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Effect of track geometry on the measurement uncertainty of wear in pin-on-disc tribological test

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Abstract
Wear is connected to friction and hence affects energy efficiency and the environmental footprint of the process. The precise evaluation of wear damage will gain further relevance because it is a core input for developing prediction models of mechanical behaviour of materials, to be applied in the design stage of components and systems, and in the optimisation of new manufacturing processes and innovative materials, within the framework of Industry 4.0 and circular economy.
Given the complexity of wear phenomenon, simplified wear tests are required; amongst these, pin-on-disc is a widespread test. It consists in sliding a pin against a disc either according to a circular path or along a linear alternate motion, to generate a track, whose volume is the characterisation target. Its characterisation standards rely upon gravimetric and volumetric method, which have several limitations, though. The former is inadequate for low-wear application and multi-material and multi-phase components, due to the difficulty in locally estimating material density. The latter, requiring profilometric measurements, does not suffer from these limitations; however, profilometric measurements are superseded by high-resolution and information-rich inspection techniques based on surface topography measurement, with respect to whom are less robust and representative. The profilometric method relies on a-priory defined track geometry; despite it is largely exploited, the effect of this approximation is unreported within a rigorous metrological framework.
This work aims at assessing the effect of the track geometry on the accuracy and precision of the volumetric method, both according to standardised and surface topography approaches, within the current standards for topography measuring instruments based on metrological characteristics. This provides insights in the performance comparison of standard and non-standard volumetric methods in quantifying wear in pin-on-disc testing. The results will support the standardisation of topography-based method by providing users with confidence in their use and establishing traceability for this tribological test.

Keywords: Wear; Topography; Uncertainty; Tribology

1. Introduction

Huge efforts have been made towards the deeper understanding of tribological problems. They source high economic costs, frequently cause mechanical components failure and replacement, and impact on industry's environmental footprint. Wear control and its quantification are indeed involved in this process and have become central for the application of the modern principles of Industry 4.0. The upcoming effort towards smart design and optimisation of engineering systems also require accurate evaluation of wear damage [1]. Because tribological phenomena are very complex, the experimental practice often looks for simplified approaches, as model tests, since identifying the effect of the influence factors is non-trivial [1,2]. Model tests allow comparative analysis of results in standard conditions, as their conventionality makes them highly reproducible, even though it limits their representativeness.

Amongst the model tests, pin-on-disc has been extensively used. It consists in applying a known force on a static pin orthogonal to the surface of a moving sample [2]. The sample is rotated or linearly displaced to generate a relative motion with constant or continuously variable speed, respectively, see Fig. 1. The choice of the type of motion may be motivated by the specific application of the materials under study, e.g. for application involving static-dynamic friction or stick-slip phenomena the linear reciprocating layout usually performs better.

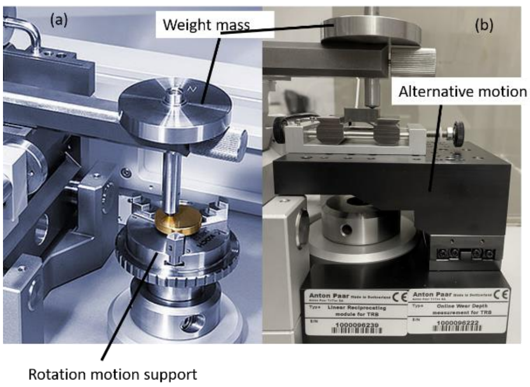

Figure 1. Anton Paar TRB tribometer: (a) rotation and (b) linear alternating motion pin-on-disc set up.

This method has produced a vast amount of scientific literature and is still used today because setup and control of test parameters is very easy. Pin-on-disc is successfully applied in the aerospace [3,4], automotive and aeronautical fields to characterize new low-density and high strength alloys, e.g. Mg-Al-Si-Zn alloys and cermet coatings as Ti[Nb,V]N [5], and to explore the tribological properties of innovative 2D-coatings, e.g. graphene sheets [6]. Vast use of this test method exists for the characterisation of manufacturing processes, e.g. to analyse the performance of coatings for tools [7] and to investigate the behaviour of additive manufactured components [8]. Lubrication-related issues are also widely investigated by pin-on-disc and similar model tests [9].

The purpose of any wear testing is typically the quantification of the wear damage. ASTM G99-17 [10] prescribes two measuring techniques for pin-on-disc tests: weighing of samples with precision balance (gravimetric method) and stylus-profilometry of the wear tracks (volumetric method). However, present-day technologies make available much more information-rich inspection measuring techniques based on topography. An increasing number of laboratories rely on these methods [11,12], despite a rigorous metrological characterisation in literature and the recognition by standards are still lacking in the tribological field.

This work exploits the evaluation of the measurement uncertainty for surface-topography based methods in quantifying surface damage after the pin-on-disc test to compare the performances of available topographical characterisation methods and investigate the effect of the track geometry on the obtained results, which is unreported in the literature. Section 2 discusses the available state-of-the-art methods for wear volume evaluation. Section 3 addresses the evaluation of measurement uncertainties. Section 4 describes the experimental set-up by which results are obtained and discussed in Section 5. Section 6 draws conclusions.

2. Methods for wear quantification in pin-on-disc test

The relevant standards, i.e. ASTM G40 and ASTM G99 and ASTM G133 [10,13,14], require to measure wear in terms of the volume of the damaged material. The overall damage can be considered as consisting of protuberances caused by plastic flow (or debris deposition), i.e. galling, and voids caused by material loss, i.e. namely wear; their summation is the total surface damage, V_D.

Two standardised approaches are available to measure wear. The gravimetric approach is frequently used because of the relative ease of measurement [15]. However, it cannot detect damages related to plastic effects and errors may occur if some material binds to the interface surfaces. Moreover, the low sensitivity makes it unsuited for measuring small wear occurring on large bodies. Another relevant limitation is the accuracy required for the density value to get reliable volumetric data which further limits this method's application to homogeneous materials [16]. Conversely, the volumetric approach directly measures volumes, thus being independent on phases and densities, and is sensible to surface damages due to removed, displaced and, sometimes, transferred material, enabling for separate assessment. Therefore, the volumetric method seems more flexible because it allows to characterise the right quantity according to every application's requirements. In the following, the analysis will focus only on the volumetric methods applied to the measurement of the material loss. The standards require to measure some profiles [17] across the wear track, so that V_D for the rotary and linear reciprocating tests, respectively, are:

$$V_{D,ASTM,circ} = \frac{2\pi}{N} R \sum_{j=1}^{N=8} S_j \quad (1)$$

$$V_{D,ASTM,lin} = \frac{L}{N} \sum_{j=1}^{N=6} S_j \quad (2)$$

$$S_j = p_s \sum_{i=1}^{M} |z_i| \quad (3),$$

where R is the radius of the circular wear track, L the length of the linear track; S_j is the cross-section area of the wear track at the j-th location, M the number of sampled points in the profile with height z_i and p_s is the lateral sampling step, i.e. the pixel size.

The standard approach might suffer from the approximation of real track geometry with an ideal one, e.g. the radius of the circular track can be highly irregular. Moreover, the profiles can be measured either by means of contact stylus or by areal surface topography measuring instruments. In the latter case, it is even more evident how the standard procedure features an inherent information loss. Profiles have to be measured, equally spaced, radially and transversally to the track for the rotary and linear test, respectively.

Alternatively, methods are available in literature to exploit in full topographical measurements. Amongst the others, the material and void volume parameters, V_m and V_v, that represent the galling and wear volume respectively [18], can be applied. They are computed from the areal material ratio curve (MRC) as:

$$V_{wear} = V_v = K\left((z_{max} - h) - \sum_{j=B+1}^{N_{bin}} \Delta z_j m_{r\,j}\right) \quad (4)$$

$$V_{galling} = V_m = K \sum_{j=1}^{B} \Delta z_j m_{r\,j} \quad (5),$$

where $h = S_{mc}(m_r)$, i.e. the inverse of the areal material ratio function at the material ratio m_r; N_{bin} the number of bins to which the material ratio curve is discretised and B the bin containing the threshold height to distinguish the contributions. K is a factor to convert the relative volume into the most appropriate unit and represents the horizontal area and is $K = n_p p_s^2$, with n_p the number of pixels. Summing them yields a total damage wear volume, $V_{D,MRC}$.

3. Measurement uncertainty in wear quantification

To enable statistically meaningful comparison of the performances of methods available in literature to measure wear, it is necessary to evaluate the related measurement uncertainty. This provides users with confidence in their usage, by establishing traceability, and information on the precision. If the output is a linearisable function of a set of input, i.e. $V_D = f(\boldsymbol{\vartheta})$, uncertainty can be estimated by propagating model inputs contribution through the law of uncertainty propagation:

$$U(V_D) = k\sqrt{\sum_{a=1}^{n}\left(\frac{\partial f}{\partial \vartheta_a}\right)^2 u^2(\vartheta_a)} \quad (6),$$

where k is the coverage factor, at the given confidence level [19]. The output of topographical measurements is a set of heights $z(x,y)$ that are input in Eqs.(1)-(5). Consequently, the uncertainty contributions are those describing the coordinate axes of the measuring instrument. When performing topographical measurements, a simple, compact and thorough framework to metrologically characterise the influence factors of measuring instruments is provided by the Metrological Characteristics (MC): *characteristics of the measuring equipment, which may influence the result of measurement, may require calibration and have an immediate contribution to measurement uncertainty* [20]. They describe the measurement noise, u_N, the flatness deviation, $u_{Z_{FLT}}$, the repeatability, u_{Rep} (i.e. the surface topography repeatability), the axes linearity deviation after the adjustment of the axes amplification, $u_{x,y,z}$, and the lateral resolution, u_{W_R}. They can be combined to estimate the standard uncertainty of measurement axes as [21]:

$$u(z) = \sqrt{u_N^2 + u_{Z_{FLT}}^2 + u_z^2 + u_{Rep}^2} \quad (7)$$

$$u(x,y) = \sqrt{u_{W_R}^2 + u_{x,y}^2} \quad (8).$$

Literature establishes methods for their calibration, which thus allows for measurement traceability [21,22]. Applying Eq.(6) to Eqs.(1)-(5), the uncertainty of the wear evaluation methods is obtained as:

$$u(\overline{V_{D,ASTM,circ}}) = \sqrt{\frac{\frac{4\pi^2}{N}\left(\bar{S}^2\mathbb{E}[u^2(R_j)] + \bar{R}^2\mathbb{E}[u^2(S_j)]\right)}{N}} \quad (9)$$

$$u(\overline{V_{D,ASTM,lin}}) = \sqrt{\frac{\bar{S}^2u^2(\mathrm{L}) + \mathrm{L}^2\frac{\mathbb{E}[u^2(S_j)]}{N}}{N}} \quad (10)$$

$$u^2(S_j) = \left(\frac{S_j}{p_s}\right)^2 u^2(p_s) + p_s{}^2Mu^2(z) \quad (11)$$

$$u^2(R_j) = \frac{1}{8}\left(u^2(x)\cos\vartheta^2 \ + u^2(y)\sin\vartheta^2\right) \quad (12)$$

$$u(\overline{V_{D,MRC}}) = \sqrt{\frac{\left[\left(\frac{V_m(m_r)}{K}\right)^2 + \left(\frac{V_v(m_r)}{K}\right)^2\right]u^2(K) + 2K^2\left[1 + \sum_{j=1}^{N_{bin}} m_{r_j}^2\right]u^2(z)}{n_p}} \quad (13)$$

$$u^2(K) = 4Kn_pu^2(p_s) \quad (14),$$

where *u(L)* is approximately computed considering a uniform distribution with half-width of 2 units of the least significant digit of the nominal stroke [23] and $u(p_s)$ associating a triangular distribution to the pixel resolution [21]. R_j is the radius of the circular track at the *j*-th location, described by the angle ϑ. As standard methods ultimately require the evaluation of an average volume, the standard uncertainty of averages is computed.

4. Experimental set-up

The previous sections introduced the theoretical analysis that is now applied to a set of pin-on-disc tests in rotary and linear reciprocating motion. Tribological tests were performed by an Anton Paar TRB tribometer (see Fig. 1) by wearing-out an aluminium sample and a PTFE sample against a 6 mm steel ball (100Cr6). Samples were accurately prepared before tests to improve the surface finish: grinding and polishing were performed to achieve a smooth surface roughness (Sa of 0.3 µm and Sq of 0.4 µm) on both samples. A single test was performed on each sample in similar testing conditions (5 N load, 0.05 m/s average speed and 50 m of test duration in terms of length) in rotary (track radius 5 mm) and linear reciprocating mode (track length 4 mm). Fig. 2 shows the surface damage on the two samples at the end of the rotary tests. The two materials were chosen because they react very differently against a steel ball: aluminium generates large debris due to strong adhesion and is characterised by a highly irregular track, whereas PTFE features a smooth regular track due to abrasion and plastic effects, with limited galling.

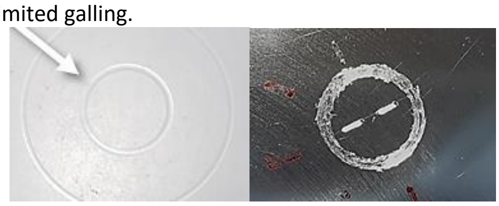

Figure 2. Wear track on the PTFE sample (on the left) and wear track appearance on the aluminium sample (on the right) after a rotary pin-on-disc test

After the tribological test, the samples were cleaned with acetone. Surface topography was measured using a CSI Zygo NewView 9000, with a 5.5× objective lens, with a field of view (1.56×1.56) mm with a pixel size of 1.56 µm. To cover the whole tracks stitching of several field of views was necessary. Profiles required to apply the standard method were extracted from the surface topography measurements.

5. Results discussion

Measured surface topographies of linear alternating and rotary test of the wear tracks on the two samples are shown in Fig. 3. The aluminium is characterised by a more irregular topography, with galling on the edges of the scar and attached debris inside. The linear alternating motion introduces smaller galling and less debris in the track, which, though, is deeper. The PTFE track, as intended, is regular.

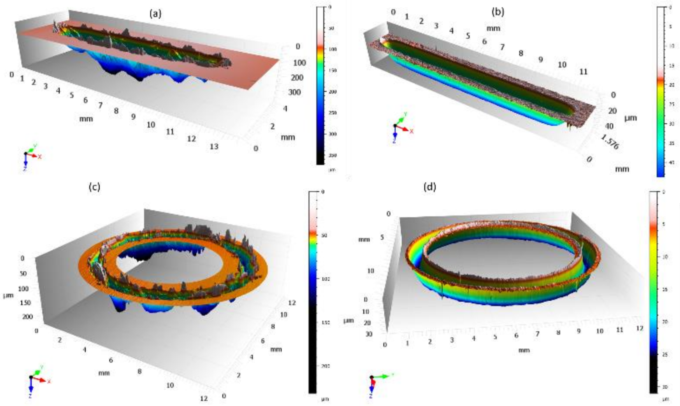

Figure 3. Surface topography of linear alternating test on (a) Al and (b) PTFE and on rotary test on (c) Al and (d) PTFE.

The uncertainty contributions of the metrological characteristics were introduced in the model as Type B contributions [19] exploiting the characterisation of a similar measuring instrument [21]; repeatability as Type A based on 30 measurements [22]. Table 1 reports the corresponding values. Law of uncertainty propagation was applied and expanded uncertainty with a coverage factor of 2 was computed, see Eq.(6). Results are shown in Fig. 4 and 5, respectively for PTFE and aluminium sample. It results that the wear track geometry introduces a systematic difference in the measured wear volume; this effect, as can be noticed comparing Fig. 4 and 5, depends on the material.

For a given geometry, the tribological standard approach (ASTM), is less accurate and precise than the MRC approach. The accuracy performances result from the lower representativeness of the ASTM method: for the regular track on the PTFE sample, the relative difference of the mean wear volumes is 1% and 3%, respectively for the linear and the circular track; these, due to the irregular topography of the tracks (see also Fig. 3), are 1% and 15%, respectively, on the aluminium sample. The worst precision of the ASTM method to evaluate wear has to be ascribed to the greater impact on the final expanded uncertainty of the lateral scale uncertainty contributions, see again Table 1.

Table 1. Metrological characteristics (MC) considered for the evaluation.

MC	u_N	$u_{Z_{FLT}}$	u_{Rep}	u_z	$u_{x,y}$	u_{W_R}
u / nm	0.2	5	0.04	10	100	902

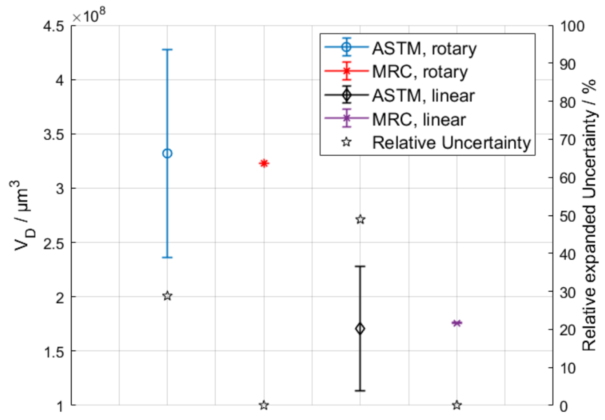

Figure 4. Comparison of the effect of track geometry and methods to estimate wear volumes on the wear characterisation of the PTFE sample. Uncertainties are computed with a coverage factor of 2 (i.e. at 95% confidence level).

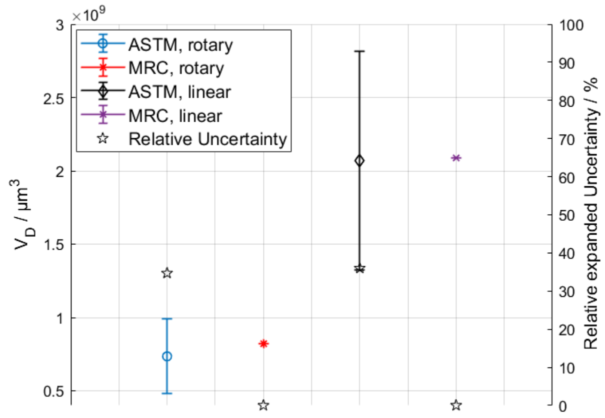

Figure 5. Comparison of the effect of track geometry and methods to estimate wear volumes on the wear characterisation of the aluminium sample. Uncertainties are computed with a coverage factor of 2 (i.e. at 95% confidence level).

6. Conclusions

Measuring wear is core for several applications where friction and energy consumption are critical. Today innovative materials are designed to optimise the mechanical systems' durability, energy consumption, and pollutant emission. To test innovative materials' wear in terms of volume of damaged material, industry and academia often resort to pin-on-disc tests, because of its conventionality, repeatability and realisation simplicity. Different layouts are available, i.e. rotary and linear alternating motion, whose effect on the estimated volume is unreported in literature. This work compared the performances of the most accredited methods available in literature to assess wear volume exploiting the measurement uncertainty. Results show that the wear track geometry introduces significant differences in the results, also dependent on the characterised material. Moreover, it is shown that the material tribological response impacted relevantly on the accuracy of the characterisation method. These were proven to feature dramatically different precision performances; in particular, the one currently suggested by tribological standards is more uncertain than other approaches which exploit topographical measurements and rely on accepted surface topography parameters.

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References

[1] Blau P J 2008 Friction science and technology: from concepts to applications. CRC press, Boca Ranton, FL (USA).
[2] Bhushan B 2000 Modern tribology handbook CRC press, Boca Ranton, FL (USA).
[3] Sharma S, Patel B, Patel R 2020 Friction and wear characteristics of robust carbon-carbon composites developed solely from petroleum pitch without reimpregnation *Friction* **8**:945–56.
[4] Biagi R, Verna E, Kazasidis M, Bemporad E, Galetto M, Yin S, Lupoi R 2021 Cold Spraying of IN 718-Ni Composite Coatings: Microstructure Characterization and Tribological Performance *Mat Sc Forum* **1016**:840-845.
[5] Madhukar P, Selvaraj N, Rao C S P, Veeresh Kumar G B 2020 Fabrication and characterization two step stir casting with ultrasonic assisted novel AA7150-hBN nanocomposites *J Alloys Compd* **815**:152464.
[6] Mura A, Canavese G, Goti E, Rivolo P, Wang H, Ji X, Kong J 2020 Effect of different types of graphene coatings on friction and wear performance of aluminum alloy *Mech Adv Mater Struct*.
[7] Ambadekar P K, Choudhari C S 2020 Measurement of Tungsten Carbide Tool Wear by Tribological Investigations *J Bio- Tribo-Corrosion* **6**:44.
[8] Bochkareva S A, Grishaeva N Y, Buslovich D G, Kornienko L A, Lyukshin B A, Panin S V, Panov I L, Dontsov Y V 2020 Development of a Wear-Resistant Extrudable Composite Material Based on an Ultrahigh-Molecular Polyethylene with Predetermined Properties *Mech Compos Mater* 2020 **56**:15–26.
[9] Bai L, Meng Y, Khan Z A, Zhang V 2017 The Synergetic Effects of Surface Texturing and MoDDP Additive Applied to Ball-on-Disk Friction Subject to Both Flooded and Starved Lubrication Conditions *Tribol Lett* **65**:163.
[10] ASTM G99-17 Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus. ASTM, West Conshohocken, PA (USA).
[11] Bolelli G, Cannillo V, Lusvarghi L, Manfredini T 2006 Wear behaviour of thermally sprayed ceramic oxide coatings *Wear* **261**:1298–315.
[12] Wang X, Zhang Y, Yin Z, Su Y, Zhang Y, Cao J 2019 Experimental research on tribological properties of liquid phase exfoliated graphene as an additive in SAE 10W-30 lubricating oil *Tribol Int* **135**:29–37.
[13] ASTM G133-95 Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear. ASTM, West Conshohocken, PA (USA)
[14] ASTM G40-17 Standard Terminology Relating to Wear and Erosion. ASTM, West Conshohocken, PA (USA)
[15] Bayer R G 2004 Mechanical Wear Fundamental and Testing. Marcel Dekker Inc, New York, NY (USA).
[16] D'Amato R, Calvo R, Ruggiero A, Gómez E 2017 Measurement capabilities for ball bearing wear assessment *Procedia Manuf* **13**:647–54.
[17] Colbert R S, Krick B A, Dunn A C, Vail J R, Argibay N, Sawyer W G 2011 Uncertainty in pin-on-disk wear volume measurements using surface scanning techniques *Tribol Lett* **42**:129–31.
[18] Leach R K 2013 Characterisation of Areal Surface Texture. Springer, Berlin.
[19] JCGM 100: Evaluation of measurement data — Guide to the expression of uncertainty in measurement (GUM) 2008. JCGM, Sèvres, France.
[20] ISO 25178-600:2019 Geometrical product specification (GPS) - Surface texture: Areal Part 600: Metrological characteristics for areal-topography measuring methods. ISO, Genève.
[21] Giusca C L, Leach R K 2013 Calibration of the metrological characteristics of a Coherence Scanning Interferometers (CSI) and Phase Shifting Interferometers (PSI). NPL - Good Practice Guide. Teddington, UK.
[22] ISO 25178-604: 2013 Geometrical product specifications (GPS) - Surface texture: Areal Part 604: Nominal characteristics of non-contact (coherence scanning interferometry) instruments. ISO, Genève.
[23] ISO 14253-2: 2011 Geometrical product specification (GPS) – Inspection by measurement of workpieces and measuring equipment: Part 2: Guidance for the estimation of uncertainty in GPS measurement, in calibration of measuring equipment and in product verification. ISO, Genève.