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Potentiality of triboscopy to monitor friction and wear

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ABSTRACT

Triboscopy was proposed over 20 years ago, but despite the powerful insight it brings to analyse friction and wear with temporal evolution of localised events, its use is still limited. In this paper, triboscopy has been further developed. A LVDT sensor measures the position of the counter-body inside the wear track in a reciprocating tribometer. A high frequency acquisition system allows 10 points to be acquired within the elastic contact width, calculated by Hertz equations. The necessary number of acquired points is computed as a function of reciprocating frequency and stroke length, which enables to represent inherent details of the phenomena involved without producing excessively large files. Triboscopic maps of the acquired data are generated, where colours quantify the *Z* variable under measurement, *X* is the position of the counter-body within the wear track and *Y* is the number of cycles. Four examples where the use of 3D colour maps has helped to visually phenomena that would be hard to detect otherwise are presented. First, sintered composites containing solid lubricant particles dispersed in a Fe–Si–C matrix were tested. Under dry sliding, triboscopic friction maps showed higher friction at the ends of the strokes, which was more significant for harder specimens. Evidence showed that this friction increase was due to the accumulation of wear debris at the ends of the wear tracks. Second, triboscopic images of reciprocating tests of DLC–CrN coatings clearly indicated the region of the wear tracks where spalling occurred. Third, bronze disks containing regularly distributed inserts composed of graphite particles dispersed in bronze presented triboscopic maps where friction decreased periodically following approximately the size and spacing of the graphite inserts. Fourth, starved lubrication tests of textured surfaces showed no effect of surface texturing on average friction, but triboscopic maps suggested a tendency for lower friction with texturing.

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1. Introduction

The investigation of tribological phenomena is a very complex task, particularly due the fact that the interactions within a tribological contact are (i) systemic, i.e., they are a response to a specific tribological system; (ii) irreversible, and (iii) they evolve with time. The tribological interactions can modify the initial conditions of the tribological system, altering the characteristics of the contacting surfaces, and therefore forming a third-body or tribo-layer at the interface [1–3]. This makes modelling of tribological phenomena very difficult, so that most studies in tribology are experimental.

The main responses of a tribological system, which will have direct implications on its practical application, are friction and wear. However, this systemic irreversible and evolving character of the tribological interactions makes friction and wear not only time-dependent but also space-dependent, since the tribological parameters and the materials in contact vary along the wear track and with time. Starting from this basic point, Belin and Martin [4] proposed a synthetic representation of the variables measured during a tribological test by a numerical imaging method, which in principle could account for this double-sided reality of tribological phenomena. They called this technique "triboscopy".

Triboscopy is particularly suited to reciprocating sliding tests, where the position of the counter-body on the sliding track repeats periodically as the number of reciprocating cycles increases. Therefore, it is possible to produce numerical images from the data collected during reciprocating tests, where the *X* axis represents the relative position of the contact, the *Y* axis represents the number of cycles, and the grey level of each pixel corresponds to the level of the measured value, in general friction coefficient or contact electrical resistance [4,5]. Therefore, triboscopy enables to follow the global evolution of data during an entire test, as well as to observe specific heterogeneities and therefore localised events, which provide important information about the sliding interface and its evolution [6].

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When they first proposed the technique, Belin and Martin. [4] showed that by combining friction and electrical resistance triboscopic images relative to dry sliding of a spherical steel counterface against a surface coated with a textured graphite–polymer coating, they could visualise the localised effect of the texture in the solid lubricating coating, which could not be accounted for when the evolution of the mean friction values with time was analysed.

Triboscopy has been pointed out as particularly useful to analyse the tribological behaviour of coatings [5,7]. For example, the investigation of the effect of different surrounding atmospheres and testing conditions on the tribological performance of carbon nitride films deposited by ion-beam-assisted deposition onto silicon was helped by the use of triboscopy [8]. The numerical images helped to detect the modification of the nature of the contacting surfaces during a short running-in period before super-low friction regime could be achieved. Another interesting example involves sliding experiments of hydrogenated amorphous carbon films (a-C:H DLC) deposited onto Si substrates by PECVD against AISI 52100 spherical counter-bodies under different hydrogen pressures. The study aimed to investigate the role of the presence of hydrogen gas on the loss of super-low friction and on its restoration. The use of triboscopy was of paramount importance to elucidate the role of hydrogen in restoring and preserving super-low friction due to its effect on the build-up of a transfer film on the steel counterface, which is responsible for friction decrease [6].

One attempt was found to use triboscopy to assess the tribological behaviour of pure crystalline zinc orthophosphate under boundary lubrication in order to model zinc phosphate-based anti-wear additives. Although they are not presented in the paper, the authors claim that the triboscopic images for the electrical resistance confirm that for the tests where anti-wear additive are not added to the base oil, metal-to-metal contact occurs for low speeds conditions, but in the presence of zinc-of orthophosphate, an insulating film is always present under boundary lubrication conditions [9].

Triboscopy was also adapted to a lateral force microscope (LFM) apparatus due to the similarity in the nature of the movements involved in the tests when compared with a reciprocating sliding tests. Therefore, triboscopy could be extended to a much smaller scale, helping to understand nanometre-scale wear phenomena [10].

Different processing of the sampled data can be used to extract relevant information during triboscopic imaging. When commercial visualisation softwares are used, basic functions such as contrast enhancement and digital filtering can be used. Belin et al. [5] proposed a statistical method to extract quantitative information about the sliding contact using the triboscopic imaging, which involves temporal and spatial filtering of the data.

Despite having been proposed over 20 years ago, the use of triboscopy in the literature is scarce and almost limited to the group that originally proposed the technique. In our group, we have been using triboscopy due to powerful insight it gives to the temporal and spatial visualisation of tribological phenomena and a few examples are presented in this paper. Our aim is to further improve and explore potentialities of the technique and hopefully increase its use within the tribological community. We use an approach where the sampling frequency is chosen depending on the size of the events that occur during a tribological test. Therefore, the need for averaging and processing of the data is reduced. The use of a sensor to record position simultaneously with the variables under measurement removes the need for statistical methods to obtain spatial information from the triboscopic maps. Instead of using grey-scale 2D imaging, a specially-developed software analyses the data and produces 3D colour-imaged triboscopic maps, which helps the visualisation of the phenomena.

2. Description of triboscopy

In this work, the variables measured during reciprocating tests are represented using the principles of triboscopy proposed by Belin et al. [4,5]. However, some new features were developed aiming to improve significance and interpretation of the triboscopic maps produced.

Adaptations were implemented into a commercial tribometer (TE67 Plint) to help the triboscopic analysis. They involved a new acquisition system with much higher acquisition rates (50 kHz for simultaneous acquisition of eight differential channels) and a LVTD sensor to monitor the position of the pin within the stroke length, as shown in Fig. 1. Since data are sampled and recorded simultaneously as a function of time at a constant acquisition rate, the values of all variables measured can be associated with specific points within the stroke length. The variables recorded in the examples described are friction force and contact potential, but the acquisition system presents additional input channels, which could be used to record other variables, such as contact capacitance [11], pin wear, temperature, etc.

One new feature of the methodology here presented involves the adjustment of the parameters used to sample and record data during the tests, so that the acquiring rate is large enough to represent the phenomena involved within the tribological contact without producing excessively large files. For that, it was considered that the acquiring rate should take into account the size of the elastic contact area between pin and sample, to ensure a minimum amount of points to be sampled within the contact. According to Belin and Martin [4], the contact zone itself is the "probe" during a tribological test. Hertz equations (Eq. (1)) were used to calculate elastic contact widths (a) depending on geometric and loading conditions [12]. The algorithm developed to adjust the acquisition parameters during data sampling is represented in Fig. 2

$$a = \begin{cases} \left(\frac{3F_N D}{8E^*}\right)^{\frac{1}{3}} \text{for a point contact (sphere on plane)} \\ \left(\frac{4F_N D}{2\pi L_D E^*}\right)^{\frac{1}{2}} \text{for a line contact (cylinder on plane)} \end{cases} \quad (1)$$

where F_N is the normal load, D is the diameter, L_D is the cylinder length and E^* is the combined elastic modulus, given by

$$\frac{1}{E^*} = \frac{1-\nu_B^2}{E_B} + \frac{1-\nu_{CB}^2}{E_{CB}} \quad (2)$$

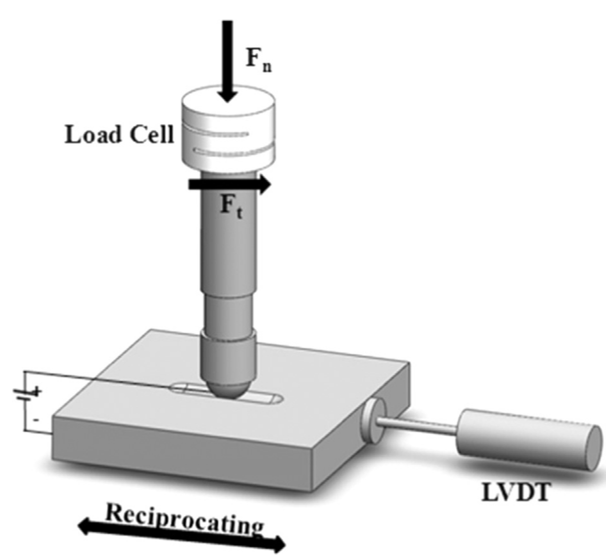

Fig. 1. Scheme of the reciprocating tests.

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