NASA/TM—2010-216347

Standardization of a Volumetric Displacement Measurement for Two-Body Abrasion Scratch Test Data Analysis

Ryan L. Kobrick and David M. Klaus
University of Colorado at Boulder, Boulder, Colorado

Kenneth W. Street, Jr.
Glenn Research Center, Cleveland, Ohio

May 2010

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 443–757–5803

- Telephone the NASA STI Help Desk at 443–757–5802

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2010-216347

Standardization of a Volumetric Displacement Measurement for Two-Body Abrasion Scratch Test Data Analysis

Ryan L. Kobrick and David M. Klaus
University of Colorado at Boulder, Boulder, Colorado

Kenneth W. Street, Jr.
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

May 2010

Acknowledgments

This research was supported by a NASA Graduate Student Researchers Program (GSRP) grant (NNX07AR55H) provided by the Dust Management Project, under the Exploration Technology Development Program. Matlab assistance was provided by Kevin Higdon, Ph.D. Candidate (UCB) and Bradley W. Cheetham, Ph.D. Student (UCB). SEM work was conducted by Prof. Sayed M. Khalil (Sohag University, Egypt) at the Nanomaterials Characterization Facility, UCB. Test equipment and support were provided by NASA Glenn Research Center. Additional support was provided by BioServe Space Technologies (UCB) and the Achievement Rewards for College Scientists (ARCS) Foundation, Inc.

This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

Trade names and trademarks are used in this report for identification only. Their usage does not constitute an official endorsement, either expressed or implied, by the National Aeronautics and Space Administration.

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://gltrs.grc.nasa.gov

Standardization of a Volumetric Displacement Measurement for Two-Body Abrasion Scratch Test Data Analysis

Ryan L. Kobrick and David M. Klaus
University of Colorado at Boulder
Boulder, Colorado 80309

Kenneth W. Street, Jr.
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

A limitation has been identified in the existing test standards used for making controlled, two-body abrasion scratch measurements based solely on the width of the resultant score on the surface of the material. A new, more robust method is proposed for analyzing a surface scratch that takes into account the full three-dimensional profile of the displaced material. To accomplish this, a set of four volume displacement metrics are systematically defined by normalizing the overall surface profile to statistically denote the area of relevance, termed the "Zone of Interaction" (ZOI). From this baseline, depth of the trough and height of the ploughed material are factored into the overall deformation assessment. Proof of concept data were collected and analyzed to demonstrate the performance of this proposed methodology. This technique takes advantage of advanced imaging capabilities that now allow resolution of the scratched surface to be quantified in greater detail than was previously achievable. A quantified understanding of fundamental particle-material interaction is critical to anticipating how well components can withstand prolonged use in highly abrasive environments, specifically for our intended applications on the surface of the Moon and other planets or asteroids, as well as in similarly demanding, harsh terrestrial settings.

Introduction and Background

When reviewing existing data analysis techniques for conducting two-body abrasive scratch tests, it was found that the ASTM International (ASTM) Standard, G 171 (Ref. 1), specified a generic metric based only on an observed scratch width as a way to compare abraded materials (see Fig. 1). A limitation to this method was identified in that the scratch width is based on optical surface measurements, manually defined by approximating the boundaries, but does not consider the three-dimensional (3D) volume of material that was displaced. With large, potentially irregular deformations occurring on softer materials, it becomes unclear where to systematically determine the scratch width (Ref. 2). This issue arose when scratch tests were conducted using custom indenter tips that did not leave traditional uniform wear scars. Specifically, as indicated in Figure 1, surface scratches on different samples may look the same from a top view resulting in an identical scratch width measurement, but may vary in actual penetration depth and/or ploughing deformation. Therefore, two different scratch profiles would be measured as having identical abrasion properties, although they differ significantly. Another limitation was encountered when considering the use of a variety of scratch tips for different test needs, since the ASTM G 171 Standard is only intended to be directly applicable for spherical diamond tips.

The goal of this study was to define and evaluate more robust standardized data analysis metrics for abrasion testing capable of distinguishing volumetric impacts to the material. With these refined measurements, a wider variety of testing needs can be addressed with greater resolution while using the most appropriate abrasive tip and test material combination for the intended application.

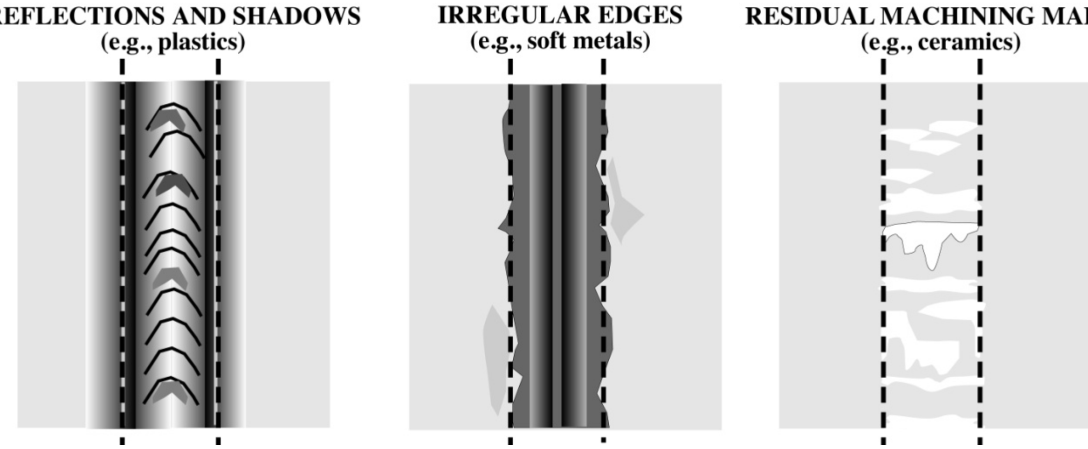

Figure 1.—Top view of materials illustrating the potential for equal scratch width measurements to be made for varying volumetric displacement results. Width is used in ASTM Standard G 171 to define two-body abrasion from scratch testing [1, Courtesy of P.J. Blau, Oak Ridge National Laboratory].

Our motivation for improving the existing two-body abrasion metrics stemmed from related lunar surface exploration research being conducted within the Dust Management Project (DMP) of the National Aeronautics and Space Administration (NASA). During the Apollo era, astronauts exploring the Moon experienced numerous material wear issues that were attributed to the fine-grained lunar dust (Ref. 3). The Moon's near-vacuum environment and the constant bombardment of micrometeorites allow lunar dust particles to retain their irregular shape, consequently making them especially abrasive (Refs. 4 and 5). The fine particles in this context are typically characterized by their different sizes, ranging from <1 to 50 µm (Refs. 6 and 7). Although specific definitions between groups vary, on average, researchers refer to particles with diameters less than 20 µm as "dust" (Refs. 8 and 9).

One goal of the research being conducted within the DMP is to develop recommendations and standard testing protocols for evaluating the impact of lunar dust abrasion on proposed surface system materials and operations. Both two-body and three-body abrasion modes are currently being investigated for future NASA testing of lunar equipment in a more relevant environment using abrasives that parallel lunar regolith. Lunar regolith occupies the upper several meters (in some cases potentially to 15 to 20 m) of the Moon and consists of unconsolidated rocks, pebbles, and dust over lunar bedrock (Ref. 10). Two-body abrasion was selected for these initial studies because it thoroughly characterizes the fundamental interaction of a defined single particle asperity abrading a material with known properties. To more accurately represent the anticipated dust abrasion that will occur on the lunar surface, custom tips were developed for scratch testing using terrestrially-obtained minerals similar to the lunar mineralogy (Ref. 4) and the tests were conducted on typical spacecraft materials. Our observations of the results led to a series of recommended standardization metrics, described in the following section.

Experimental Materials and Methods

The core of this two-body abrasion research was conducted using a CSEM (now CSM Instruments, Neuchatel, Switzerland) Revetest automatic scratch tester with ASTM G 171 used as a guideline for determining the number of tests to be conducted (specified as three scratches, each with three width measurements). By using a standard test approach and changing the output methodology, new metrics could strengthen the shortcomings of the ASTM G 171 Standard. Calibration scratches (shown in Fig. 2) were first made to record the scratch speed. Since the tester was moved from NASA Glenn Research Center (GRC) to the University of Colorado in Boulder (UCB) and back, three calibration runs were conducted. Table 1 summarizes all of the scratch tests performed (except calibrations) with their respective test location. Unless indicated, three scratches were conducted for each normal load and three surface profiles were taken for each scratch. Aluminum (Al) 6061-T6 and stainless steel 304, which are

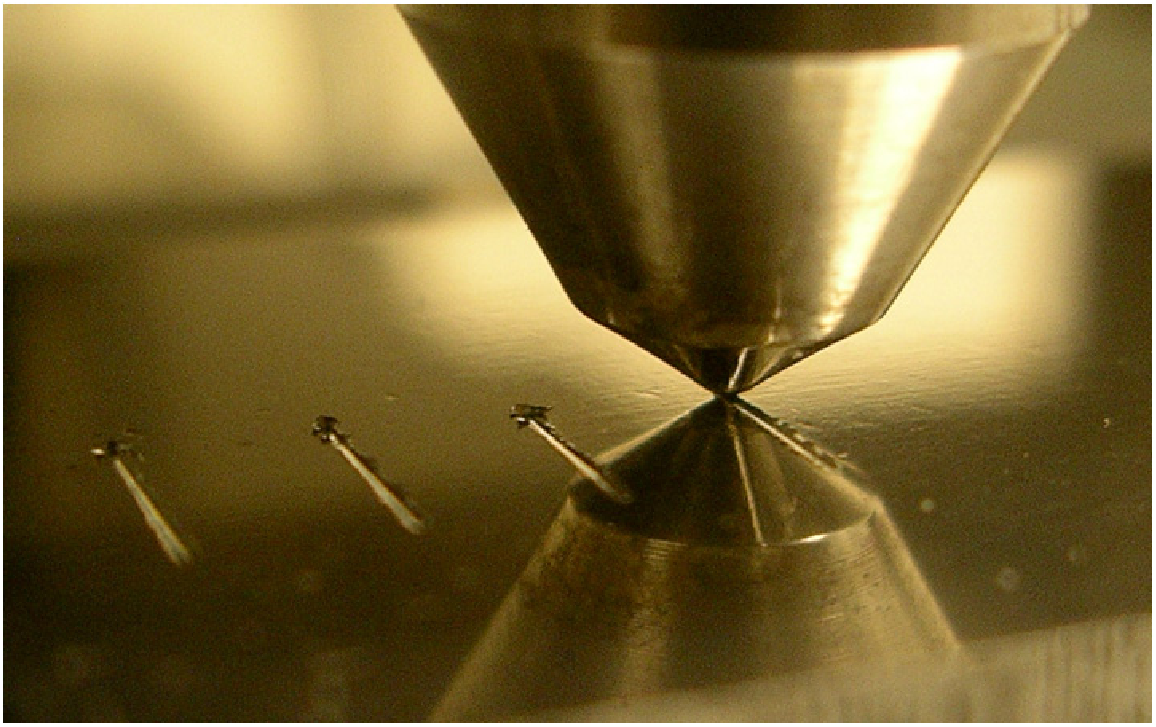

Figure 2.—Diamond 200 µm radius tip mounted on Revetest automatic scratch tester abrading Al 6061-T6 as specified by ASTM G 171.

TABLE 1.—TWO-BODY ABRASION SCRATCH TEST SUMMARY

Set	Purpose	Scratch tip (radius)	Abraded material	Applied normal load (N)	# Scratches	# Profiles	Location
1	Baseline data	Diamond (200 µm)	Al 6061-T6	5, 10, 15, 20, 40, 60	36	108	GRC
2	Proof of Concept	Anorthosite	Al 6061-T6	5, 10, 15, [a]20, [a]40, [a]60	12	36	GRC
3	Full data set	Ruby spinel	Al 6061-T6	5, 10, 15, 20, 40, 60, 80	42	128	UCB[c]
4	Baseline data	Diamond (200 µm)	Al 6061-T6	10, 20, 30, 40, 50, [a]55 60, 80, 100, 120	28	84	UCB
5	Alternative geometry	Diamond (109 µm)	Al 6061-T6	10, 20, 30, 40, 50, 60, 80, 100, 120	27	81	UCB
6	Nonmetal data set	Diamond (200 µm)	Polycarbonate +TiO_2 coating	5, 10, 20, 30, 40	15	45	GRC
7	Full data set	Diamond (200 µm)	Stainless Steel 304	10, 20, 30, 40, 50, 60, 70, 80, 100, 120, 140, 160, 180	39	119	GRC[d]
8	Full data set	Diamond (109 µm)	Stainless Steel 304	10, 20, 30, 40, 50, 60, 70, 80, 100, 120, 140, 160, 180	39	117	GRC
9	Proof of concept	Olivine	Al 6061-T6	5, 10, 20, [b]30	11	33	GRC[e]
10	Proof of concept	Enstatite	Al 6061-T6	5, 10, 15	9	27	GRC
11	Speed testing	Diamond (200 µm)	Al 6061-T6	40 (5 speeds)	15	45	GRC
				TOTAL	**273**	**823**	

[a]1 scratch only
[b]2 scratches only
[c]2 extra scans - Begin and End
[d]2 extra scans - Polish versus Unpolished
[e]2 extra scans - Tip indent x2, 1st 30 N scratch 1 scan only

common spacecraft structure materials, were used as the abraded material. Each sample was polished with a 1 μm alumina powder and water on a polishing wheel to remove minor surface imperfections and even out any material thickness differences. The polycarbonate with titanium dioxide (TiO_2) coating is typically used for spacesuit helmet visors and is considered a critical material to characterize. Crystal pedigree and orientation for the custom mineral tips are not reported in this paper. Diamond tips used in these scratch tests are described by their radius dimension (200 and 109 μm both with a 120° apex tip angle).

For nonmetallic materials, hardness is affected by relative humidity (Ref. 11). 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 (Ref. 12), which is a function of material density or active loading from the abrading material. Since scratching depth can be estimated as being 1/10th of a particle's 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 to 20 percent of the particles are finer than 20 μm. Simulant particles less than 6 μm in diameter will likely have lower hardness throughout than lunar counterparts. Simulant particles lying between these dimensions will have an unaccounted for hardness (Refs. 5 and 7). Multiple scratches from dust can penetrate surface coatings and treatments, while larger particles could penetrate a coating in a single scratch.

Ambient temperature and relative humidity were recorded for all tests. In some cases, samples were kept in a low humidity chamber until tested. Since most of the materials investigated were metals, however, the effect of humidity is not included in this analysis of surface wear. Observations from the nonmetallic specimen scratch volumes were similar to the metal specimens, but the key aim of this analysis was to analyze the final deformation state of the material surface, not to fully evaluate the interaction mode.

The resultant profiles of each scratch were digitized using Veeco Instruments Inc.'s NT-1000 optical interferometer and WYKO Vision32 software for NT-2000. The platform was leveled before each measurement with a bubble indicator. For consistency, all profiles were measured at 5.2x magnification, which results in a 3D array measuring 1.2 mm in the x-direction consisting of 736 pixels, 0.91 mm in the y-direction with 480 pixels, and surface heights for all points in the z-direction.

A Fowler 320 Rockwell hardness tester (Model TH320) was used to measure the aluminum and stainless steel hardness on the Rockwell Hardness B scale, HRB, in order to verify our results against standard data. For the custom tips mentioned in Table 1 (dataset 2, 3, 9, and 10), the minerals were potted in epoxy and held by a steel fitting that could be placed into the scratch tester. The tips were photographed before and after testing to assess mass loss and related geometry alteration. More friable minerals were tested until destruction.

To generate consistent data in abrasion testing, systematic quantification of metrics relating to area or volume measurements can be defined that avoid limitations associated with making measurements based on a two-dimensional (2D) scratch width alone. Applications using modern profilometry can also be incorporated to better resolve potential operator inconsistencies that can occur when visually determining the boundary conditions. The Veeco profiles result in 480 cross-sections being calculated for each profile. For each test combination, three profiles were generated for each of three scratches, totaling 4,320 cross-sections. This increase in measurement resolution capability compared to visual inspection allows more reliable data to be generated, hence, enabling more accurate measurements to be recorded. It should be noted that transparent materials require a dye coating for the surface to be visualized by the Veeco profilometer.

Representative case studies from two-body abrasion tests conducted during this study are used to help explain and rationalize the definition of the proposed new metrics. To address inconsistencies observed between multiple scratches on a given material sample, fundamental differences have been subcategorized into variability of the material specimen, the abrasive tip, and the surface profiler. Each of the following parameters needs to be included in the analysis in order to systematically collect abrasion data.

Material Specimen Surface Variations

To define a normalized baseline against which a scratch can be measured, several potential surface discrepancies must be addressed. First, all surfaces are inherently rough at some level and this topographical variability and its effect on the resultant scratch profile need to be taken into account. In addition, any roll, pitch or yaw offsets of the scratch must be corrected before visualization. These issues are discussed in terms of defining a baseline surface, termed the “Zeroline”, by describing an ideal scratch, identifying specimen tilt, and averaging surface roughness, as follows.

Zeroline Definition

A key issue encountered while analyzing a full 3D profile was defining reproducible boundaries to ensure that the width measurements abided by the ASTM G 171 Standard. For several profiles taken early during the investigation, the occurrence of irregular scratch scars with multiple peaks and valleys led to inconsistent scratch width measurements being made. To standardize this metric, the concept of defining a “Zeroline” (ZL) was introduced (Ref. 9). This topographical ZL was defined by determining the average surface roughness (R_a) of an undisturbed profile of the material and noting where this projected surface level intersected the final scratch trough or valley (see Fig. 3). In some cross-sections, the peaks displaced to the sides appear larger than the area removed because the material is simultaneously being pushed forward and up by the scratch tip as the trough is being formed, making it difficult to define the edges of the actual scratch. The silhouette in Figure 3 also illustrates the potential for obtaining a false width from using the peak-to-peak distance alone.

Ideal Scratch Definition

To create a geometric standard for all material specimens, an “ideal scratch” was defined as being when the material removed exactly matches the cross-sectional area of the scratch tip as shown in Figure 4, leaving behind no plastically-deformed ridges and ignoring any elastic recovery. Potential compression of the impacted area around the scratch, however, was not considered for this analysis, but could be further assessed using a form of x-ray crystallography.

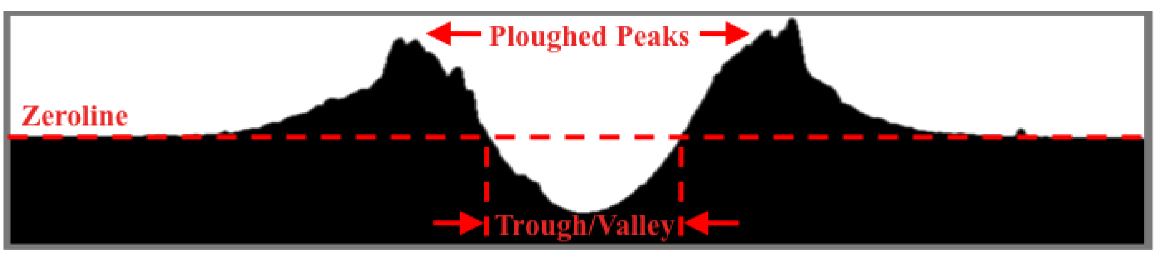

Figure 3.—Side view of typical scratch profile cross-section with location of Zeroline indicated.

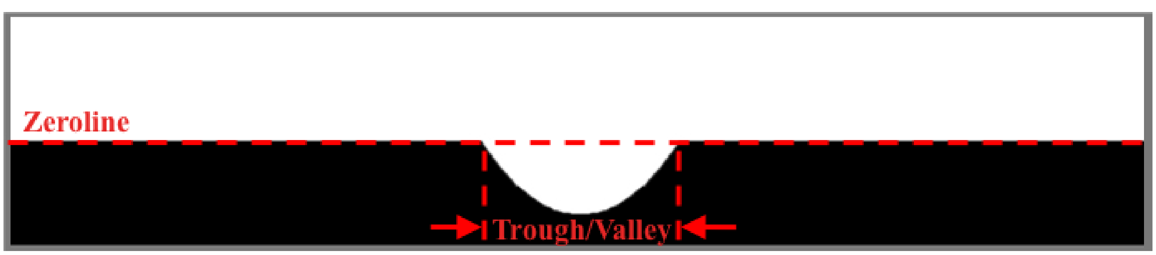

Figure 4.—Side view of ideal scratch and perfect surface Zeroline.

Tilted Material Identification

Any off-horizontal tilt of the mounted material specimen also needs to be considered. As depicted in Figure 5, the material may have an imperfection in the roll or pitch axes causing the specimen to be tilted while undergoing a surface scan. This would cause the data to have false height values that must be adjusted for proper analysis.

Surface Roughness of Material

Inherent surface roughness must be taken into account to characterize local deviations from the mean at the point of measurement, as illustrated in Figure 6. This parameter is important for determining the average Zeroline that is used to define the boundaries of where the scratch zone begins and ends. It also will be used to quantify how the average surface topography has changed after being abraded.

Abrasive Variations

As the motivation behind this research is to characterize how the irregular shapes of lunar dust interact with materials, using a spherical diamond tip to make the scratches is not necessarily the most representative approach. This concern also exists for other test applications similarly requiring non-traditional abrasives. Although data can be analyzed using a theoretical scratch volume, scratch tips are rarely perfect and in some cases a slight defect can lead to drastically different results. Figure 7 is an example case of two different sized diamond tips, radii of 200 and 109 µm described in Table 1 (dataset 7 and 8), scratching stainless steel 304 with a normal force of 100 N. The larger 200 µm tip scratched a wider area as expected and, using the ASTM G 171 Standard, the estimated widths of the scratches are scalable to the tip dimensions.

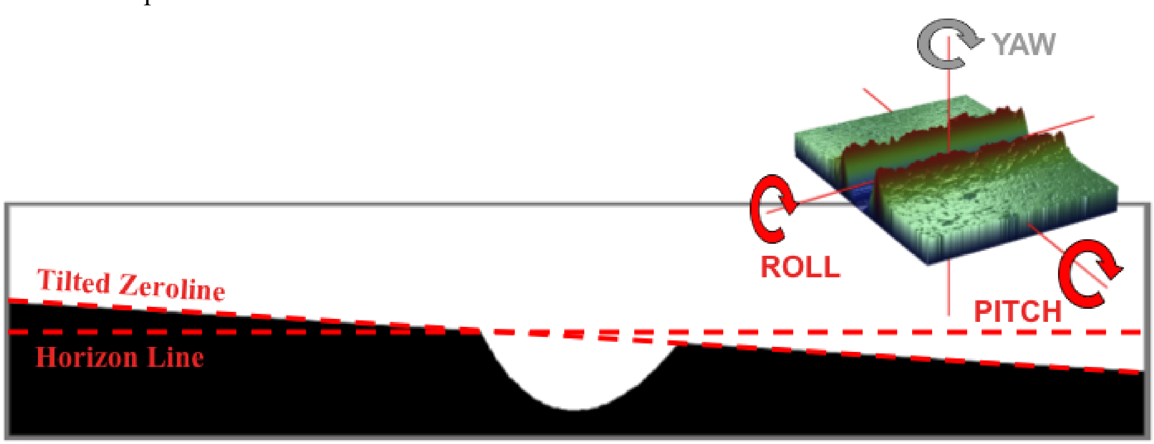

Figure 5.—Side view of tilted material may lead to incorrect measurements.

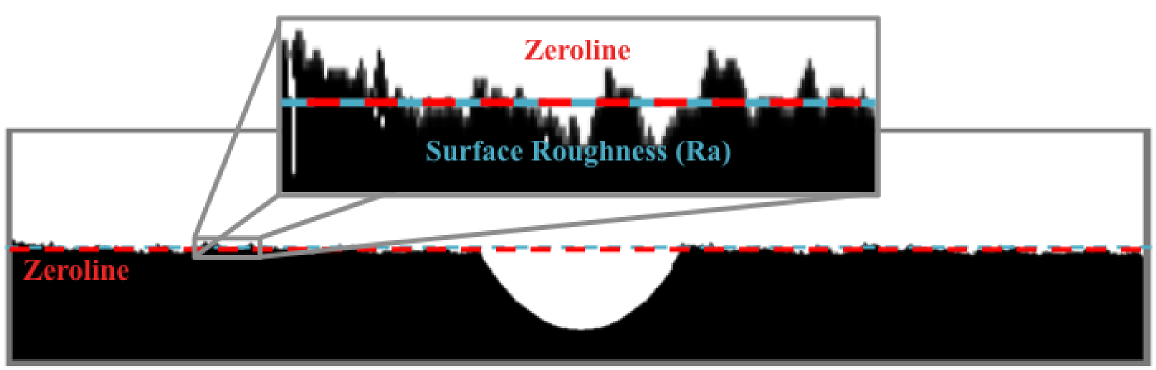

Figure 6.—Side view of surface roughness of material.

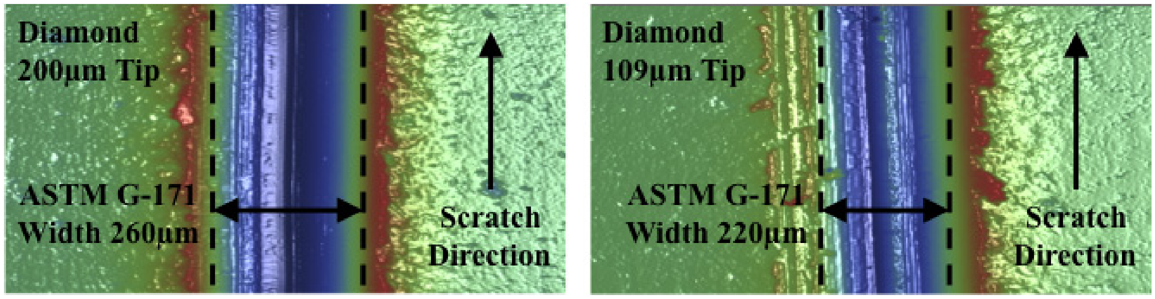

Figure 7.—Top view of two scratches on stainless steel 304 using different diamond tip dimensions with scalable width differences.

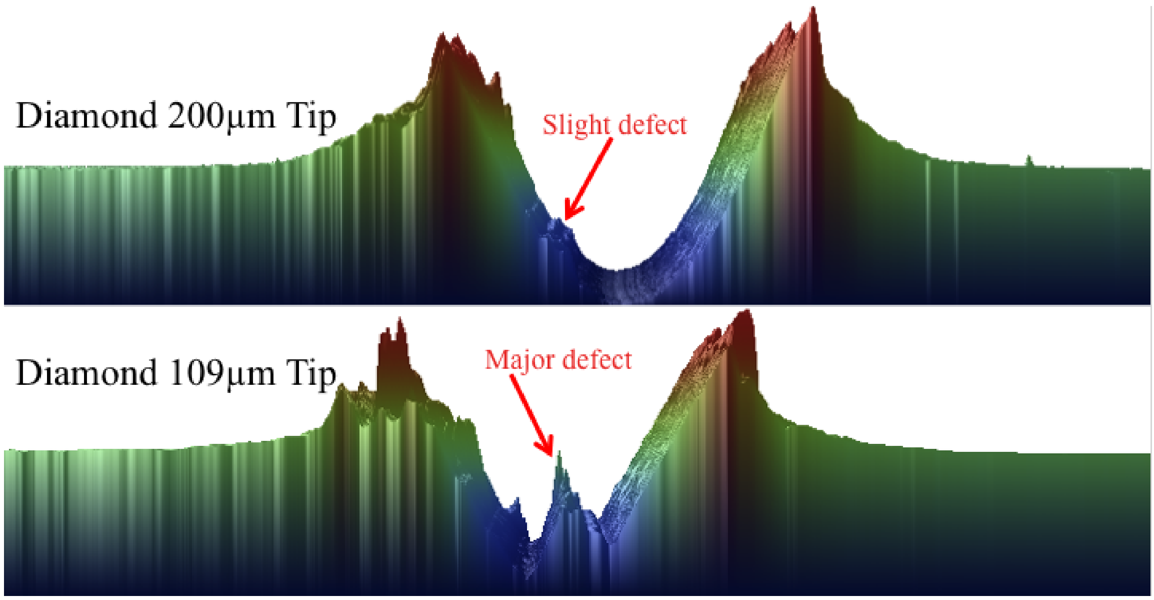

Figure 8.—Three-dimensional view of two scratches on stainless steel 304 using different diamond tip dimensions with different cross sections due to tip defects (scale is 1.2 mm left to right, 0.9 mm in depth, and 34 and 46 µm vertical for 200 and 100 µm tips, respectively). Vertical axes are not to scale.

Per the ASTM G 171 Standard, as noted earlier, this width measurement would be the primary metric used to classify the amount of abrasive wear. Looking more closely at the 3D cross sections of these scratches shown in Figure 8 however, it becomes apparent that the volume removed is not linearly scalable to the width due to geometrical defects in the scratch tips (Note: the vertical scales are different in the figure). This non-detectable difference exemplifies one concern of using width measurement alone to characterize the scratch. In addition, even defining the boundaries for measuring the width is complicated by the irregularities of the ploughed peaks in the absence of using the Zeroline determination.

Surface Profilometer Variations

Since different laboratories will use various instruments for surface profiling, potential sources of equipment error that might be encountered during testing must also be considered. The first major normalization that needed to be made was defining an offset height. The Veeco scans used the abraded area as part of the calculation for the location of an average surface height. Large valleys or peaks, like those in Figure 3, would skew the data so an offset height was calculated to shift the data to the proper zero (Zeroline) along the surface using data from outside of the scratch zone. Each profile needed to be normalized to properly determine net volume removal and displacement (Refs. 8 and 9).

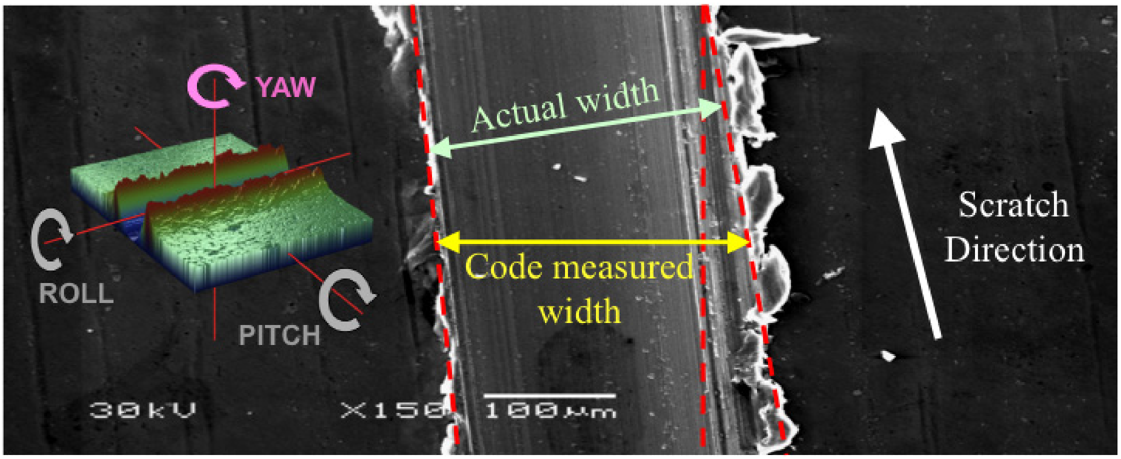

Figure 9.—Top view SEM of scratched Aluminum 6061-T6 showing how a yaw rotation could alter width measurements (yaw rotation angle shown with dashed line differential).

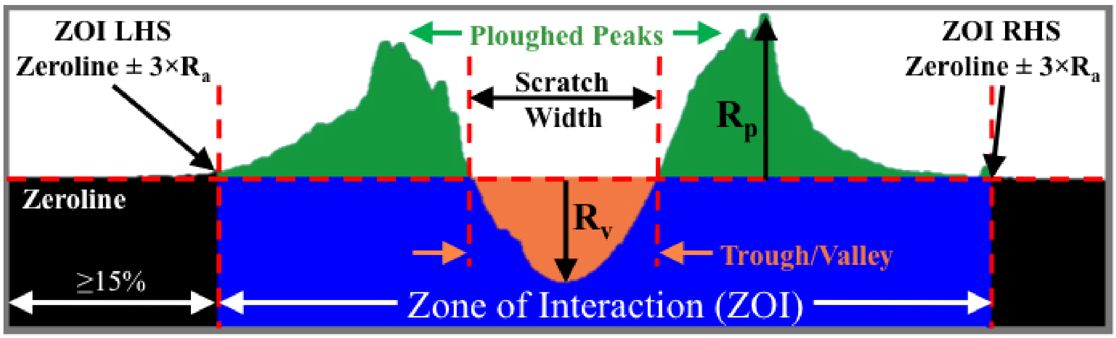

Figure 10.—Example of boundary conditions for Zone of Interaction at $\pm 3\times R_a$ showing negative and positive displacements.

A second error source exists if the scratch material is not correctly aligned on the surface profiler. Any rotation in the yaw direction (see Fig. 9) will cause incorrect measurements to be made when analyzing the data if the technique assumes that the profiles were properly aligned and simply scans horizontally across the profile in the image to make the measurement. Care must be taken to avoid the potential for this misalignment or incorporate the use of profilometry software to correct its occurrence.

Standardization Theory

The standardization of metrics to measure two-body abrasion should be robust enough to handle the majority of material interactions anticipated and should be thoroughly systematic in approach. This can be accomplished using modern scanning technology to define a "Zone of Interaction" on the abraded material within defined boundaries. Since the intended application of this research is to investigate abrasive wear on lunar equipment, the damage caused to the abrading material, lunar dust, is inconsequential. If the dust fragments break into smaller pieces however, this might present a concern for astronaut safety (e.g., through inhalation), clogging of equipment and/or secondary abrasion. Analysis of the scratch tip before and after testing may be warranted to address these concerns as applicable.

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 Figure 10 as $\pm 3\times R_a$, a value that was selected to define six-sigma total deviation from the baseline surface within a 99.9997 percent confidence interval. This multiplier can be adjusted to obtain more or less statistical accuracy, as desired. The standard surface roughness parameters that need to be systematically defined for abrasion studies are summarized in Table 2.

TABLE 2.—SURFACE ROUGHNESS PARAMETERS (REF. 13)

R_a	Surface roughness	$R_a = \frac{1}{n}\sum_{i-1}^{n}\left\|Z_i - \overline{Z}\right\|$
R_q	Root-mean squared roughness	$R_q = \sqrt{\frac{1}{n}\sum_{i-1}^{n}\left(Z_i - \overline{Z}\right)^2}$
R_v	Maximum depth of penetration	a.k.a. max through or valley depth
R_p	Maximum displaced height	a.k.a. max plough or peak height
R_z	Average ten greatest peak-to-valley separations	$R_z = \frac{1}{n}\left[\left(H_1 + H_2 + \ldots H_n\right)\left(L_1 + L_2 + \ldots L_n\right)\right]$ Where, n = 10, H_n highest points, L_n lowest points
R_t	Peak-to-valley difference	$R_t = R_p - R_v$

Four standard metrics are formulated by calculating the total volume removed below the ZL and material displaced (ploughed) above the ZL in the ZOI as seen in Figure 10. These metrics were designed to systematically describe an abraded surface and account for major differences that can occur from the scratch process that may not be discernable by measuring the width of the scratch alone. This can be systematically achieved using the following steps to characterize the 3D profile:

1. Determine scratch length
2. Determine offset height from ZL
3. Determine tilt within sample (roll and pitch)
4. Normalize data to proper ZL and for tilt removal (if needed)
5. Determine surface roughness parameters from un-abraded section of specimen
6. Perform cross-section analysis across scratch (Veeco scan has up to 480 profiles)
    a. Start/end points of ZOI = ZOI_{length}
    b. Sum of negative/positive areas in ZOI using interpolation
    c. Calculate roughness parameters inside of the ZOI
7. Calculate average of ZOI across all cross-sections = $ZOI_{Average}$
8. Sum ZOI negative/positive areas separately and calculate corresponding volumes
9. Calculate average roughness parameters inside of the ZOI
10. METRIC A1: Negative Volume Displaced/$ZOI_{Average}$/scratch length [μm]
    NOTE: This value should be left as a negative value
11. METRIC A2: Positive Volume Displaced/$ZOI_{Average}$/scratch length [μm]
12. METRIC A3: Net Displaced Metric = METRIC A1 + METRIC A2 [μm]
13. METRIC A4: Absolute Displaced Metric = |METRIC A1| + |METRIC A2| [μm]
14. METRIC SET B: Change in roughness parameters [%] in Table 2.

The initial and final roughness parameters of the surface undergoing abrasion testing are important to determine because an abraded surface (i.e., increased roughness) can cause damage to other interacting materials. For example, if a stainless steel cuff ring for connecting a spacesuit arm to the glove became scuffed from dust abrasion, it could rub on other parts of the suit and cause damage to the outer fabric layers even without further dust interaction. The initial and final surface conditions should therefore be recorded. In this research, a clean area void of wear was included in every scan on the left hand side of the scratched surface. An approximate distance of 0.20 to 0.25 mm from the left hand side of the specimen in every profile scan of the 1.2 mm profile was included to represent the initial surface conditions and to be outside of the ZOI boundary. To decrease the potential for overlap with the ZOI that occurs with wider scratch profiles, a smaller factor of 15 percent of the entire specimen cross-section is used to calculate the initial conditions as seen in Figure 10. A 15 percent minimum would be a desired distance from the left edge of the specimen scan for calculating the undisturbed conditions in a total profile using Veeco because it can be used for adjusting the data to a proper ZL and removing any tilt from a computational standpoint. Alternatively, a pre-scratch scan of the material surface could be conducted to measure the initial roughness parameters.

The final roughness parameters are measured within the ZOI to calculate the change in all six key values (METRIC SET B). These parameters indicate the change that the material has undergone during abrasion. In a subsequent paper we will use these metrics to construct a table that ranks materials from best to worst with recommended limits.

Results and Discussion

To investigate a range of potential values using the proposed abrasion metrics, four scratch profiles were analyzed from the diamond 200 µm radius tip on stainless steel 304 (Table 1, dataset 7) for profiles obtained from 10, 100 (two profiles from the same scratch), and 180 N normal loads. Two scratch profiles from the diamond 200 µm tip on Al 6061-T6 (Table 1, dataset 4) for 10 and 100 N loads were also analyzed. The values obtained were measured using a newly developed Matlab code. The R_a multiplier was intuitively set at ten times for this discussion, knowing that three times may be more appropriate as the code is refined. The estimated ASTM G 171 width values were calculated using an older version of the code. This width takes the distance internal to the scratch slopes intersecting the ZL. Table 3 is a summary of data obtained from analyzing the case study profiles.

As seen in the trial cases summarized in Table 3, the ZOI width is approximately double that of the scratch width estimated per ASTM G 171 (rows one and two). This means that half of the interaction zone is not being accounted for using the current scratch standard and a significant part of material interaction area is being neglected. G 171 does not define a ZOI to calculate any metrics, which will be a recommended amendment per this study to allow a more complete analysis of abrasive wear. Defining the ZOI as a function of the scratched surface takes into account the full area of the deformed material rather than just using the scratch width, which is currently the basis for the ASTM G 171 metric. Having this additional 3D volumetric characterization can be used to distinguish differences in scratch depth and/or shape that a simple 2D width measurement alone would not detect.

Metric A3 complements A4 in describing both material removal and the magnitude of the deformation associated with the wear volume. These sample data suggest that an increasing trend in Metric A4 is correlated with load; however, Metric A3 may be related to a cut-to-plough ratio, although an extensive data set will have to be evaluated to definitively establish this relationship.

It was found that changes in surface roughness are very sensitive to the initial conditions. For example, a variation in R_a from 0.3 to 0.6 µm would lead to a doubling of the percentage change (ΔR_a). All of the “change in roughness” parameters are excellent indicators of how a surface has been altered and can reveal important design information regarding the potential for secondary abrasion, as was noted above. It may be better to express all of the surface roughness parameters as initial, final and change in measurement rather than just as a percentage change. This can be advantageous for parameters like R_v and R_p, because the maximum penetration and height deformation can then be related to requirements for surface coatings and material thickness.

The two profiles taken from the stainless steel 304 at 100 N are along the same scratch but in two different locations. The data are relatively close in value and this demonstrates the consistency of the measurements derived in the code and of the scratch. This preliminary data, shown in Table 3, can be used to show that the Al 6061-T6 scratch had a more concentrated and smaller ZOI (ZOI width) than the stainless steel 304, but the amount of ploughing (A1) was five times greater and the peaks formed in deformation were twice as high (A2). The resultant material removal was noticeably greater (A3) and the material displacement was three times larger (A4). There was a deeper penetration into the Al 6061-T6 (ΔR_v), but the peaks on the stainless steel 304 were larger (ΔR_p). Because of the independent material changes, the overall changes in peak-to-valley (ΔR_t) and top ten peak-to-valley separation values were similar between metals (ΔR_z). The root-mean squared roughness (ΔR_q) was twice the value for steel versus aluminum, but the implications of this particular metric are not as obvious. Further analysis will be conducted with all of the scratch profiles recorded to reduce the variability that exists from looking at only 3 profiles.

TABLE 3.—CASE STUDY DATA OF NEW METRICS ON SIX PROFILES

			Normal Load (N)					
			Stainless Steel 304				Al 6061-T6	
Metric	Formula	Units	10	100 (1)	100 (2)	180	10	100
ZOI	$ZOI_{Average}$ (width)	µm	150 ±172	622 ±121	626 ±121	747 ±21	213 ±9	562 ±44
Scratch width	Estimated ASTM G 171 Value[a]	µm	75 ±2	208 ±2	209 ±2	272 ±4	108 ±2	350 ±1
A1	$\frac{\text{Negative Volume Displaced}}{ZOI_{Average} \times \text{Scratch Length}}$	µm	–2.59 ±0.6	–11.25 ±1.2	–11.41 ±1.1	–19.70 ±20.7	–5.09 ±4.9	–51.59 ±37.8
A2	$\frac{\text{Positive Volume Displaced}}{ZOI_{Average} \times \text{Scratch Length}}$	µm	0.60 ±0.6	11.05 ±2.7	11.01 ±4.1	18.28 ±31.0	4.40 ±15.1	23.95 ±99.5
A3	A1 + A2	µm	–1.99 ±0.4	–0.21 ±3.5	-0.39 ±4.4	–1.42 ±38.0	–0.69 ±17.8	–27.64 ±118.8
A4	$\lvert A1 \rvert + \lvert A2 \rvert$	µm	3.19 ±1.1	22.31 ±2.3	22.42 ±4.1	38.0 ±36.5	9.49 ±13.7	75.54 ±92.5
ΔR_a	$\frac{ZOI\,R_{a\,final}}{R_{a\,initial}} \times 100\%$	%	784	4,843	5,273	6,052	5,598	1,630
ΔR_q	$\frac{ZOI\,R_{q\,final}}{R_{q\,initial}} \times 100\%$	%	621	3,676	3,906	5,579	5,214	1,592
ΔR_v	$\frac{ZOI\,R_{v\,final}}{R_{v\,initial}} \times 100\%$	%	301	698	750	1,353	2,115	1,385
ΔR_p	$\frac{ZOI\,R_{p\,final}}{R_{p\,initial}} \times 100\%$	%	194	4,149	4,237	3,415	4,010	1,976
ΔR_z	$\frac{ZOI\,R_{z\,final}}{R_{z\,initial}} \times 100\%$	%	254	1,354	1,448	2,154	3,278	1,705
ΔR_t	$\frac{ZOI\,R_{t\,final}}{R_{t\,initial}} \times 100\%$	%	244	1,308	1,407	1,947	3,113	1,683

[a]Calculated from an older version of MATLAB code that locates the scratch width as the ZL intercept with scratch slopes.

Conclusions

Carrying out appropriate abrasion testing is viewed as a critical step in selecting materials for use in the design of future lunar surface exploration equipment. Before any test can be conducted, however, a quantifiable, reproducible and robust set of metrics needs to be defined to allow direct comparison of material wear results. Limitations were identified in existing two-body abrasion test standard measurements that are currently based solely on an estimated width of the resultant material deformation, as summarized in Table 4. This paper proposes a new method for systematically analyzing a controlled surface scratch, taking into account the full 3D volumetric profile of the displaced material and other measurement correction factors. Standardized material displacement metrics are obtained by normalizing the overall surface profile using a defined "Zone of Interaction" and noting specified changes in standard surface roughness parameters. Proof-of-concept data was collected and analyzed to demonstrate the power of the methodology presented herein and it's superiority over the existing ASTM method G 171. This technique overcomes previous analysis limitations by taking advantage of advanced imaging capabilities that now allow resolution of the scratched surface to be quantified in greater detail. A sensitivity study is being conducted to evaluate the influence of the R_a multiplier value used in defining the boundary conditions of the ZOI and will be discussed in a subsequent paper.

TABLE 4.—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 (1D)	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

Characterization of two-body abrasion analysis and the understanding of fundamental particle-material interactions will both provide critical insight into anticipating how components will wear during use on the lunar surface, other planets or asteroids, as well as in similarly abrasive environments on Earth. By defining a systematic approach for evaluating a single scratch, analytical models can be developed to extend this application to broader scratch scenarios. This study, aimed at enabling lunar exploration, ultimately offers a means to refine test standards for use industry-wide.

References

1. ASTM (2003): "Standard Test Method for Scratch Hardness of Materials Using a Diamond Stylus," G 171-03, Annual Book of ASTM Standards.
2. Budinski, K.G. (2007): "Guide to Friction, Wear, and Erosion Testing," ASTM International, West Conshohocken, PA. MNL56.
3. Gaier, J.R. (2007): "The Effects of Lunar Dust on EVA Systems During the Apollo Missions," NASA GRC. NASA/TM—2005-213610/REV1.
4. Heiken, G.H., Vaniman, D.T., French, B.M. (1991): "LUNAR Sourcebook: A User's Guide to the Moon," Cambridge University Press and Lunar and Planetary Institute.
5. Taylor, L.A., Schmitt, H.H., Carrier, W.D. & Nakagawa, M. (2005): "The Lunar Dust Problem: From Liability to Asset," AIAA 1st Space Exploration Conference: Continuing the Voyage of Discovery. Orlando, FL. AIAA–2005–2510.

6. Rickman, D. and Street, K.W. (2008): “Expected Mechanical Characteristics of Lunar Dust: A Geological View,” Proceedings of the Space Technology and Applications International Forum, Albuquerque, NM. AIP Conf. Proc., 969, 949–955.
7. Plescia, J. (2008): “Lunar Regolith Formation and Properties,” Presentation, Lunar Regolith Community of Practice (LunRCoP) Webinar, 26 Feb 2008.
8. Kobrick, R.L., Klaus, D.M., and Street, K.W. (2009): “Developing Abrasion Test Standards for Evaluating Lunar Construction Materials,” 39th ICES, Savannah, GA. SAE Technical Paper 2009-01-2377 [accepted for publication (2010) SAE Transactions Journal of Aerospace].
9. Kobrick, R.L., Street, K.W., Klaus, D.M., Greenberg, P.S., and Hyatt, M.J. (2008): “Developing Abrasion Testing Hardware to Evaluate Effects Caused by Lunar Dust on Construction Materials,” 59th IAC, IAC-08-A3.2.INT3, Glasgow, UK.
10. Colwell J.E., Batiste S., Horányi M., Robertson S., and Sture S. (2007): “Lunar surface: Dust dynamics and regolith mechanics,” Rev. Geophys., 45, RG2006, doi:10.1029/2005RG000184.
11. Westbrook, J.H. and Jorgensen, P.J. (1968): “Effects of Water Desorption on Indentation Microhardness Anisotropy in Minerals,” The American Mineralogist, Vol. 53, pp. 1899–1909.
12. Tabor, D. (1970): “The hardness of solids,” Review of Physics in Technology 1, pp. 145–79.
13. WYKO (1999): “WYKO Vision32 Online Help,” WYKO Vision32 software for NT-2000, Version 2.210, Veeco Instruments, Inc., Metrology Group. Release Date 1/8/1999. Available via software package.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*
01-05-2010

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Standardization of a Volumetric Displacement Measurement for Two-Body Abrasion Scratch Test Data Analysis

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Kobrick, Ryan, L.; Klaus, David, M.; Street, Kenneth, W., Jr.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 936374.03.01.03

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17283

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2010-216347

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Categories: 42 and 88
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES
Submitted to the WEAR Journal/Elsevier.

14. ABSTRACT
A limitation has been identified in the existing test standards used for making controlled, two-body abrasion scratch measurements based solely on the width of the resultant score on the surface of the material. A new, more robust method is proposed for analyzing a surface scratch that takes into account the full three-dimensional profile of the displaced material. To accomplish this, a set of four volume displacement metrics are systematically defined by normalizing the overall surface profile to statistically denote the area of relevance, termed the “Zone of Interaction” (ZOI). From this baseline, depth of the trough and height of the ploughed material are factored into the overall deformation assessment. Proof of concept data were collected and analyzed to demonstrate the performance of this proposed methodology. This technique takes advantage of advanced imaging capabilities that now allow resolution of the scratched surface to be quantified in greater detail than was previously achievable. A quantified understanding of fundamental particle-material interaction is critical to anticipating how well components can withstand prolonged use in highly abrasive environments, specifically for our intended applications on the surface of the Moon and other planets or asteroids, as well as in similarly demanding, harsh terrestrial settings.

15. SUBJECT TERMS
Two-body abrasion

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
U	U	U	UU	19	STI Help Desk (email:help@sti.nasa.gov) / 443-757-5802

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18