pair of materials.

Hardness is the resistance to plastic deformation. The traditional and earliest quantifiable method of measuring hardness is by a scratch test, which compares the ability of the substance to scratch or be scratched by a series of standard minerals. With several standard tests methods available, lunar dust hardness can be approximated (see Figure 1 for scale comparison and commonly used or proposed space construction materials). In passing, it should be noted that hardness ranges occur for minerals due to compositional variation (e.g., Diamond) and crystal orientation (e.g., Apatite).

A wear coefficient, k , can be determined by measuring the wear volume after an abrasive test and knowing the load used, the sliding distance, and the hardness of the softer material as seen in Equation 1 [15] (Note, when calculating k , the wear volume divided by the sliding distance is the average cross sectional wear area).

$$\text{wear volume} = k \left(\frac{\text{load} \times \text{sliding distance}}{\text{hardness of softer material}} \right) \quad \{1\}$$

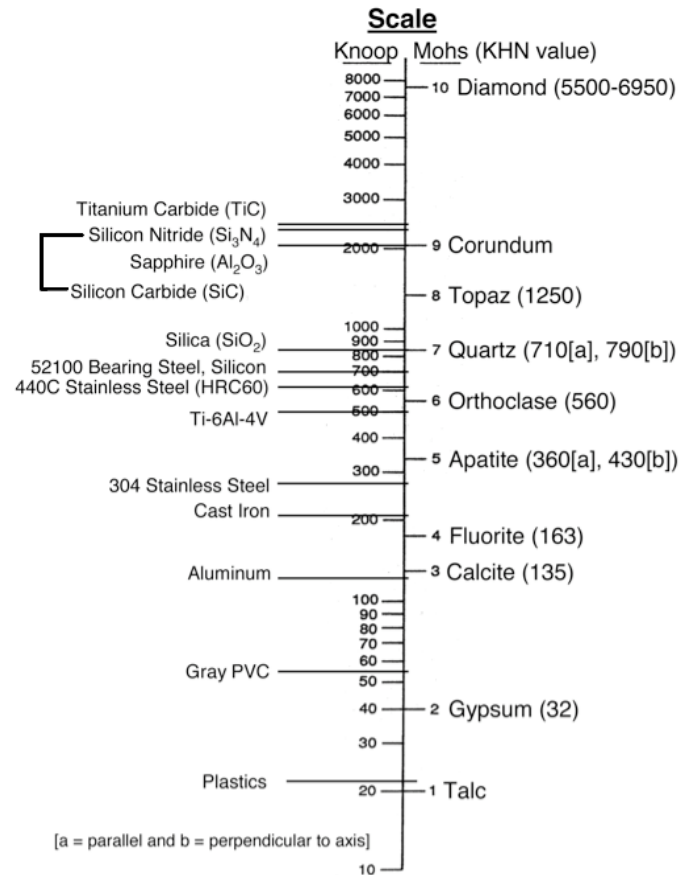


Figure 1. Comparison of Mohs to Knoop hardness [7] with typical spacecraft materials

When the material and abrasive hardness's are similar, the interactions approach polishing, and wear resistance improves by an order of magnitude. Since the wear coefficients for these materials would be similar, Equation 1 would no longer be valid. The k -value for abrasion relates to the sharpness, or geometry, of the asperity or particle causing the wear. Equation 1 is the simplest form of the wear equation, where k also physically represents the average tangent of the roughness angle divided by π [16] as seen in Figure 2. In Figure 2, the abrasive grain removes material from a bearing surface over a distance of x .

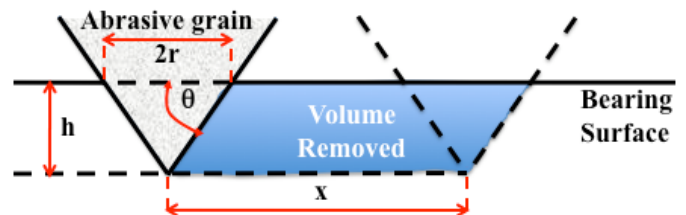


Figure 2. Simplified abrasive wear model showing how a cone removes material from a surface [adapted from 16]

ASTM Standard G 171-03 [17] specifies calculating a Scratch Hardness Number, HS_p (Pa), based on applied normal load, P (N), and scratch width, w (m) as shown in Equation 2.

$$HS_p = \frac{8P}{\pi w^2} \quad \{2\}$$

This relationship assumes a hemispherically-tipped stylus that produces a groove whose leading surface has a radius of curvature, R , the tip radius of the stylus. The projected area of the contact surface is a semi-circle with diameter equal to the scratch width [17]. With scratches on the order of microns, expected values of HS_p are in the GPa range.

The two main failure modes relating to hardness were noted by Rickman and Street [7] as occurring along preferential orientations controlled by crystallography or independent of orientation. These failure modes can then be related to the abundant lunar minerals and how conchoidal fractures occur in minerals and glass creating sharp, serrated edges or highly angular (pointed) tips. The crystal orientation relating lunar mineral shape formation to hardness and then to abrasion will be further investigated. Another observation was that two minerals with similar hardness values but different toughness values (ability to absorb mechanical or kinetic energy up to failure) produced different wear levels.

For nonmetallic materials, hardness is also affected by relative humidity [18]. Westbrook and Jorgensen showed that micro-hardness was lowered by absorbed water, but confined to a region not more than 3 μm from the free surface. In addition, hardness can change with depth of penetration from the surface [19]. Since scratching depth can be estimated by $1/10^{\text{th}}$ of a particles diameter, a particle with a diameter larger than 30 μm would scratch below the absorbed water region of a nonmetallic material. In the lunar regolith, 10-20% of the particles are finer than 20 μm with an unaccounted for hardness [6, 8]. Multiple scratches from dust can penetrate surface coatings and treatments, while larger particles could penetrate a coating in a single scratch.



Figure 3. CSM Revetest Scratch tester with glovebox enclosure for humidity reduction

TWO-BODY SCRATCH TESTING

In order to investigate the fundamental science of material interactions, a two-body scratch test was determined to be the most efficient apparatus. The American Society for Testing and Materials (ASTM) standard G 171-03 [17] prescribes using a diamond tipped stylus with a constant normal load with recommendations for speed of travel. The CSM Revetest Scratch Tester (see Figure 3) was used with a 200 μm radius diamond tip with 120° angle to acquire baseline scratch data on commonly used aluminum alloy, Al 6061-T6 (see Figure 4). Al 6061-T6 was chosen as the initial testing phase material for the following reasons.

- Al 6061-T6 is commonly used in space structures
- Al 6061-T6 has well documented material properties
- It is known that the abrasives will wear the material in a measurable amount

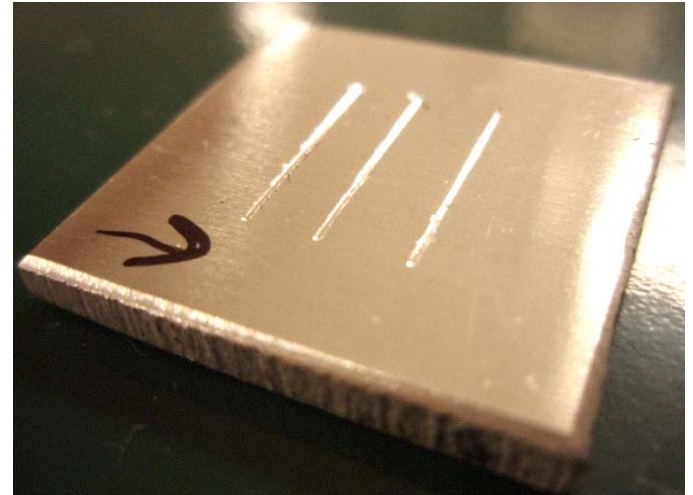


Figure 4. Specimen of Al 6061 T6 with three scratches

The spherical tip of the diamond indenter allows for theoretical width measurement, $2 \times a$, to be calculated from the semi-angle of the apex, θ , tip radius, R , and scratch depth, δ_p (see trigonometry formulas in Equation 3 [20] and Figure 5). This dimensionality can be expanded to custom shaped tips and will be investigated in this research effort.

$$\begin{aligned} \delta_s &= R(1 - \sin \theta) \\ \phi &= \cos^{-1}(1 - \delta_p/R), & \text{for } \delta_p \leq \delta_s \\ a &= R \sin \phi, & \text{for } \delta_p \leq \delta_s \\ a &= R \cos \theta + (\delta_p - \delta_s) \tan \theta, & \text{for } \delta_p > \delta_s \end{aligned} \quad \{3\}$$