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Validation of proposed metrics for two-body abrasion scratch test analysis standards

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ABSTRACT

The objective of this work was to evaluate a set of standardized metrics proposed for characterizing a surface that has been scratched from a two-body abrasion test. This is achieved by defining a new abrasion region termed 'Zone of Interaction' (ZOI). The ZOI describes the full surface profile of all peaks and valleys, rather than just measuring a scratch width as currently defined by the ASTM G 171 Standard. The ZOI has been found to be at least twice the size of a standard width measurement, in some cases considerably greater, indicating that at least half of the disturbed surface area would be neglected without this insight. The ZOI is used to calculate a more robust data set of volume measurements that can be used to computationally reconstruct a resultant profile for detailed analysis. Documenting additional changes to various surface roughness parameters also allows key material attributes of importance to ultimate design applications to be quantified, such as depth of penetration and final abraded surface roughness. Data are presented to show that different combinations of scratch tips and abraded materials can actually yield the same scratch width, but result in different volume displacement or removal measurements; therefore, the ZOI method offers a more robust assessment than the current ASTM analysis method. Furthermore, by investigating the use of custom scratch tips for our specific needs, the usefulness of having an abrasion metric that can measure the displaced volume in this standardized manner, and not just by scratch width alone, is reinforced. This benefit is made apparent when a tip creates an intricate contour having multiple peaks and valleys within a single scratch. This work lays the foundation for updating scratch measurement standards to improve modeling and characterization of three-body abrasion test results.

1. Introduction

A key physical property associated with lunar regolith (as well as regolith from other extraterrestrial destinations) is its highly abrasive quality. Abrasion of mechanical components and fabrics by soil on Earth is typically minimized due to the effects of atmosphere and water eroding sharp and pointed geometrical features from potential abrasive particles. In environments where these erosive forces do not exist, such as the vacuum of the moon, particles retain geometries associated with the abrupt fracturing of their parent particles by micrometeorite impacts. The relationship between hardness of the abrasive and that of the material being abraded is well understood, such that the abrasive ability of a material can be estimated as a function of the ratio of the hardness of the two interacting materials, ignoring toughness [1]. Applying this simplified relationship to the lunar mineral composition, one would expect the moon to have modest abrasive ability, considering that many of the lunar particles also have sharp edges and points [2].

Similar analogies can be made with regard to the particulate hardness and toughness, although direct correlation between lunar and terrestrial mineral counterparts has recently come into question due to friability documented for grain particles composed of lunar breccias [3]. Recent discoveries in lunar geology indicate that the moon is not as homogeneous as previously thought; therefore, a simple generic Mare and Highlands regolith composition may no longer be realistic. Instead, there may be vast regions of interest where the composition is nearly pure spinel, which is considerably harder than the bulk constituents of either Mare or Highland material [4]. Hence, our interest in fabricating custom scratch tips for use in fundamental abrasion studies for lunar and other extraterrestrial exploration systems are growing. When changing tip materials and geometries, the standard scratch test method based on scratch width alone leaves much to be desired, as it ignores a considerable amount of information associated with a scratch, such as material removal versus displacement and the magnitude of the actual region of interaction in the test material.

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Table 1
Summary of improvements to current scratch standard.

Current standard (ASTM G 171 properties)	Identified limitations for current ASTM G 171	Proposed new standard
Manual measurements by optical investigation	-Measurement errors/variations -One dimensional	3D profile generation by optical interferometery
Scratch width is key variable	-Volume not considered	Total volume and surrounding area (ZOI)
Determination of width boundary conditions	-Random boundary placement for width measurement on fringes	Knowledge of width location not required
Diamond tip stylus	-Limited testing scenarios	Application specific tip materials. Ex. Lunar mineral tips demonstrated

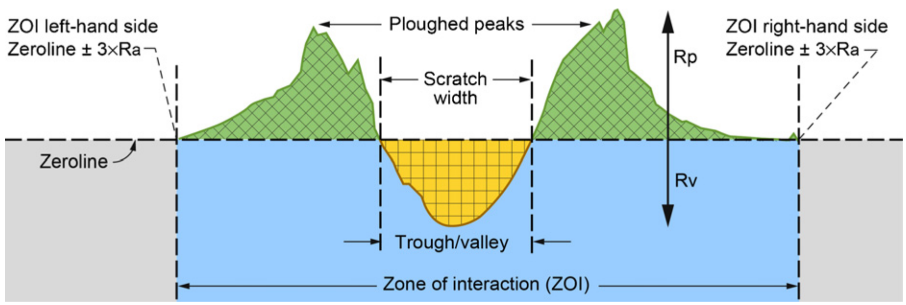

Fig. 1. Example of boundary conditions for Zone of Interaction at ±3× surface roughness (R_a) showing negative and positive displacements.

This paper is a continuation of prior work that proposed a set of standardized volumetric displacement metrics for analyzing two-body abrasion scratch test results [5]. Technology limitations were identified in the current ASTM G 171 Standard for scratch testing [6], which specifies scratch width as the key measurement. The development of new imaging capabilities that allow a complete profile to be characterized in a three-dimensional (3D) array was developed to enable a more detailed analysis of the scratched surface to complement the current standard. Table 1 summarizes the proposed new standard attributes. The 'Zone of Interaction' (ZOI) is used to characterize the entire abrasive wear area, including the surface outside of the scratch width boundaries, as indicated in Fig. 1. The ZOI extends to either side of the scratch as far from the scratch as the surface disturbance occurs. The ZOI was developed to distinguish between two scratches with the same width that do not necessarily have the same volumetric profile shapes. To define a set of boundary conditions for the ZOI, surface roughness (R_a) is used to provide a standardized indicator of transition zones along the Zeroline (ZL). The ZOI transition occurs when the surface height from the ZL is plus or minus a pre-determined multiplier times the R_a. This boundary and multiplier is represented in Fig. 1 as $\pm 3 \times R_a$, a value that was selected to provide a high degree of confidence in locating the intersection of the ZOI edge and the ZL which is also verified by a variable sensitivity study [5]. The study showed that the surface roughness blemishes from specimen polishing were captured in the ±3× value for most of the 823 scratches analyzed by this method and that the ZOI boundaries could be accurately located. For example, changing the multiplier to 10× ensured that essentially no surface imperfections set off boundary false-positives, but part of the ZOI was lost in the initial transitions, which begin at less than $10 \times R_a$. The multiplier will be dependent on the edge detection coding used by an individual researcher and the $3 \times R_a$ should be used as an initial guideline value. This work provides quantitative results obtained using our previously developed protocol [5] to demonstrate the benefit of augmenting the current ASTM standard to include the enhanced 3D volumetric measurements that are now achievable using optical interferometry.

The standard roughness parameters, which complement the new proposed metrics and help define the material surface before and after abrasion include: surface roughness (R_a); root-mean squared roughness (R_q); maximum depth of penetration or deepest point (R_v); maximum displaced height or highest point (R_p); peak-to-valley difference ($R_t = |R_p| + |R_v|$); and average ten greatest peak-to-valley separations (R_z) [7]. R_q and R_z are included in the calculations in this paper because they are part of an industry standard set that may be useful in future work.

Table 2
Proposed metrics normalized by ZOI and scan length.

Metric	Description	Formula [μm]
A1	Negative Displaced Metric	$\frac{\text{Negative Volume Displaced}}{\text{ZOI}_{\text{Average}} \times \text{Scratch Scan Length}}$
A2	Positive Displaced Metric	$\frac{\text{Positive Volume Displaced}}{\text{ZOI}_{\text{Average}} \times \text{Scratch Scan Length}}$
A3	Net Displaced Metric	$A1 + A2$
A4	Absolute Displaced Metric	$\lvert A1 \rvert + \lvert A2 \rvert$

The proposed metrics defined in Table 2 use the ZOI to normalize a scratch volume and the length of the scratch scanned in each profile (not complete scratch length) yielding units of μm. The surface roughness parameters are referred to as Metric Set B, and include initial measurements on the polished material and final conditions bounded by the ZOI (units are μm for all six values).

2. Materials and methods

All two-body abrasion scratches were made using a CSEM (now CSM Instruments, Neuchatel, Switzerland) Revetest automatic scratch tester CH-2000 Neuchatel 7 (FR-A 121) per ASTM G 171 guidelines (see Fig. 2). In the scratch tester, a material specimen is horizontally translated at a controlled speed (10 mm/min) while a stationary diamond tip stylus is applied vertically under a specified normal load. For this study, a variety of tip sizes with differing mineralogy were examined on typical spacecraft materials to investigate the potential abrasive wear from lunar dust for surface exploration design applications.

Aluminum (Al) 6061-T6 and stainless steel 304 were used as two common spacecraft material specimens. Each sample was polished with 1 μm alumina powder and water on a polishing wheel to remove minor surface imperfections and even out any material thickness differences. Polycarbonate with titanium dioxide (TiO_2) coating is typically used for spacesuit helmet visors and represents another critical application-driven material to characterize. The