Ball-on-flat linear reciprocating tests: Critical assessment of wear volume determination methods and suggested improvements for ASTM D7755 standard

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Abstract

This work presents a critical assessment of wear volume determination methods for ball-on-flat linear reciprocating sliding tribological tests. It revealed that the ASTM D7755-11 standard leads to the highest relative errors (up to 106%) and deviations (up to 27%) depending on the regularity of the wear track shape. The present study suggests improvements for the ASTM D7755-11 wear computation, which can reduce errors from 106% to 17% when analysing irregularly shaped wear tracks. In addition, a five-year period review of two relevant tribology journals revealed that the most used methods for wear determination, namely three-dimensional (3D) profilometry (46%) and nonstandard profile-based methods (36%), are overall reported with incomplete procedural information for wear computation. Furthermore, as many as 8% of the papers specify no data regarding the computation method and only 3% explicitly cited and followed the existing standards (ASTM D7755-11 or G133-05). The present study highlights the importance of the correct selection, implementation, and reporting of wear volume computation method and quantifies the potential errors.

Keywords: Wear, Sliding, Surface, Analysis, ASTM, D7755-11

Nomenclature

Abbreviations

AFM	Atomic force microscopy
ASTM	American Society for Testing and Materials
AOI	Area of interest
CV	Coefficient of variation
CSIL	Cross-section profile integration over the length
OM	Optical microscopy
RSTT	Reciprocating sliding tribological tests
SD	Standard deviation

Symbols

d_3	Total length of wear track in the sliding direction
d_4	Width of the wear track
R	Radius of the ball counterbody
$\overline{R}$	Resulting radius of the cross-sectional shape of the wear track after the test
s	Sliding stroke
$W_{q,avg}$	Average cross-sectional worn area
W_q	Planimetric cross-sectional worn area
$W_{v,flat}$	Wear volume on the flat specimen

1 Introduction

Despite the quantification of wear volume being key in tribological testing, current methods for volume calculation in triboelements have several limitations, as was deeply discussed by Blau [1]. The gravimetric method cannot be used for determining small wear amounts [2]; characterisation of the wear track using 2D techniques can only be applied to flat specimens [3–6]; and finally, 3D profilometry can be time-consuming, especially for calculating the wear volume of large testing campaigns [2,7]. Simple and fast methodologies are desirable; however, the robustness and accuracy of measured data are fundamental in conducting valid tribological research.

A recent study discussed the repeatability and validity of tribology research, demonstrating that the experimental designs were overall rather poor [8]. Similarly, Blau [9] revisited aspects of the quality and content of wear research manuscripts, stating that *'Progress in wear science and engineering depends on effective communication, and archival tribology journals and conferences help to serve those communication needs'*.

The effectiveness of communication is strongly based on the appropriate description and implementation of the method. Efforts are currently made to establish universal standardised tribology databases [10–12]. The major issues to tackle are equipment comparability [13] and the selection of appropriate methods for determining tribology metrics such as friction [14] and wear [15]. Accordingly, robust universal characterisation procedures must be established to ensure that comparable data are generated with both archival capacity and added value.

The present study conducted a critical analysis of wear track volume calculation methods for ball-on-flat linear reciprocating sliding tribological tests (RSTT). The remainder of this paper is structured as follows. In Section 2, the prevalence of the computation methods used in the published literature is analysed based on a review of two highly regarded tribology journals, namely *Tribology International* and *Wear*, for the period 2014–2018. In Section 3, the most commonly used methods are introduced and compared for different wear track typologies, and their robustness and accuracy are analysed. Finally, the variables that could introduce bias into the calculation according to the ASTM D7755-11 standard [16] are experimentally analysed in Sections 4 and 5, and good practice guidelines are proposed for wear volume quantification.

2 Literature review of wear volume characterisation methods

A systematic literature search was performed on the *ScienceDirect* website [17] by entering the keywords *reciprocating sliding* and *wear volume*. The search was limited to a set time frame (2014–2018) and to relevant tribology journals (*Wear*, current Impact Factor: 4.108, and *Tribology International*, current Impact Factor: 4.271). Altogether, 541 papers were identified and subsequently screened to select those related to ball-on-flat linear reciprocating sliding tribological tests. The remaining 271 papers (164 from *Tribology International* and 107 from *Wear*) were divided between four reviewers who examined them independently to identify the applied wear volume calculation methods. Finally, the reliability of the results was validated by cross-checking 10% of the results of each evaluator.

The tribological system [18] consists of both sample and counterbody, along with the intermediate body, environment, and test conditions. However, only 14% of the reviewed papers reported the wear volume of both the sample (flat) and counterbody (ball). Table 1 presents the wear volume characterisation methods identified for both flat and ball specimens along with the percentage of usage of each.

Table 1: Prevalence of wear volume characterisation methods for both flat and ball specimens.

Wear volume characterisation method	Flat specimen (total papers = 236)	Ball specimen (total papers = 46)
3D profilometry	108 papers (46%)	19 papers (41%)
Gravimetry	16 papers (7%)	4 papers (9%)
Standard (ASTM D7755-11 or G133-05)	7 papers (3%)	2 paper (4%)
Other calculation methods	85 papers (36%)	11 papers (24%)
Not reported	20 papers (8%)	10 papers (22%)

The larger prevalence of flat specimen wear volume reporting (236 papers, 87%) compared to the ball specimen (46 papers, 17%) is noteworthy, although the methods used are common. Based on the observed trend, the subsequent analysis focuses on the flat specimen wear volume computation methods.

Figure 1(a) shows that the two most commonly used methods are 3D profilometry (46%) and the so-called other calculation methods (36%). The claim of specifically using the existing specific standards ASTM D7755-11 [16] and ASTM G133-05 [19] is rather seldom (3%), and mentioned in only one and six identified papers, respectively.

The other volume calculation methods referred to in Fig. 1 most commonly included integrating the cross-sectional wear profile along the entire wear track or stroke length (61 papers, 73%). This calculation approach is referred to here as cross-section profile integration over the length (CSIL). Among the remainder, referred to as 'Alternative methods' in Fig. 1(b), 27% (21) of the papers employed diverse mathematical equations, whereas a few applied specific methods published in scientific papers ([5] and [3], respectively).

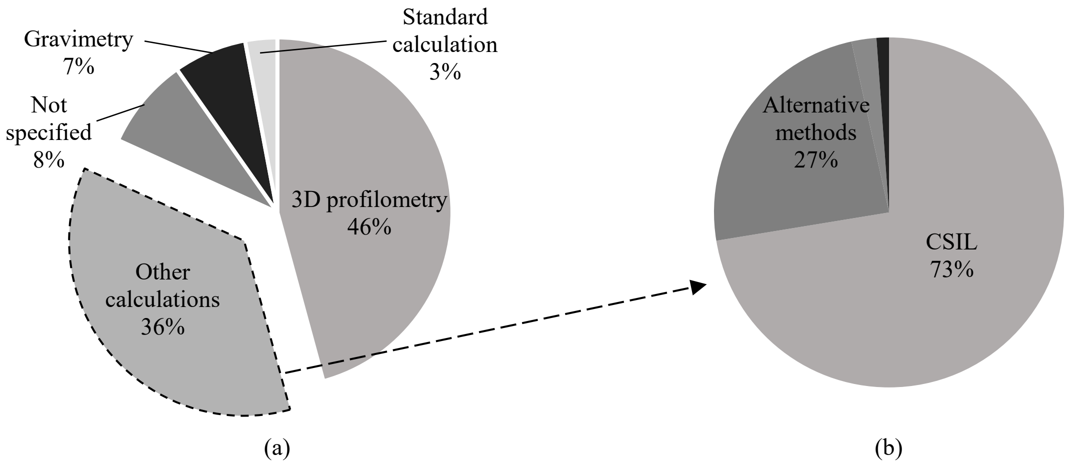


Fig. 1: Representation of the most widely employed methods for calculating the wear volume on the flat specimen. (a) Overview of methods. (b) Detailed representation of the other calculation methods based on [5] and [3].

Based on the obtained results, the following section reviews the common methods for computing wear volumes (i.e., 3D profilometry calculation and CSIL calculation), along with the identified standard-based calculations ASTM D7755-11 and ASTM G133-05. Although these two standards are not widely used in the scientific community, as demonstrated above, they provide a clear benchmark.

3 Review of wear volume calculation methods

The main wear track volume calculation methods (see Section 2) are reviewed in this section. The advantages and limitations of each method are described and general guidelines are suggested.

3.1 The ASTM G133-05 standard

First adopted in 2005 and reapproved in 2016, the ASTM G133-05 standard [19] covers laboratory procedures for determining the sliding wear under a linear reciprocating ball-on-flat test configuration. The principal quantities of interest involve the wear volumes of the contacting ball and flat specimen materials.

The flat specimen wear track volume is computed by multiplying the average cross-sectional worn area ($W_{\mathrm{q,avg}}$) with the sliding stroke (s), see Eq. 1.

$$W_{\mathrm{v,flat}} = W_{\mathrm{q,avg}} \cdot s \qquad \text{Eq. 1}$$

The number of profiles for calculating the average cross-sectional worn area depends on the homogeneity of the wear track (see Fig. 2). Additionally, due to the varying sliding velocities in RSTT (maximum in the middle of the stroke, zero at its ends, and something in between), the depths of the wear tracks may also vary. In case the difference between the first equally spaced three profiles is less than 25% (homogeneous track), this is considered sufficient. If larger deviations are obtained due to non-homogeneity of the wear track, six cross-sectional profiles (W_{q}) are extracted to compute the average worn area ($W_{\mathrm{q,avg}}$) (see Fig. 2(c) and Fig. 2(d)).

This method omits the worn round zones (B in Fig. 2(b)) at the two ends of the strokes that correspond to the sliding direction reversion. Accordingly, it is suitable for relatively large stroke length tests, where the stroke length of 10 mm is prescribed by the standard.

The literature review revealed that only six studies adopted this standard wear computation method. CSIL, on the other hand, was used extensively. Those papers described the use of profile integration to compute the volume, although most failed to explicitly mention the number of profiles. It can thus be concluded that the vast majority of publications adopt modifications of the ASTM G133-05 standard, although this practice is often reported ambiguously, and is therefore a departure from the standard.

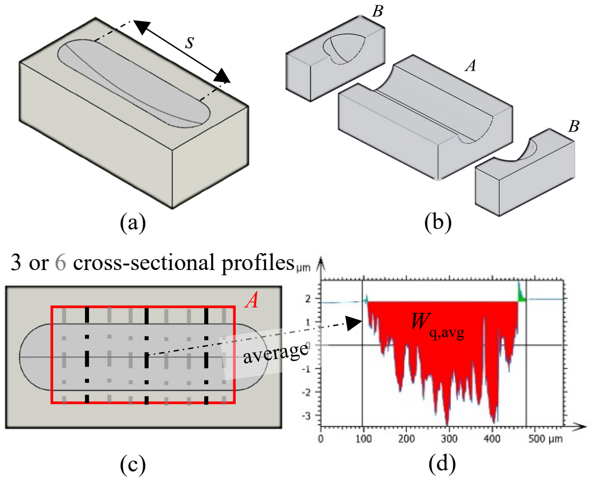


Fig. 2: Schematic of the flat specimen wear volume calculation according to the ASTM G133-05 standard. (a) Representation of an idealised RSTT wear track along with the stroke identification. (b) Segmentation of the wear track: (A) central section and (B) round side areas. (c) Identification of the cross-sectional profiles to measure inside the central section. (d) Representation of a single planimetric cross-sectional wear profile (W_q); $W_{q,avg}$ is calculated based on three or six cross-sectional profiles.

3.2 The ASTM D7755-11 standard

In contrast to the ASTM G133-05 standard, the ASTM D7755-11 standard [16] (first introduced in 2011 and reapproved in 2017) was developed for considering the contribution of both round edges to the sliding direction reversion zone of the wear track (see Fig. 3). This contribution greatly affects the wear volume calculation for short strokes. Accordingly, the standard is aimed at high-frequency linear-oscillation equipment with stroke lengths s below 2.5 mm.

As shown in Fig. 3(b), the wear track for the flat specimen can be divided into three segments, the central part (A) and both round edges (B). The variables required to compute the wear volume are schematically summarised in Fig. 3(a) and Fig. 3(d).

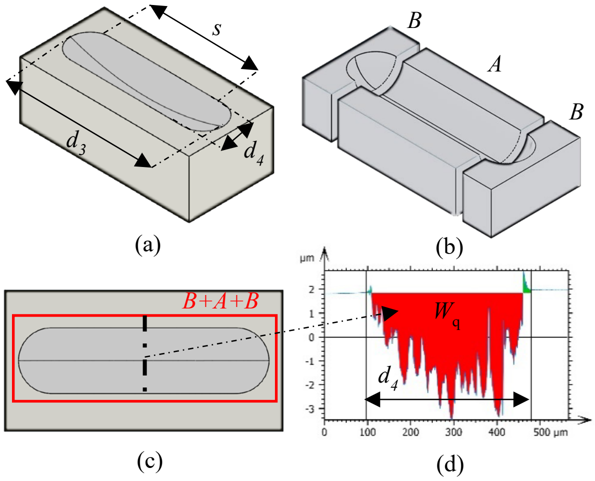


Fig. 3: Schematic of the flat specimen wear volume calculation according to ASTM D7755-11 standard. (a) Representation of an idealised RSTT wear track along with the main parameter identification. (b) Segmentation of the wear track: (*A*) central section, and (*B*) side round areas. (c) Identification of the middle cross-sectional profiles. (d) Representation of the planimetric cross-sectional wear (W_q).

The wear volume of the wear track on the flat specimen, considering both the central section (*A*) and the rounded edges (*B*), is calculated as follows (Eq. 2):

$$W_{v,\text{flat}} = \underbrace{\frac{\pi \cdot d_4^2 (d_3 - s)^2}{64} \cdot \frac{1}{\bar{R}}}_{2B} + \underbrace{s \cdot W_q}_{A} \qquad \text{Eq. 2}$$

where d_3 is the total length of the wear track in the sliding direction, d_4 is the width of the wear track, and $\bar{R}$ corresponds to the resulting radius of the cross-sectional shape of the wear track after testing (Eq. 3).

$$\bar{R} = \frac{d_4^3}{12 \cdot W_q} \qquad \text{Eq. 3}$$

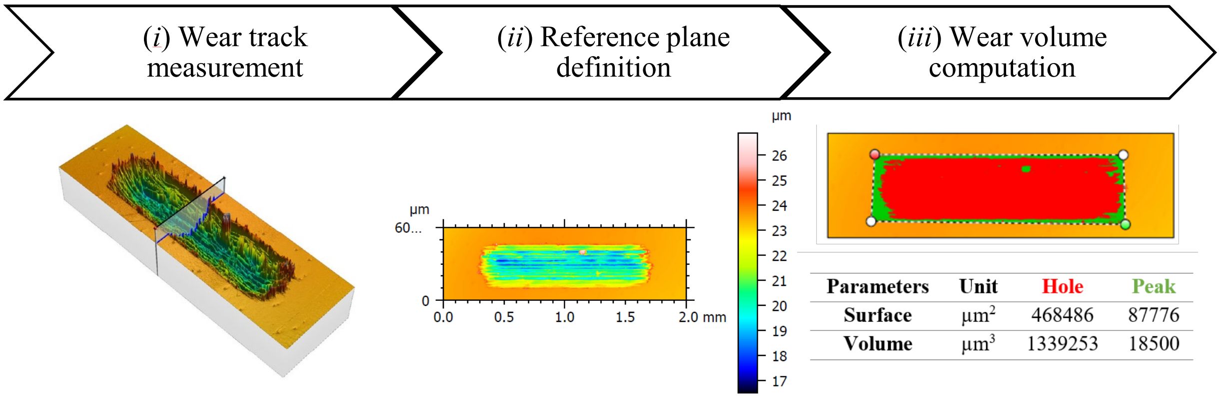
Unlike the ASTM G133-05 standard, the planimetric wear (W_q) is computed using only one perpendicular cross-sectional worn area in the centre of the wear track. However, additional measurements are required here (i.e., the entire track length (d_3) and its width (d_4)) to consider the edge rounded sections.

Note that Eq. 2 and Eq. 3 above are approximated equations for strokes smaller than 2 mm. The application of this method has a limited validity when *R* (radius of the ball) is smaller than $\bar{R}$ (approximate radius of the wear track on the flat after sliding). Additionally, it is assumed that the wear depth of the track is much smaller than *R*.

3.3 3D profilometry calculation

Previously introduced methods are based on the use of mathematical expressions or simplifications of the wear track geometry to compute the wear volume, which are applicable depending on the wear track length. However, noncontact 3D optical surface metrology allows computing volume loss on samples and components of various shapes and sizes without any simplification at all; therefore, it measures the 'real' worn volume.

When the original (tribologically non-tested) surface is known, the wear volume can be computed by subtracting the measured wear track topography from that of the original non-tested surface. This, however, requires previously measuring the surface at the same location, and then aligning both measurements, which is cumbersome and time-consuming. The most widely used approach computes the wear volume based on the measurement of the wear track. The measured topographical data are processed to determine the volume loss from abrasion and wear with micron precision. Three steps constitute the process (see Fig. 4).



Parameters	Unit	Hole	Peak
Surface	µm²	468486	87776
Volume	µm³	1339253	18500

Fig. 4: Representative diagram of the steps that constitute the wear volume calculation of a wear track on the flat specimen using 3D profilometry.

First (*i*), the 3D topography of the wear track and the surrounding plane surface is measured. Second (*ii*), a mathematical reference plane is constructed, usually from a least-squares fit of the plane to the data of the non-affected surface in the wear track surroundings. Third (*iii*), the wear volume is computed by subtracting the wear track topography from that of the modelled plane surface.

Considering that a wear track is three-dimensional and irregular, 3D analysis may be the most appropriate technique. It should be noted that the computed wear value may include a plastic deformation component in addition to real material loss, since the residual depth – if any – will be considered. Although this effect is neglected overall, the contribution of plastic deformation can be accounted for by performing indentation tests using the same counterpart and loading as in the wear tests [29].

Noncontact optical methods such as white light interferometry [20,21], confocal profilometry [22,23], and more recently focus variation [24–26] are used to measure volumetric wear. Each technique differs in its measuring capabilities [27]; moreover, the optical resolution and spatial sampling rate vary depending on the magnification used, affecting the measurement resolution. All variables included in the volume characterisation process must thus be reported. Wäsche et al. [30] analysed the use of atomic force microscopy (AFM) for measuring macroscopic wear scars through stitching. They concluded that even if AFM is more precise than interferometry, the overall precision of the optical method is acceptable. Furthermore, the AFM measurement process is time-consuming and cumbersome, which limits its applicability.

Currently, optical profilometry may be the most suitable technique for obtaining accurate wear-volume measurements in a reasonable time, and according to the literature review, it is the most commonly used. However, the results depend on the measurement technique, configuration selected, and post-processing for volume computation. Consequently, the definition of guidelines for wear volume measurement using optical profilometry would be of interest.

4 Experimental

With the objective of covering different ranges and typologies of wear tracks to perform a critical analysis, diverse wear-track typologies were produced based on the observations made in our previous work [31]. In brief, an in-house-built tribometer was used and operated in ball-on-flat linear reciprocating test conditions with a stroke of ~1 mm at a reversing frequency of ~1 Hz. Plane polished titanium alloy (Ti6Al4V) samples were used along with 10 mm diameter counterbodies (hardened 100Cr6 steel or Si_3N_4 ceramic) in dry or oil-lubricated conditions at a normal load of 1 N. All RSTT were performed in an ambient laboratory environment with a relative humidity ranging between ~28% and 53%. The detailed experimental parameters are listed in Table 2.

Table 2: Linear reciprocating sliding tribological test conditions related to each wear track type. * Details in [31].

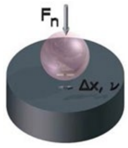
Tribosystem	RSTT 			
Samples	Ti6Al4V – disks (polished, roughness R_a = 5 nm)			
Wear track typology	Small irregular	Small regular	Large irregular	Large regular
Counterbody (ø = 10 mm)	100Cr6	Si_3N_4	Si_3N_4	100Cr6
Lubrication*	Dry	VPX oil + 0.5% RC 3180 (ZDDP)	Dry	VPX oil
Relative humidity [%]	53.2	51.0	38.7	28.3
Stroke [µm]	1022			
Frequency [Hz]	1			
Normal load [N]	1			
Number of cycles	1000			
Atmosphere	Laboratory air			

Figure 5 depicts the optical micrographs of the wear tracks subjected to the present investigation. The wear tracks on Ti6Al4V samples were classified as irregular (Fig. 5(a–b)) or regular (Fig. 5(c–d)) according to the homogeneity of the wear track shape. Additionally, wear volumes were also classified as either small (0–~700×10^{-6} mm^3) or large (700–~2500×10^{-6} mm^3).

Both the flat and ball specimens were cleaned in benzene (petroleum ether) for 15 minutes using an ultrasonic bath to remove the residual lubricants and wear debris before characterisation.

Wear tracks were analysed by light optical microscopy (Carl Zeiss, Discovery V20 [Oberkochen, Germany] or Keyence, VHX 5000 [Oberkochen, Germany]). Next, 3D confocal profilometry (Nanofocus, µ-surf Expert, Oberhausen, Germany) by means of a 20× objective (lateral resolution: 0.67 µm, vertical resolution: 8 nm) was used for 3D topographical measurements of the wear tracks on the flat specimen. The acquired topographical data were post-processed through the metrological software Digital Surf Mountains (V7.4) to compute planimetric cross-sectional worn areas and the wear volume from the 3D measurements. The least-squares plane was computed with the AOI as described in Section 3.3.

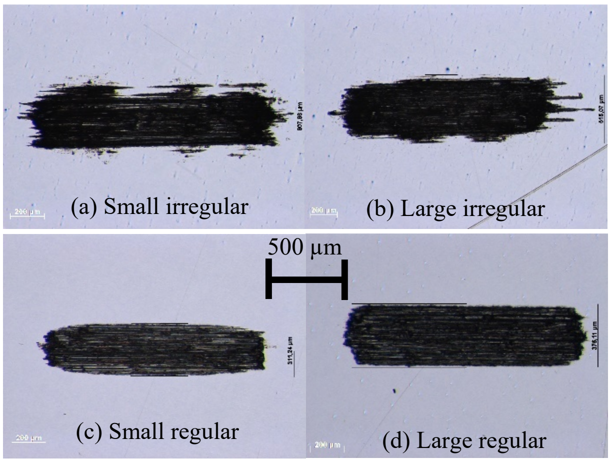


Fig. 5: Optical micrographs of the different wear track typologies taken with Keyence, VHX 5000. The labels (a–d) indicate the name of the tracks classified into small and large wear volumes and regular and irregular shapes.

It should be noted that the computation of the wear track volume involves subjective judgements when determining some measurands for an irregular wear track, such as the total wear track length (d_3), average cross-sectional worn area ($W_{q,avg}$), and wear track width (d_4), as discussed in the following section. Accordingly, three independent users computed each wear track volume following the methods described in Section 3 (CSIL, ASTM G133-05, ASTM D7755-11, and 3D profilometry measurements) to assess the reproducibility of each method.

5 Results and discussion

This section presents a comparison of the most used methods for computing the wear volume in ball-on-flat RSTT identified in the literature (see Section 3). Wear tracks that differed in their degree of worn volume (small *vs*. large) and homogeneity (regular *vs*. irregular) were selected for qualifying the computation methods (see Fig. 5, Section 4). Additionally, each wear track was analysed and characterised as defined in Section 3 by three different users to reveal differences and determine the reproducibility of each method. The mean worn volume (W_v) value along with the standard deviation (SD) computed from the three measurements performed by different users are summarised in Table 3.

Table 3: Data compilation of the obtained results, classified according to the wear track typology and wear volume determination method. The mean worn volume (W_v)

and its standard deviation (SD) correspond to the calculations performed by three independent users.

Test method	CSIL		ASTM G133-05		ASTM D7755-11		3D profilometry	
	W_v [10^{-6} mm^3]	SD	W_v	SD	W_v	SD	W_v	SD
Small irregular	479.30	48.99	451.38	60.60	633.38	48.09	515.88	7.43
Large irregular	1083.87	93.68	783.36	47.07	1843.23	494.58	894.70	3.93
Small regular	452.88	31.60	377.29	19.79	530.58	48.45	427.99	14.19
Large regular	1080.73	12.03	1112.39	31.57	1357.66	19.76	1352.48	20.82

Wear volume calculation using 3D profilometry has been the benchmark because it is considered the most precise (the whole track is considered without simplifications), with the smallest SD, and has the highest reproducibility (concerning the three operators). Figure 6 and Figure 7 show the relative error (with respect to the 3D profilometry method) and the coefficient of variation (CV) of each method, respectively.

As shown in Fig. 6, the wear volume calculated by the CSIL method exhibited relative errors in the ~±20% range. Considering that this calculation is based only on a single cross-sectional profile (W_q), errors could probably be associated with the low representativity of the selected profile. This is discussed later in more detail.

Calculations based on the ASTM G133-05 standard [19] always lead to underestimations in the range of 12–18%. This effect can be expected as the method does not consider the semi-spherical worn areas created on the edges of the wear track (see Fig. 2, Section 3.1). In contrast to CSIL, this method uses several cross-sectional profiles to compute the planimetric worn area ($W_{q,avg}$), and therefore, is less sensitive to the wear track typology (i.e., regular or irregular).

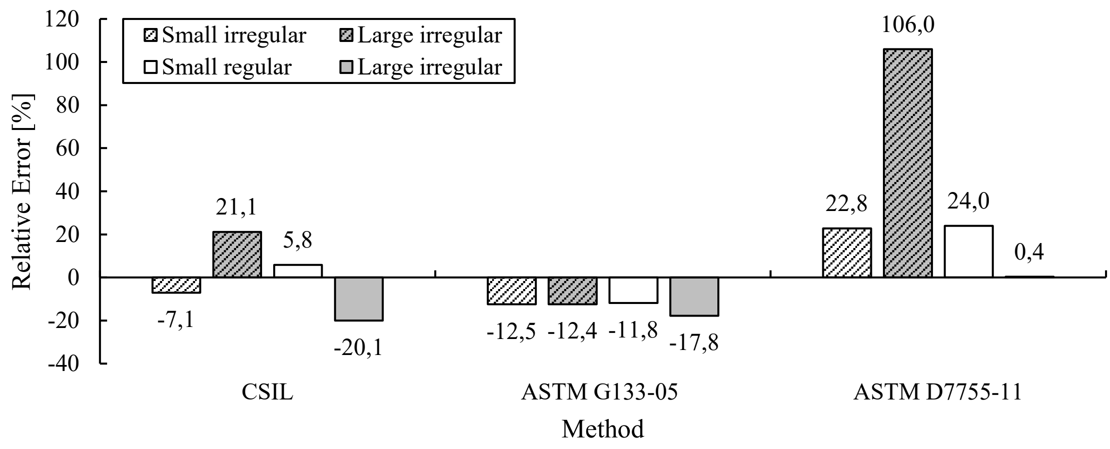


Fig. 6: Representation of the relative errors in respect to 3D profilometry calculation considering the mean worn volume values in Table 3.

The ASTM D7755-11 standard, on the other hand, overestimates the wear volume computation, which is highly pronounced in the case of a large irregular wear track (error of 106%). As for the other wear track typologies, the overestimated value is approximately 20%, except for the large regular wear track, where the calculated worn volume is almost negligible (relative error of 0.4%). This large difference in relative errors hints at the existing dependence on the wear track typology and ambiguity when applying the standard measurement procedure.

Another crucial aspect to consider when determining the applicability of a method is its reproducibility (i.e., its sensitivity or variability) when applied by different users. Figure 7 presents the coefficient of variation (CV) of each calculation approach depending on the wear track typology to assess user influence. A significant difference can be observed between the typologies of wear tracks, being the irregular track deviations unsurprisingly greater.

The 3D profilometry method shows very good reproducibility with deviations below ~3%, distinguishing it as a robust method. Among the remaining methods, it can be observed that the deviations for regular wear tracks lie below 10%. However, the deviations are greater for irregular wear tracks, especially in calculations based on the ASTM D7755-11 standard, where a CV up to 27% was obtained.

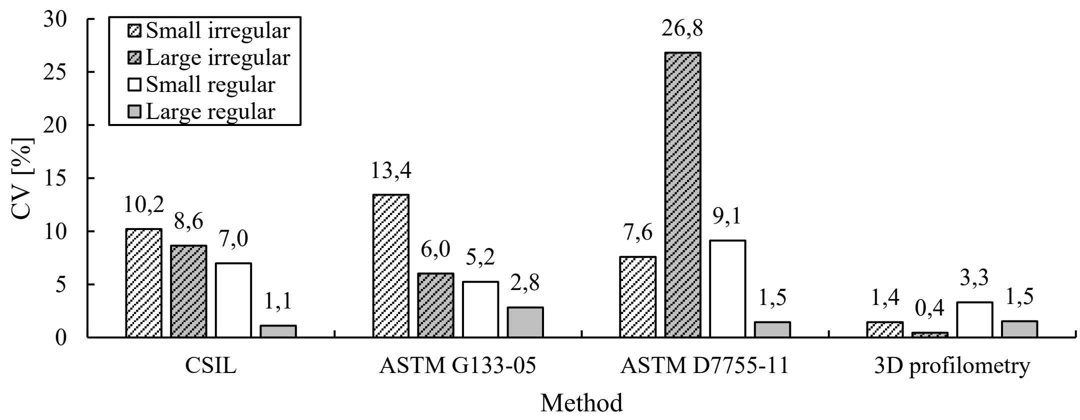


Fig. 7: Representation of the coefficients of variation (CV) based on the data in Table 3.

Based on earlier observations, the highest errors and dispersions are generally obtained with calculations based on the ASTM D7755-11 standard. This finding is remarkable since the standard is specifically prescribed for the wear track type presented in this study with a stroke of 1.022 mm [16]. Surprisingly, the ASTM G133-05 standard overall leads to lower errors, although it is out of the scope because its usage is suggested for strokes larger than 10 mm.

To determine the origin of the discrepancies in the ASTM D7755-11 standard, the impact of each necessary input data (W_q, d_3 and d_4) was analysed. The magnitude of wear volume variations associated with positive or negative reading/measuring errors of the input data were analysed for irregular shaped wear tracks (see Figure 8).

The most sensitive parameter was W_q (variations as high as 40%), followed by d_3 (variations up to 10%), and finally d_4 (maximum variation of 8%). Below, an in-depth analysis is presented of these variables, aimed at identifying measurement criteria and guidelines for ASTM D7755-11 implementation.

Because of the influence of the planimetric worn area on wear volume computation, two approaches were tested: (i) the approach prescribed by the ASTM D7755-11 standard using one cross-sectional profile (W_q, see Fig. 3), and (ii) the approach prescribed by the ASTM G133-05 standard using averaged criteria ($W_{q,avg}$, see Fig. 2).

Figure 9 depicts the relative errors incurred for the different wear track typologies when each of the aforementioned approaches is adopted for determining the planimetric worn area under the ASTM D7755-11 method.

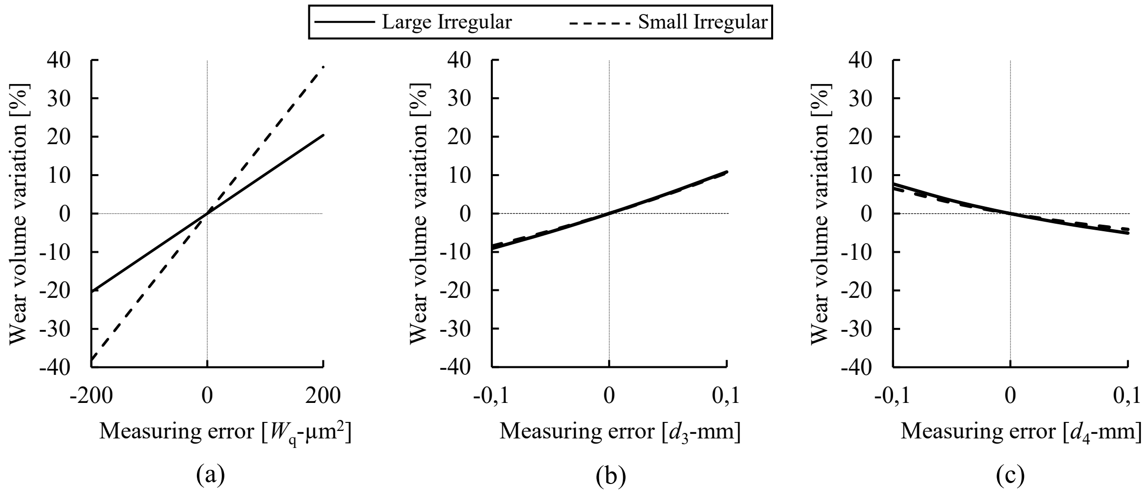


Fig. 8: Variation in wear volume related to measurements errors in (a) the planimetric cross-sectional worn area (W_q), (b) total length of wear track in the sliding direction (d_3), and (c) total width of the wear track (d_4).

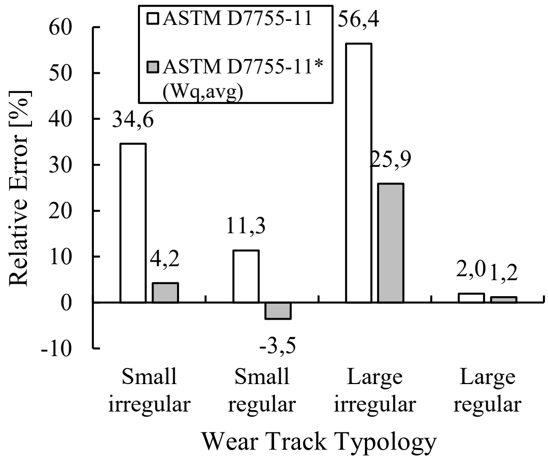


Fig. 9: Representation of relative errors in 3D profilometry for the different wear track typologies following the procedure described in the ASTM D7755-11 standard. *: Standard computed including $W_{q,avg}$ (as stated in the ASTM G133-05 standard).

Figure 9 indicates that the relative error was reduced by approximately 30 percentage points for irregularly shaped wear tracks when using $W_{q,avg}$. As expected, the reduction was less significant for the regular wear tracks due to their higher homogeneity.

Regarding the determination of d_3 (i.e., total length of wear track in the sliding direction), the definition may be somewhat ambiguous, especially regarding irregular wear tracks where outliers are present (see Fig. 10(a)). Given the observed differences in the measuring criteria across users, two measurement approaches were analysed for d_3, namely the inner zone of the wear track (inner) and the extremes of the wear track (extreme). This study focused on the irregularly shaped wear tracks since for the regularly shaped tracks d_3 selection did not differ significantly across users (Fig. 10(b)).

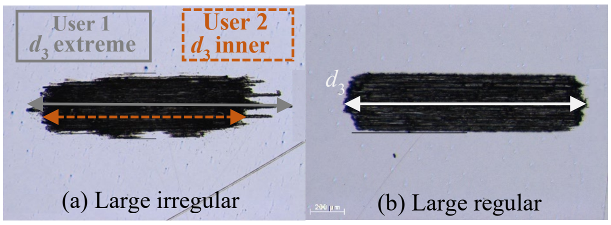


Fig. 10: Representation of the d_3 length measuring criteria for a large irregular (a) and a large regular (b) wear track.

To provide an accurate visualisation of the computed area for each d_3 definition approach (inner *vs.* extreme), an algorithm was generated in MATLAB® that draws the computed area over the track position according to the performed measurements (this algorithm is available in the Additional Material Section). Figure 11 and Figure 12 present images of the computed area and the computation results, respectively. Note that in the following, the calculation according to the ASTM D7755-11 standard has been modified according to the earlier suggestion, including the $W_{q,avg}$ in the computation.

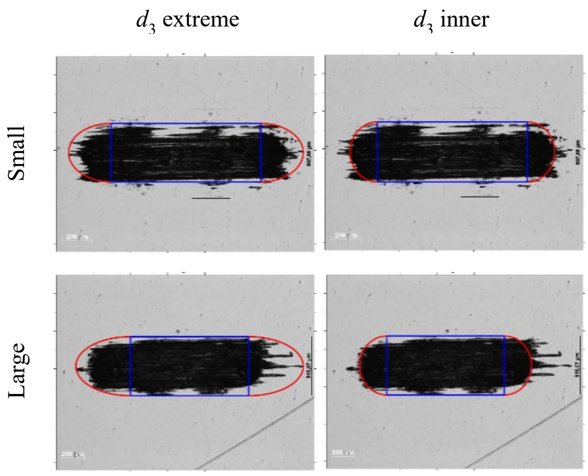


Fig. 11: Representation of the geometrical idealisation defined by Eq. 2 for the irregular wear track typologies considering the d_3 parameter according to the extreme and inner measuring criteria (see Fig. 10). The blue lines correspond to the area computed by A and the red lines correspond to the sliding motion reversion zone computed by B (see Fig. 4 and Eq. 2, Section 3.2).

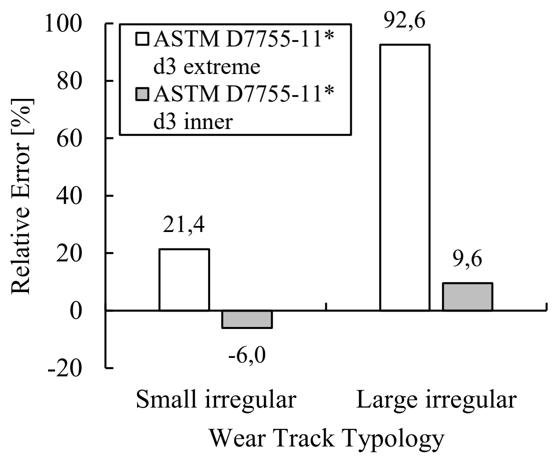


Fig. 12: Representation of the relative errors with respect to 3D profilometry for the irregular wear tracks: comparison between two criteria (inner and extreme) to measure the d_3 length. *: Standard computed with suggested improvement, including $W_{q,avg}$ (as stated in the ASTM G133-05 standard).

The geometric idealisations presented in Fig. 11 indicate that the extreme criteria compute a large area, much of which does not correspond to the real wear track. The numerical results in Fig. 12 corroborate this observation, revealing much greater overestimation errors for the extreme criteria. It can therefore be concluded that, for irregularly shaped tracks presenting outliers, the conservative (inner) criterion for the d_3 selection is superior, decreasing the error to 83 percentage points compared with the extreme criteria.

Finally, the effect of the value of parameter d_4 is worth noting (width of the wear track), which is defined when selecting W_q (Fig. 3(d), Section 3.3). Similar to the previous discussion for W_q, the impact of measuring a single d_4 value corresponding to one cross-sectional profile versus the $d_{4,avg}$ value obtained for different cross-sectional profiles was analysed. Figure 13 summarises the ensuing results.

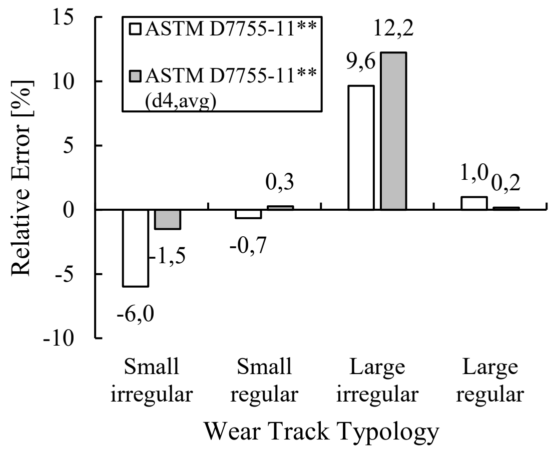


Fig. 13: Representation of the relative errors with respect to 3D profilometry for the different wear tracks: analysis of the impact of including averaged d4. **: Standard computed with suggested improvements: (i) including $W_{q,avg}$ (as stated in the ASTM G133-05 standard), and (ii) d_3 defined with a conservative criterion.

The application of the $d_{4,avg}$ criterion revealed neither a clear trend nor a considerable influence on the results. Accordingly, this study suggests computing the d_4 parameter measured in the intermediate section, as established in the ASTM D7755-11 standard.

The present investigation elucidates that the application of the ASTM D7755-11 standard on irregularly shaped wear tracks may lead to significant errors due to the lack of track homogeneity. Therefore, to obtain more robust and reliable results, the following two points are suggested as improvements:

- The incorporation of $W_{q,avg}$ (following the ASTM G133-05 standard), instead of a single-profile based W_q.
- The use of a conservative criterion (omitting outliers) in defining the d_3 parameter.

Figure 14 presents the relative errors of different methods for comparison, including the results obtained when computing the ASTM D7755-11 standard following the guidelines proposed in this paper.

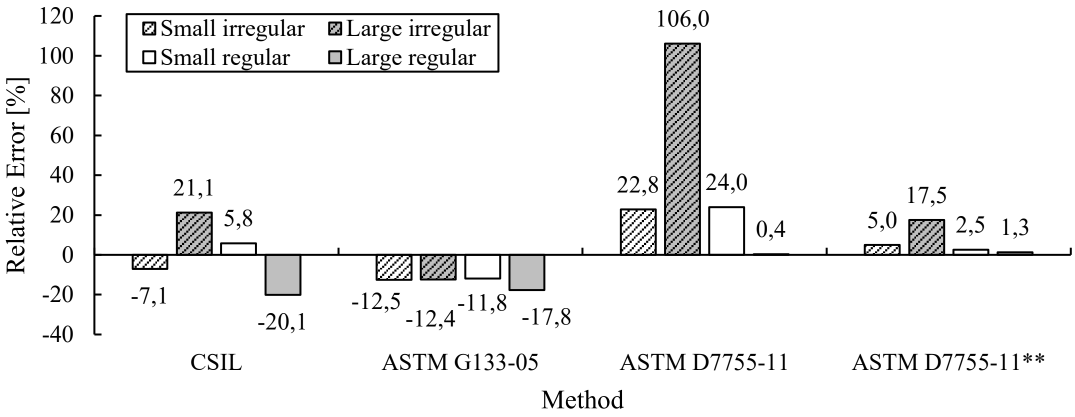


Fig. 14: Representation of the relative errors with respect to 3D profilometry calculation considering the mean worn volume values calculated by three independent users. **: Standard computed with suggested improvements: (i) including $W_{q,avg}$ (as stated in the ASTM G133-05 standard), and (ii) d_3 defined with a conservative criterion.

A significant error reduction of the ASTM D7755-11 standard when applying the additional guidelines could be observed. More specifically, the relative errors were reduced by 17.8, 88.5, and 21.5 percentage points for the so-called small irregular, large irregular, and small regular wear tracks, respectively. Conversely, for the large regular track, an insignificant increase occurred in error percentage from 0.4% to 1.3%.

In conclusion, the incorporation of the averaged planimetric wear and the use of a conservative criterion for the d_3 measurement leads to significant error reduction in ASTM D7755-11 standard computation, providing more accurate wear volume characterisation. If other material pairs exhibit similar wear track shapes, the same volumetric errors can be expected to occur. It has been demonstrated that the errors are not related to a specific material, but rather to the irregularity of the wear track shape as well as user judgements when selecting certain measurands. Accordingly, although material pairing is rather limited, the discussions and findings presented in this paper have an extended impact and can be used as generalised guidelines for other materials.

6 Conclusions

In this study, a critical assessment of wear volume determination methods of ball-on-flat linear RSTT was performed. The following conclusions can be drawn from this study:

- Most publications present incomplete procedural information regarding the wear computation method. The most commonly used methods are 3D profilometry (46%) and CSIL (36%).
- Only 3% of published works explicitly cited and followed the existing standards (ASTM D7755-11 or G133-05).
- A systematic comparison between the most used methods revealed that the ASTM D7755-11 standard leads to the highest relative errors (up to 106%) and deviations (up to 27%) on irregularly shaped wear tracks.
- The present study suggests including the following two improvements in ASTM D7755-11 computation, which can reduce errors from 106% to 17% when analysing irregularly shaped wear tracks:
    - (i): Calculating $W_{q,avg}$ (following the G133-05 standard), instead of one profile-based W_q.
    - (ii): Using a conservative criterion (omitting outliers) for the measurement of the d_3 parameter.

Progress in tribology strongly depends on rigorous and effective communication. Accordingly, correct descriptions of wear volume computing methodologies are essential for research of archival value. Although the present study focused on the wear volume computation of flat specimens, the authors highlight the necessity of reporting counterbody data for full description. Future studies should describe further guidelines for the most used wear volume computation methodology, namely 3D profilometry.

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