Needs and Challenges in Precision Wear Measurement

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Abstract

Accurate and precise wear measurements are a key element in solving both current wear problems and in basic wear research. Applications range from assessing the durability of micro-scale components to accurate screening of surface treatments and thin solid films. The need to distinguish small differences in wear rate presents formidable problems to those who are developing new materials and surface treatments. Methods for measuring wear in ASTM standard test methods are discussed. Errors associated with using alternate methods of wear measurement on the same test specimen are also described. Human judgmental factors are a concern in common methods for wear measurement, and an experiment involving measurement of a wear scar by ten different people is described. Precision in wear measurement is limited both by the capabilities of the measuring instruments and by the non-uniformity of wear process. A method of measuring wear using nano-scale indentations is discussed. Current and future prospects for incorporating advanced, higher-precision wear measurement methods into standards are considered.

Key words: wear, wear testing, wear measurements, accuracy, precision, surface roughness, tribology

* Research sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies, as part of the High Temperature Materials Laboratory User Program, under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

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Introduction

Wear has been of concern to users of materials for thousands of years. One need only consider the importance of maintaining sharp hunting knives, axes, and swords to realize that the search for more wear-resistant materials dates back to before the dawn of recorded history. Dowson cites the use of stone bearings for potters' wheels in ancient Mesopotamia 5,000 or more years ago, about the time when writing itself was first being developed. However, it has only been within the past two centuries, and mainly within the present one, that a concerted effort has been expended to quantify precisely the amount of wear which materials have experienced in machinery and other engineering applications.

Wear is defined by Standard G 40-95 of the American Society for Testing and Materials (ASTM) as “damage to a solid surface, generally involving the progressive loss of material, due to relative motion between that surface and a contacting substance or substances.” Use of the broad term substance in the ASTM definition allows wear to be produced not only by rubbing contact with a solid surface, but also by particles, liquids, electric arcs, or gas streams. Wear is measured for a number of reasons including: determination of proper maintenance intervals for existing machines, obtaining data for the design of new machines, and for the research and development of lubricants, surface treatments, and materials. Other, less obvious examples of the need for precision wear measurement include assessing the amount of wear debris contamination in the manufacturing of products like foods, high-purity ceramic powders, and pharmaceuticals, and the production of harmful wear debris within the tissue surrounding implanted body prostheses.

In the ASTM definition of wear, the key phrase is “the progressive loss of material.” Thus, galling, which can occur on only one movement, is strictly not a form of wear, but rather surface damage. The progression of material loss implies the need to obtain a cumulative wear volume or wear rate. Measuring large amounts of wear on simple, convex geometric shapes is obviously a much easier task than measuring very small amounts of wear on internal surfaces of complex parts. Sometimes the rate of wear is so small that it is only barely detectable by scanning electron or atomic force microscopes. Yet, that minuscule amount of wear may have large consequences on component operation. Witness the effects that a small leak in a propeller shaft seal can have on the operation of an ocean-going vessel or the effects that loss of a micrometer of plating can have on the performance of an electrical contact. Those who conduct wear studies of ion-implanted surfaces know that placing a numerical value on the material loss is difficult. Wear testing apparatus can be designed to use simple specimens to facilitate wear measurement, but it is usually
not so easy to measure wear in engineering components, particularly if adherent deposits of debris or lubricant degradation products coat their contact surfaces.

While ASTM has a clear definition for wear, the definitions for the term precision are less straightforward. In fact, if one consults the sixth edition of the Compilation of ASTM Standard Definitions one will find twenty-two definitions for precision developed by about forty different standards committees, separately or in collaboration. The key ASTM standard which addresses precision and accuracy is E 177. According to section 18.1 of that standard:

"The precision of a measurement process, and hence the stated precision of the test method from which the process is generated, is a generic concept related to the closeness of agreement between test results obtained under prescribed like conditions from the measurement process being evaluated."

Precision is important in wear measurement when there is a need to distinguish clearly between the relative wear resistances of materials or surface treatments; especially, in applications where the amount of tolerable wear for component performance is very small, perhaps being on the same scale as the original surface finish of the contact surfaces. Areas where precision wear measurement is important include the following:

- thin solid films or coatings to be used for wear or friction modification
- surface-modified materials where the depth of the layers is less than a few micrometers
- tiny, precision wear parts including those in micro-electro-mechanical systems (MEMS)
- parts which operate under lubricated conditions in which the wear rate is very small
- the wear of surfaces which is similar in magnitude to the starting surface finish of the part
- screening of new types of materials or surface treatments where small differences in wear must be detected

Wear measurement problems presented to the investigator are significantly dependent on the characteristics of specific tribosystems - be they laboratory testing machines or engineering parts, and therein lies the formidable challenge in precision wear measurement. Each method available to measure wear carries with it a measure of uncertainty and a potential for inaccuracy. This article will address a number of generic aspects of measuring wear with precision using common testing geometries to illustrate these points.
Approaches to The Accurate Quantification of Wear and Wear Rates

Just as there has been an effort to develop standard weights and measures for general use, there have been efforts to systematically define quantities for wear and wear rate. German Standard DIN 503216 describes one such system of wear measurement. Table 1 lists and summarizes the DIN wear measurement quantities. Note that the last entry in the table, from section 4.13 of the standard, states “other indirect measures.” These may include such indicators as level of vibration in the machinery, leakage rate (indicating seal wear), loss of compression in an internal combustion engine cylinder (indicating ring or liner wear), and the concentration of wear debris in a sample of the lubricant. In some cases, the function of the part or machine rather than the normalized wear rate of a surface within it is the most important practical measure of wear for that tribosystem.

The wear testing standards, practices, and guidelines developed by ASTM Committee G-2 on Wear and Erosion tend to emphasize gravimetric (mass loss) measurements, as indicated by the summary in Table 2, which also includes several standards from committee D-2 on Petroleum Products and Lubricants. Weight measurements are among the easiest type to perform, but they have several significant drawbacks if one is interested in measuring wear with a high degree of precision. First, some sort of cleaning process is usually employed to remove wear debris, lubricant by-product deposits, and transferred particles from the opposing body from the post-test surface before weighing. This cleaning process may not be completely effective. For example, particles used in erosion tests may be tightly embedded into the test surface, adding weight to the specimen initially. Second, the process of mounting and demounting specimens from the apparatus (handling) may inadvertently alter the weight (edge chipping, material on screw threads, etc.). Thirdly, moisture and other contaminants may adsorb onto all specimen surfaces, other than the wear surface, and the amount of adsorbent may increase with time after pre-test cleaning. Of these factors, the first is probably the most insidious and likely to produce the most significant errors.

Several of the ASTM G-2 standards also involve wear scar dimensional measurements and profilometry to determine wear scar cross-sectional areas. All of the measurements described in Table 1 and 2 have limitations. The more parameters that are involved in the wear rate calculations (e.g., mass, time, density, etc.), the more inaccuracies are compounded. For example, errors in the density used for the worn material add uncertainty to the conversion of mass loss to wear volume. Sliding wear rates are sometimes expressed as volume lost per unit sliding distance per unit applied normal force. Errors in all of these quantities (force, distance, and volume) add to the inaccuracy of the final wear rate. Measurement limitations are based on the precision and bias of
the instruments used to make the measurements, the number of measurements made on each specimen, and often, judgmental factors introduced by the individual performing the measurements.

The requirements of precision and the level of precision obtainable vary greatly with the method of measurement. Consider, for example, the case of a wear scar from a block-on-ring wear test. The equation specified in ASTM G-77 to calculate wear volume from the scar width on the block specimen is:

\[ V_w = \frac{D^2 t}{8} \left[ 2 \sin^{-1} \left( \frac{b}{D} \right) - \sin \left( 2 \sin^{-1} \frac{b}{D} \right) \right] \]  

(1)

where \( V_w \) = wear volume (mm\(^3\)), \( b \) = width of the wear scar (mm), and \( D \) = diameter of the ring specimen (mm). Based on Eqn. (1), it is possible to calculate the magnitude of error in wear volume associated with various positive or negative reading errors from the mean scar width, herein called the baseline scar width. These errors are shown in Fig. 1 for three baseline scar widths ranging from 0.5 mm to 5.0 mm. As expected, a given error in measuring scar width would result in a significantly larger error for a smaller scar than for a larger one.

One can compare the scar width method to one based on measurements of maximum scar depth by profilometry. For a perfectly cylindrical scar of radius \( (D/2) \), the depth \( (d) \) is related to the scar width \( (b) \) by

\[ b = 2.828 \sqrt{d \left( \frac{D}{2} - d \right)} \]  

(2)

If we substitute Eqn. (2) in Eqn. (1), it is possible to estimate the errors in wear volume associated with the same magnitude in of errors in depth measurement. The depths associated with wear scars of widths 0.5, 1.0, and 5.0 mm, using a non-wearing ring of constant 34.99 mm diameter are respectively, 1.8, 7.2, and 180.0 \( \mu \)m. This large sensitivity of the calculated wear volumes to micrometer-sized errors in depth measurement of the three aforementioned scar depths is shown in Fig. 2. When the wear scar is 1.0 mm wide, for example, a 2 \( \mu \)m error in the depth measurement would result in a wear volume overestimate of nearly 50\%. Thus, when measuring the wear rates of thin coatings using the block-on-ring test, precise wear measurements require not only that the wear scars be of extremely uniform depth and shape, but that extreme care is taken in measuring
those depths. Multiple readings are also recommended to assure that depth measurements are as representative of the wear pattern as possible.7

Surface damage, such as that produced in scuffing and galling, presents a significant challenge because the deformation of the contact surfaces is highly localized and the damaged zones vary in shape and size. Clearly, weight change would be an inadequate measure of such damage because there may be no weight loss involved. It is necessary to survey the entire nominal contact area, to locate areas with damage, and to measure the extent of that damage. Several years ago, Peterson et al.8 investigated several ways to characterize the damage done to metals by galling in a button-on-plate apparatus. They found that using the average maximum peak-to-valley roughness from twenty profiles taken across each sliding path provided a reasonable method to determine galling response. Four profile traces across each specimen were not found to be as effective as twenty in measuring the extent of damage.

Gravimetric measurements could be considered for measuring small block-on-ring wear volumes, but a simple calculation indicates the problem here. Consider the weight changes associated with wear volumes which correspond to cylindrical scars having 0.5, 1.0, and 5.0 mm widths, as above. Assume that the block specimen is composed either of cartridge brass (Cu-30 wt% Zn, density = 8.53 g/cm3) or of polytetrafluoroethylene (Teflon™, density = 2.2 g/cm3). Given that mass is by definition the product of the density and the volume, the weight changes associated with the corresponding wear volumes are given in Table 3. For very shallow wear depths, as in the first row, the microgram weight changes are usually beyond the capabilities of all but the most expensive laboratory electronic or analytical balances, and the weight changes are less than the precision specified by several of the ASTM wear standards which only require measurements within 0.1 mg.

Several years ago, the author conducted a series of four block-on-ring sliding wear tests using a bronze (CDA 638) alloy as the block materials and 52100 steel as the ring material. The test was run for 1000 m sliding distance in air at room temperature. Wear volume of the block specimen was calculated in three ways for each of the four repeat tests: by weight change, by scar width, and by scar depth. Results in Fig.3 show that scar width produced the highest values and weight change the lowest. However, this type of sliding combination tends to produce transfer layers which are very tightly adherent to the test specimens and it is likely that the weight loss for the block was inaccurate due to the presence of adherent transfer layers.
Currently, methods such as non-contact laser profiling and atomic force microscopy are available to map surface topography, and these may be used to some advantage for volume measurement small wear scars. Unfortunately, both these types of instruments are relatively expensive, require carefully trained operators, and in the case of non-contact profilometry, significant errors can be introduced in non-metallic or translucent surfaces due to probe-spot light diffusion in the surface and poor surface reflectivity.9

Table 3.

Weight Changes for Various Wear Scar Sizes
(based on ASTM G-77 test method, 34.99 mm diameter ring)

<table>
<thead>
<tr>
<th>Scar Width (mm)</th>
<th>Scar Depth (μm)</th>
<th>Scar Volume (mm³)</th>
<th>Mass of Brass (mg)</th>
<th>Mass of PTFE (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.8</td>
<td>0.0038</td>
<td>0.032</td>
<td>0.008</td>
</tr>
<tr>
<td>1.0</td>
<td>7.2</td>
<td>0.0303</td>
<td>0.258</td>
<td>0.066</td>
</tr>
<tr>
<td>5.0</td>
<td>180.0</td>
<td>3.804</td>
<td>32.4</td>
<td>8.37</td>
</tr>
</tbody>
</table>

Judgmental Factors Affecting the Precision of Wear Measurements

Judgment of some kind is usually necessary when wear is to be measured quantitatively, regardless of the units used. Even when a machine is used and the machine outputs a digital, numerical value for the wear-related quantity, there must be a process (algorithm) which the instrument uses to obtain a value and round to the number of decimal places it outputs to the display or recording device. Conversely, the instrumental output may include far more decimal places than the sensor is physically capable of detecting, and the apparently high precision of the numerical values is therefore false and misleading.

Human judgment can be a major factor in the precision of the wear measurements. Sometimes, the operator is required to estimate or interpolate a value by observing a dial or other indicator. Sometimes, as in the case of the measurement of wear scar dimensions, the precision of the instrumentation exceeds the uniformity of the wear scar, so that operator judgment is required as to where to place the reference cursor for measurement. This was demonstrated using the hypothetical wear scar pictured in Fig. 4. The two “edges” of the wear scar were each produced by entering the coordinates of 100 random points into a graphing computer program. Knowing the coordinates of the points enabled the calculation of the average values for each hypothetical scar
edge. Subtracting the two averages produced an average value for the spacing between the lines. Ten individuals (engineers, students, and technicians) were asked to estimate the centers of each jagged line and, using the scale of arbitrary units provided (it is reproduced at the right of the figure and originally measured 108 mm long), asked to measure the distance between the lines. As the table in Fig. 4 shows, the average measurement for the ten observers in the experiment was 0.791 units, remarkably close to the average of the line coordinates, 0.796. In fact, no observer was more than 0.016 units (2%) removed from the average. In this case, human judgment was found to be quite good in ascertaining the correct value.

Wear test specimens of various designs present different challenges for optical scar measurement. Usually, the accuracy is not so much limited by the instruments used for scar measurement as it is by the physical nature of the wear process, itself. A circular scar on a 12.7 mm diameter, Inconel X-750 superalloy fixed specimen from a crossed-cylinders sliding wear test is shown in Fig. 5. The 13-8 PH stainless steel rotating cylinder's diameter was 60 mm. This scar exhibits considerable metal deformation and extrusion of material beyond the ends of the approximately elliptical scar shape. Digitizing the outline of the scar on the photomicrograph in Fig. 4 using a magnetic tablet with a cross-hair “mouse”, produced a wear scar area of 9.163 mm². An estimate of the length and width of the scar from the same photograph and using the formula for the area of an ellipse produced 9.82 mm², a value approximately 7% higher. Transfer of material from the metallic counterface and deformation of the material in the scar area produced an irregular scar in this case. Thus, it was not possible to obtain an accurate measurement of scar dimensions. Notably, weight measurement, as required by ASTM G-83, would also have been affected by the presence of adherent, transferred material from the opposing specimen. The G-83 standard reports a typical within-lab repeatability of 15% and between-lab reproducibility of 30% for the crossed-cylinders test which uses two 12.7 mm diameter cylinders.

Other factors adversely affecting the precise measurement of wear include the presence of adherent wear debris layers in dry sliding tests and the presence of lubricant degradation products on the wear scars of lubricated specimens. Cleaning of the wear surfaces without damaging the scar presents a challenge for these situations. In situ measurements of relative specimen displacement must contend with similar sorts of problems. In dry sliding tests of metals, it common to observe false “negative wear” indications because the trapping of debris between sliding members forces positive displacements of the sensor. The same sort of effect might be observed in higher-speed lubricated tests in which a hydrodynamic wedge of entrained lubricant forces the specimens apart.
Operator judgmental errors are a problem in measuring microindentation hardness impressions and are a major source of errors in hardness number determinations; however, observations of changes in the size of hardness impressions are one alternate method to measure wear. Thus, one can in principle measure very small amounts of wear on a flat, smooth surface in either of two ways: (1) by preparing a series of indentations at various loads and note the smallest surviving impression after wear, or (2) by producing several indentations on the test surface at the same load and accurately measuring their base-to-apex distances before and after wear. The advantage of the first method is that the load-displacement measurement system on nano-scale hardness testing machines can provide an accurate measure of each elastically-recovered impression's depth, and that measurement of the length of the base-to-apex distance is not required. The disadvantages of method (1) are that wear can smear material over the smaller indentations causing them to disappear prematurely. Also, wear can round or distort the edges of indentations making them difficult to discern clearly. Thus, the indentation method is not suitable for soft, easily sheared surface materials. Glaeser used replicated Knoop impressions to measure the wear of the inside bores of bushings, and Begelinger and de Gee used a pattern of Knoop impressions to map the wear on magnetic tape recording heads.

Some of the drawbacks to the indentation approach are illustrated in the following experiment. A specimen of directionally-solidified Al$_3$Ni alloy with an extremely uniform microstructure was polished and indented on opposite corners (identified as locations "A" and "B") with loads of 1.96, 0.981, 0.491, and 0.254 N. The major impression diagonals were measured to the nearest 0.1 µm, and the specimen was subjected to 30 minutes of vibratory polishing in a slurry of colloidal 0.5 µm silica particles. The changes in the impression lengths (ΔD) were converted to a material removal depth (Δz) using the geometry of the Knoop indenter:

$$\Delta z = 0.0328 \Delta D$$

(3)

Figure 6 shows several of the impressions before and after polishing, and Fig. 7 indicates the individual measures at opposite corners of the specimen surface. The variations in depth obtained for the different impressions was not differentiated by location; however, there appeared to be better agreement between impressions made at lower loads. The average depth change of all the impressions was 0.24 µm, but the standard deviation was 0.116 µm, which produced a coefficient of variance of 47.4%. Thus, the potential for significant errors exists using this method even on relatively uniform and homogenous microstructures. The constant in Eqn. (3) assumes that the impression shape exactly duplicates the indenter shape, but elastic recovery (springback after the indenter is removed) in the material may invalidate that assumption. In examining the data, it is not
possible to exclude the possibility that the wear rates in fact differed from one place to another on the specimen surface. Thus, the apparently high coefficient of variance may not necessarily reflect a problem with the technique but rather a combination of measurement errors and actual differences in wear rate.

Measurement of the wear of ion-implanted and similarly modified surfaces might also make use of techniques like nanoindentation dimensional changes, a variant of a method of using microindentation hardness indentations. In the nanoindentation method, a series of carefully-measured (by optical, electron, or atomic force microscopy) nano-scale indentations are located on a wear surface and their size change after exposure to wear is measured. Nanoindentation machines typically use the Berkovich indenter, a three-sided pyramid\(^4\) (Fig. 8). The depth \(d\) of the ideally-ground and reproduced Berkovich impression is related to the distance from the base to the apex of the triangular impression \(L\) by

\[
d = 0.1554 \ L
\]

(4)

Rather than using an optical microscope to measure the nanoindentations, an atomic force microscope may be used. In addition, the load-displacement data obtained from nanoindentation machines provides a way to account for errors in Eqn. (4) due to the elastic recovery of the residual impressions.

The indentation methods can also be applied to other than small, flat test specimens, but the errors associated with the impression measurements may be significant relative to the magnitude of the changes in dimensions which must be measured, and the use of the method on surfaces with appreciable starting roughness will be problematical. In some cases, as in Glaeser's work, cited earlier, plastic replicas can be made of the indentations before and after wear and these can be examined off the machine more conveniently.

**Non-Traditional and Indirect Wear Measurement Methods**

To this point, we have considered traditional wear measurements such as weight change, dimensional changes, and displacement. But there are a number of other techniques which can be used to measure wear indirectly. These include such methods as surface activation analysis\(^5\), radioactive tracers\(^6\), and lubricant analysis\(^7\). Methods such as motor-current signature analysis\(^8\) and vibration sensing\(^9\) may be useful for detecting the presence of wear but generally do not provide high-precision, quantitative wear measurements. Scott\(^10\) divided the monitoring of wear
into manual, semi-automatic, and fully-automated categories. He reviewed the following techniques: temperature measurement, pressure measurement, vibration measurement, position transducers, lubricant monitoring, spectroscopic oil analysis, wear particle counting, and ferrography. Obviously, the more precise the required measurement for component wear, the greater is the need for sophisticated sensor and wear detection technology.

Friction forces present on a sliding contact provide an indirect measure for wear. The interpretation of friction records from experiments provides an indication of the changes in the surfaces and of the nature of the materials in the sliding interface. Each tribosystem tends to progress through a number of stages during which the initial contact surfaces evolve to reach their steady-state condition. These stages can occur very quickly upon start-up, or require some detectable running-in period to complete. Detectable changes in friction forces can indicate changes in surface roughness, transfer, debris layer formation, wear-through of oxides or tarnish films, and other phenomena. The presence of such phenomena as running-in and transitions suggest that the wear rate obtained by measuring dimensional changes or weight changes after a period of running is only an approximation and do not reflect changes in the wear rate during the tribodynamic aging of the system. In certain applications, precision measurement of instantaneous wear rates may be important. Thus, beginning and end-of-test measurements, normalized by a quantity such as load or sliding distance, is at best a linear approximation of the variable wear rate.

Current Needs and Challenges in Precision Wear Measurement

While seeking high-precision in wear measurement is a worthy goal, it makes sense to ask what level of precision meets the technological needs of the investigation. In the case of ASTM standard wear test methods, the usefulness of each method is related to its ability to discriminate between the wear behavior of different materials or lubricants aimed at specific applications. Each test method has limitations on precision and accuracy. Therefore, a given type of test could prove inadequate for applications where higher precision is required.

One of the most challenging areas for precision wear measurement is in the field of surface modification (surface engineering) where techniques such as ion-implantation and thin-film deposition produce layers from 50 nm to 1 μm thick. The wear-through of affected layers can sometimes be detected by changes in friction or acoustic emission during scratching, but one might also be interested in ascertaining the specific wear rates of such layers before wear-through occurs. Techniques such as surface activation analysis, in which the surface layers are made momentarily radioactive and the signal decay during wear is compared to the normal decay under non-wear
conditions, can provide wear rate information, but only in an averaging sense. Average wear rates are calculated based on the reduction in radioactivity over an activated area, not on a localized, asperity basis. Loss of a few spalls in one location may reduce the signal implying a uniform (false) wear rate taking place over the whole activated area.

Improvements in indentation measurement methods are another challenging area for future exploration, and will require greater attention to the precision characterization of the impression geometry and the elastic recovery of the indented surfaces. The wide-spread availability of atomic force microscopes and similar precision metrology instruments will aid in such investigations, but the need for accurate calibrations of such devices will always exist.

**Future Prospects**

The need to develop and use new and improved methods for precision wear measurement will be driven by the needs of designers, materials engineers, and applications engineers. The drive toward tighter dimensional tolerances in moving parts, the development of surface modification technologies of various types (surface engineering), and the miniaturization of mechanical assemblies will present great challenges in precision wear measurement. In some cases, the accuracy and precision of the measurements will be controlled by the sensitivity and physical characteristics of sensing elements. In other cases, the non-uniformity of the material wear processes themselves will limit the precision of the measurements. Increasing utilization of computers and rapid data sampling will help reduce errors produced by human judgment. Yet, three grand challenges remain:

1) Obtaining highly-precise and accurate measurements of incremental wear in operating machinery without the need to stop the machinery.

2) Obtaining highly-precise and accurate measurements of the wear of micro-scale machine parts and on thin layers.

3) Developing better, cost-effective computer-aided systems to directly measure wear by surface scanning, eliminating the need to make simplifying assumptions about scar geometry in calculating wear volume.

As new techniques for precision wear measurement are developed, there will be a continuing need to reevaluate the measurement methods used in ASTM wear standards. Higher-precision
techniques will eventually become practical and accessible to users of those standards, and it will be the responsibility of the standards committees to assure that they have been incorporated into these standards in an appropriate and timely manner.

Acknowledgments

This research was sponsored by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Transportation Technologies, as part of the High Temperature Materials Laboratory User Program, under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp. The aluminum-nickel eutectic specimen was previously provided by F. Lempke, United Technologies Research Center, East Hartford, CT.

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References


Table 1.
DIN Standard 50321 Wear Measurement Quantities

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<tr>
<th>DIN Ref.</th>
<th>Quantity</th>
<th>Calculation*</th>
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</thead>
<tbody>
<tr>
<td>4.1</td>
<td>linear, absolute</td>
<td>( l_i - l_f )</td>
</tr>
<tr>
<td>4.2</td>
<td>linear rate of wear</td>
<td>( \frac{\left( l_i - l_f \right)}{t} )</td>
</tr>
<tr>
<td>4.3</td>
<td>linear, specific referenced</td>
<td>( \frac{\left( l_i - l_f \right)}{\left( x, n, or other \right)} )</td>
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<tr>
<td>4.4</td>
<td>linear, ratio</td>
<td>( \frac{\left( l_i - l_f \right)<em>{\text{spec}}}{\left( l_i - l_f \right)</em>{\text{ref}}} )</td>
</tr>
<tr>
<td>4.5</td>
<td>volumetric wear, absolute</td>
<td>( V_{\text{spec}} )</td>
</tr>
<tr>
<td>4.6</td>
<td>volumetric rate of wear</td>
<td>( \frac{V_{\text{spec}}}{t} )</td>
</tr>
<tr>
<td>4.7</td>
<td>volumetric rate of wear, specific referenced</td>
<td>( \frac{V_{\text{spec}}}{\left( x, n, or other \right)} )</td>
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<td>4.8</td>
<td>volumetric ratio of wear</td>
<td>( \frac{V_{\text{spec}}}{V_{\text{ref}}} )</td>
</tr>
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<td>4.9</td>
<td>gravimetric, absolute</td>
<td>( m_i - m_f )</td>
</tr>
<tr>
<td>4.10</td>
<td>gravimetric rate of wear</td>
<td>( \frac{\left( m_i - m_f \right)}{t} )</td>
</tr>
<tr>
<td>4.11</td>
<td>gravimetric rate of wear, specific referenced</td>
<td>( \frac{\left( m_i - m_f \right)_{\text{spec}}}{\left( x, n, or other \right)} )</td>
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<td>4.12</td>
<td>gravimetric ratio of amount of wear</td>
<td>( \frac{\left( m_i - m_f \right)<em>{\text{spec}}}{\left( m_i - m_f \right)</em>{\text{ref}}} )</td>
</tr>
<tr>
<td>4.13</td>
<td>wear lifespan</td>
<td>useful life before worn out</td>
</tr>
<tr>
<td>4.14</td>
<td>wear throughput quantity</td>
<td>quantity of wear-inducing process before worn to a state of unserviceability</td>
</tr>
<tr>
<td>4.15</td>
<td>other indirect measures</td>
<td>(quantities not specifically delineated)</td>
</tr>
</tbody>
</table>

* Symbols: \( l \) = length, \( V \) = volume, \( m \) = mass, \( t \) = time, \( x \) = sliding distance, \( n \) = number of contact cycles; subscripts: \( i \) = initial, \( f \) = final, \( \text{spec} \) = test specimen, \( \text{ref} \) = reference body or material
Table 2. Wear Measurement Methods in ASTM G-2 Committee Standards

<table>
<thead>
<tr>
<th>Test</th>
<th>Body 1 - Measurement</th>
<th>Body 2 / 3 - Measurement</th>
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</thead>
<tbody>
<tr>
<td>D-2714 Calibration and Operation of the Falex Block-on-Ring Friction and Wear Testing Machine</td>
<td>rectangular block - measure scar width to 0.01 mm precision</td>
<td>ring, 35 mm diameter x 8.15 mm wide - no wear measurement</td>
</tr>
<tr>
<td>D-4172 Wear Preventative Characteristics of Lubricating Fluids</td>
<td>three bearing balls, 12.7 mm in diameter - measure scar diameter to an accuracy of 0.01 mm</td>
<td>fourth bearing ball, 12.7 mm in diameter - no wear measurement</td>
</tr>
<tr>
<td>D-4170 Fretting Wear Protection by Lubricating Greases</td>
<td>ball thrust bearings, 16 mm inside diam. x 35.69 mm outside diam. - weigh bearing races to the nearest 0.1 mg.</td>
<td>no wear measurement</td>
</tr>
<tr>
<td>G-32 Vibratory Cavitation Erosion Test</td>
<td>cylindrical stub, 15.88 mm in diameter - weigh (to 0.1 mg accuracy) periodically and calculate cumulative mean depth of erosion</td>
<td>collapsing liquid bubbles - no wear measurement</td>
</tr>
<tr>
<td>G-56 Abrasiveness of Ink-Impregnated Fabric Printer Ribbons</td>
<td>steel ball, 6.35 mm diameter - optional wear volume measurement, but example shows using a surface profiling technique; calculate a wear coefficient</td>
<td>ribbon, 2-3 m in length - no wear measurement</td>
</tr>
<tr>
<td>Code</td>
<td>Test Description</td>
<td>Details</td>
</tr>
<tr>
<td>------</td>
<td>----------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
</tr>
<tr>
<td>G-65</td>
<td>Dry Sand/Rubber Wheel Abrasion Test</td>
<td>rectangular coupon 12 mm W x 76 mm L x (3.2-12.7) mm thick - mass loss [to the nearest 0.001 g or 0.0001 g (for Procedure C)] converted to wear volume, corrected for wheel diameter</td>
</tr>
<tr>
<td>G-73</td>
<td>Light Impingement Erosion Test (P)*</td>
<td>not specific, curved or flat test surface - mass loss (balance accuracy &lt; 1.0 mg) used to compute cumulative volume loss using the density; various rationalized rates can be calculated as well</td>
</tr>
<tr>
<td>G-75</td>
<td>Slurry Abrasivity</td>
<td>block, 25 L x 12.7 W x (5-9) mm thick - mass loss used to compute mass loss rate per hour</td>
</tr>
<tr>
<td>G-76</td>
<td>Erosion by Solid Particle Impingment Using Gas Jets (P)</td>
<td>strip (coupon), 30 mm L x 10 mm W x 2 mm thick - mass loss (± 0.01 mg) used to compute volume loss per unit mass of abrasive</td>
</tr>
<tr>
<td>G-77</td>
<td>Ranking Resistance of Materials to Sliding Wear Using Block-on-Ring Wear Test (P)</td>
<td>block, 15.75 mm L x 6.35 mm W x 10.16 mm H - wear scar width converted to volume</td>
</tr>
<tr>
<td>Test Method</td>
<td>Description</td>
<td>Measurement</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>G-81</td>
<td>Jaw Crusher Gouging Abrasion Test (P)</td>
<td>flat plate, adapted to crusher size - mass loss (nearest 0.1 g) converted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>to a final test wear ratio based on wear of both the stationary reference</td>
</tr>
<tr>
<td></td>
<td></td>
<td>plate and moving, opposing test plate</td>
</tr>
<tr>
<td>G-83</td>
<td>Crossed-Cylinder Apparatus</td>
<td>cylindrical (rotating) cylinder, 102 mm L x 12.7 mm diameter - mass loss</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(nearest 0.1 mg) convert to volume loss</td>
</tr>
<tr>
<td>G-99</td>
<td>Pin-on-Disk Apparatus</td>
<td>pin specimen, cylindrical or spherical (2-10 mm diam) wear scar diameter or</td>
</tr>
<tr>
<td></td>
<td></td>
<td>stylus profiling of the pin tip in two orthogonal directions</td>
</tr>
<tr>
<td>G-105</td>
<td>Wet Sand/Rubber Wheel Abrasion Tests</td>
<td>flat coupon - weigh specimen to the nearest 0.0001 g, convert to wear</td>
</tr>
<tr>
<td></td>
<td></td>
<td>volume using the density</td>
</tr>
<tr>
<td>G-133</td>
<td>Linearly-Reciprocating Ball-on-Flat Wear</td>
<td>ball, 9.53 mm diam. - wear scar diameter converted to wear volume; other</td>
</tr>
<tr>
<td></td>
<td></td>
<td>methods optional</td>
</tr>
</tbody>
</table>

* P = standard practice; no indication indicates standard test method
Figure captions:

1. Effect on wear volume of small errors in measuring the width of three wear scars whose actual widths range from 0.5 mm to 5.0 mm.

2. Effect on wear volume of small errors in measuring the depth of three wear scars whose actual widths range from 0.5 mm to 5.0 mm.

3. Comparison of three methods for measuring the wear volume on four block-on-ring tests using the same material combination and testing conditions.

4. Experiment in the estimation of wear scar width. Two jagged lines at left were measured using the scale of arbitrary units at the right. Results of individual measurements are shown in the table. The box labeled "Average of data" gives the width computed from the numerical averages of the points used to plot the lines.

5. Irregularly-shaped scar on a cylindrical wear specimen of Inconel X750 alloy slid dry against 13-8 PH stainless steel. The load was 50 N, sliding speed 0.25 m/s, and test duration 1000 revolutions of the larger cylinder. Tests were conducted in pH 5 water at room temperature.

6. Use of microindentations to assess polishing wear. Optical photomicrographs show impressions before and after polishing with silica. Information below relates to the impression geometry and the average of nine measurements.

7. The changes in depth measured in two locations on the test surface are plotted for four different indenter loads. Location-to-location differences seem to increase as impression size (load) increases.

8. Geometric characteristics of the Berkovich hardness indenter which could in principle be used to make high-precision wear measurements.
Wear volume errors associated with misreadings of the width of wear scars on block specimens (G-77)
Wear volume errors associated with errors in depth measurement on block wear scars

![Graph showing the relationship between depth measurement error and error in wear volume.](image)

Fig 2
Block-on-ring; 10 N, 20 cm/s, air
Alloy CDA 638 block on AISI 52100 ring

**WEIGHT LOSS**
- Averages: 0.35

**SCAR WIDTH**
- Averages: 0.30

**SCAR DEPTH**
- Averages: 0.25

**WEAR VOLUME (mm³)**

<table>
<thead>
<tr>
<th>SPECIMEN NUMBER</th>
<th>WEIGHT LOSS</th>
<th>SCAR WIDTH</th>
<th>SCAR DEPTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.183 mm³</td>
<td>0.291 mm³</td>
<td>0.251 mm³</td>
</tr>
<tr>
<td>2</td>
<td>0.183 mm³</td>
<td>0.291 mm³</td>
<td>0.251 mm³</td>
</tr>
<tr>
<td>3</td>
<td>0.183 mm³</td>
<td>0.291 mm³</td>
<td>0.251 mm³</td>
</tr>
<tr>
<td>4</td>
<td>0.183 mm³</td>
<td>0.291 mm³</td>
<td>0.251 mm³</td>
</tr>
</tbody>
</table>
* difference between the average vertical positions of the 100 points which comprised each of the two horizontal lines
Elliptical wear scar on a cylindrical specimen of Inconel X-750

Area from measuring the length and width = 9.82 mm²

Area from manually digitizing the scar outline = 9.163 mm²

(50N, 0.25 m/s, 1000 rev against 13-8 PH stainless steel)
For the ideal Knoop impression $D = 30.52z$

$\Delta z$ (average of 9 indentations) = 0.24 $\mu$m

Standard deviation = 0.116

COV = 47.4%
d = 0.1554 L

top angle (edge-to-face) = 141° 53'

Fig 8