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ANALYSIS OF 3D ROUGHNESS PARAMETERS FOR WEAR SCARS OBTAINED ON FOUR-BALL TESTER, LUBRICATED WITH RAPESEED OIL

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Abstract: This study aims to underline that, especially for worn surfaces, only one roughness parameter (usually Sa) is not enough to establish the influence of test parameters and lubricant on the tribological behavior of the tribosystem. The study identifies which of the analyzed 3D roughness parameters could be correlate to tribological features like friction coefficient and wear represented by wear scar diameter, in four-ball tests. The association of wear with surface quality may help evaluate the durability of the contact of interest and select a more effective lubricant that reduces wear and keeps the surface quality acceptable for further running. This analysis can be qualitative, through images of the worn zones, but also quantitative through the measured and calculated values and the dependence function between them. There were investigated the entire wear scars from a representative test campaign on four-ball machine, using as lubricant the rapeseed oil. Test parameters were load at the main shaft of the four-ball machine (100 N, 200 N and 300 N), sliding velocity (1000 rpm, 1400 rpm and 1800 rpm) and duration (1h). There were discussed amplitude and functional parameters.

Key words: rapeseed oil lubrication, wear scar, four-ball test, 3D roughness parameters, amplitude parameters, functional parameters

1. INTRODUCTION

"Classical" 2D roughness parameters do not provide a reliable functional characterization of the surface because they refer to several lines recorded on the surface of interest. It is recommended even 25 measurements in order to obtained a statistical characterization close enough to the actual quality of the surface [1]. Therefore, a solution to have a description closer to the actual surface is to investigate three-dimensionally the surfaces and it is better to do on larger areas. Initially, roughness studies were request especially for controlling the manufacturing processes and the new-produced machine components. Studies on worn surfaces have been developed due to tribologists interested in information on how evolve the texture of superficial layers in contact, under particular conditions of load, velocity and temperature.

Studying the literature [2], [3], [4], a conclusion can be drawn regarding the methodology to characterize the worn surfaces. This relies on modern equipment and software the researcher uses. Other important factors are the size and shape of the analyzed elements and the parameters selected for analysis.

There are a number of scientific papers related to the study of the quality of worn surfaces [5], [6], [7], [8], from which research directions may be outlined, namely:
- a comparison should be made between 2D and 3D parameters, using a method for sampling both lines and areas,
- the study and the tests should formulate a correlation between the evolution of texture parameters and tribological parameters, durability of the contact,
- the study should be done for both surfaces of the triboelements but, sometimes, studies are done for only one surface, usually the surface that first fails.

This study underlines that, especially for worn surfaces, only one roughness parameter (usually Sa) is not enough to establish the influence of the test parameters and lubricant on the tribological behavior of the tribosystem.

The aim of the study is to identify which 3D roughness parameters could be correlate to tribological features like friction coefficient and wear represented by wear scar diameter (WSD) in four-ball tests.

2. MATERIALS AND METHOD

The authors selected as lubricant the rapeseed oil because of the interest in using this vegetal oil as an eco-friendly lubricant.

Lubricants can strongly influence energy consumption, with repercussions on product quality, environmental impact, system durability etc. [9]. In many applications, lubricants are derived from petroleum, but the trend is to replace them with synthetic or vegetal oil-based products [10], these having the advantage of being environmentally friendly, but they also have short-cuts as low viscosity, smaller range for working temperature, oxidation tendency and additivity still too sensitive to their chemical composition [11].

Among principles of green tribology, two are dedicated to natural and biodegradable lubrication and they are based on vegetal and biomass-sourced lubricants and on water [12]. The success of vegetal oils is based on their chemical composition of fatty acids. The type, chain length and polarity of fatty acids are the influencing factors on a reliable lubrication. This is why in our research centre, there were elaborated studies related to vegetal oils (additivated or not) and their tribological behavior, the test being mainly done on a four-ball machine [13], [14], [15].

Figure 1 presents the composition of fatty acids characterizing the rapeseed oil used for this study. Two fatty acids in high concentration (linoleic acid and linolenic acid) are responsible for boundary lubrication, especially if the bodies in contact are metallic materials.

Test duration was 1 h for each sliding velocity, thus, the comparison of roughness parameters is done only for the same velocity as the sliding distance is not the same for the three tested velocities.

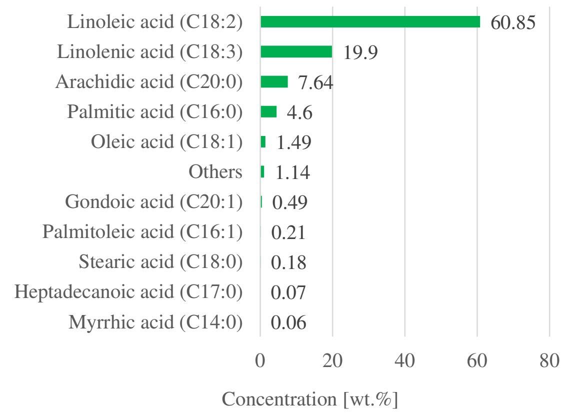

Fig. 1. Fat acid concentration for the tested rapeseed oil

The surfaces of interest were investigated with the help of NANOFOCUS SCAN laser profilometer, from " tefan cel Mare" University of Suceava. Mountains SPIP program [16] (version 6.7.2, 2017) was used to process the results. The 3D parameters were calculated for each wear scar of the three stationary balls involved in one test and the average, maximum value and minimum value were calculated. The step for recording the points (x,y,z) on the surface is 5 μm on each line. Line spacing is also 5 μm. 3D parameters are calculated for all z(x,y) values measured on the investigated area (the entire wear scar).

Figure 2 presents a wear scar (the dimension of one axis of the ellipse generated over the wear scar is 0.4 mm and the measured value was 0.4024 mm), virtually rebuilt with the software, on a ball from a test regime with F=100 N and v=0.69 m/s. Similar small differences, of several microns, were noticed for all the investigated wear scars.

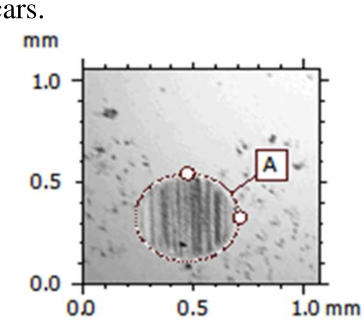

Fig. 2. Selecting wear scar area as an ellipse, the wear scar recorded on ball 1, for the four-ball test with F=100 N, v=0.69 m/s, test duration 1 h, lubricant: rapeseed oil, (after removing spherical form and after applying filters).

The wear scar was ”cut out” from the initially recorded area, the ellipse of the scar being in accordance with the measurements obtained under the optical microscope.

The balls have a diameter of 12.7 mm and were supplied by SKF, in sets of four balls. They are made of chromium alloy steel EN 10027 100CR6 (1.3505), mark 20, specially treated, having: a small diameter tolerance (±0.0005 mm), a shape deviation of 0.5 m, a diameter variation of 0.5 m per ball and 1 m on a set of four balls, high hardness (60-66 HRC) and a very fine surface quality.

Each test supplies three wear scars (on each fixed ball). Two diameters were measured for each wear scar (one along the sliding direction and the other one perpendicular to it). In the following analyses, the wear scar diameter (WSD) is the average of six diameters measured on the fixed balls.

The initial oil temperature was 20...23 ºC.

Figure 3 presents the diagram of investigating the surface texture. First, a leveling operation is done, the extremities of the investigated surface are fixed in a horizontal plane. Then the surface is rotated till the sliding direction is on the vertical direction.

The same procedure of filtering was applied to all measurements as the parameters’ values depend on the applied filters (here Gaussian, s=10 m and c=0.25 mm, ends not cut, taking into account [17]).

c filter separates waviness from roughness and its selection depends on the investigator’s abblities and experience. Recommendations are given in standards [18], [19]. For worn surfaces, the specialist may select other values in order to point out the influence of functioning regime. These filtering values have to be mentioned in the research report. They could be “responsible” for different values for the initial surface, especially for Ssk and Sku, as reported in literature [1].

Another important step is to remove the spherical shape. The ideal spherical shape of the surface (a sphere with 6.35 mm diameter) is replaced by a straight reference plane. Next, the wear scar is cropped. The wear pattern does not have a perfectly regular ellipse shape and, therefore, it is possible that the axes of the cropped area differ from those measured by a few microns.

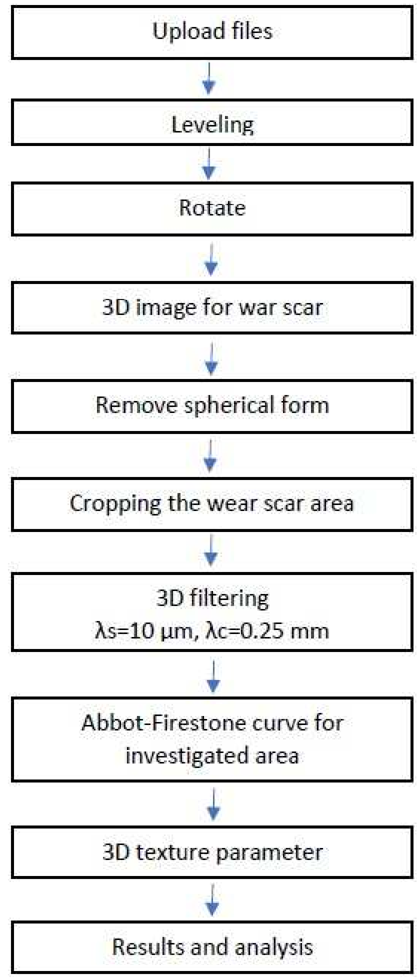

Fig. 3. The chart of investigation operations

The s filter is used to remove microroughness, which is usually due to noise or environment. After this first filtering, the primary profile is obtained, for which various parameters (Sa, St) can be calculated. Then, filtering is applied with the c filter, which separates the waviness from the roughness.

The ends of the measured profiles on the wear scar have not been cut as the authors consider that, for worn surfaces, it is not recommended to remove end values.

Hensen et al. [20] proposed a processing and calculation of 3D roughness parameters (S-parameters), in the software MountainsMap Premium 7.4 (Digital Surf, France), using a similar routine; “the curvature of the ball removed by a 2nd degree polynomial function, outliers were removed using a soft strength method, and a robust Gaussian low pass filter, =0.8 mm cutoff". These authors did not apply the standard recommendations and apply a low l c below the Hertzian contact diameter (0.5 mm in their tests).

In this study, the investigated roughness parameters are defined and calculated as in [16] and [21]: Sa – arithmetic mean height, Sq – root mean square height, Ssk – skewness, Sku – kurtosis, St – maximum height, Sv – maximum valley depth, Sp – maximum peak height, Spk – reduced peak height, Sk – core height, Svk – reduced valley depth.

3. RESULTS

Based on recent literature [22], [23], and analyzing reports on worn surface quality [8], [24], [25] the following directions of investigation are outlined:

- due to new development of measuring equipment, the areas investigated for the 3D parameters could offer a more reliable information on worn surfaces and the influence of functioning conditions on surface quality,
- studies on larger areas could correlate the texture parameters and the tribological characteristics, for a given tribosystem,
- the study should be done for both surfaces of the triboelements.

Table 1 presents the values recorded for the non-worn surface of a ball, measurement being done for a square area with 1.5 mm as side (Fig. 4). The difference between the values of the same parameter, but recorded with different step, is given here only for Sa, as

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and

$$\frac{\quad}{\quad} \qquad (2)$$

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- very rare high asperities (St=12.913 m),
- fine finished surface (Sa=0.266 m),
- plateau with few bumps and shallow pits, resulting from technological peculiarities of obtaining the ball surface (Ssk=1.090, Sku =17.548).

Of course, selecting a step of 5 m between points and lines is time consuming, but roughness values for a step of 20 m revealed different values, meaning the accuracy of the measurement is diminished.

Schmit J. et al. [25] reported roughness parameters of ball of rolling bearings, made of different materials and with two finishing methods, measured with an optical profilometer.

Marek &yłka W. [26] presented an analysis done for sampling steps of 5 m to 100 m and concluded that, based on the tests performed on anisotropic random (milled) surfaces, the sampling interval has a significant influence on the evaluation of 3D roughness parameters.

Table 1.

Values of 3D roughness parameters for the non-worn surface of the balls

	2 m	[%]	5 m	20 m	[%]
Sa [µm]	0.304	-14.169	0.266	0.304	-14.346
Sq [µm]	0.457	-15.729	0.395	0.420	-6.276
Ssk	1.551	-42.248	1.090	0.320	70.612
Sku	23.877	-36.067	17.548	6.486	63.040
Sv [µm]	9.382	-50.576	6.231	2.248	63.927
St [µm]	19.509	-51.080	12.913	5.427	57.969
Sp [µm]	10.126	-51.541	6.682	3.180	52.414
Spk [µm]	1.143	-32.787	0.861	0.703	18.345
Sk [µm]	0.787	-14.419	0.688	0.835	-21.414
Svk [µm]	0.598	-19.866	0.499	0.495	0.900

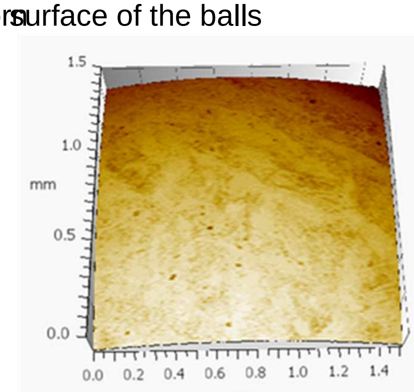


Fig. 4. Virtual image of the initial surface of the ball (5 mm between points and lines)

Accuracy of measurements decreases with increasing sampling interval and the sampling step will depend on the type of the investigated surfaces, recommending smaller steps for anisotropic surfaces. A too large step could reduce the high values of the investigated surface (these high peaks and deep valleys could be situated between the measured points). A fin step (here, that of 2 μm) reflects better the material distribution on the surface, but is too time consumer. For the step of 5 μm, the difference is small as compared to roughness values for the smallest step. It is worthy to underline that parameter values for smaller step in Table 1 are greater than those obtained with a step of 5 μm, the higher difference in percentage being obtained for the singularities of the investigated surface (St, Sv and Sp). Values for a step of 20 μm are smaller than those obtained with a step of 5 μm, except for Sa, Sq and Sk. These observations emphases the statistical feature of the texture analysis.

Figure 5 presents the average of two values of friction coefficient (COF), obtained from tests carried out under the same conditions. The value of COF for each test is the average of all values recorded during the test, with a sampling of two values per second. The average COF is higher for the regime sets of (v=0.38 m/s, F=300 N) and (v=0.53 m/s, F=200 N), suggesting that the fluid film could be locally generated in contact.

Figure 6 presents average values and spread ranges for Sa. This parameter is generally used to evaluate surface roughness of already finished part. But many type of textures could have the same value for Sa [2]. Simply using only Sa, is not sufficient. But other parameters could be different, which may affect the behaviour of the material in both dry and lubricated regime. This is why it is more beneficial to analyze a set of parameters.

The decrease of Sa for F=100 N and F=200 N, at v=0.38 m/s, seems to evidence a process of running-in. At v=0.53 m/s, Sa is almost insensitive to load, but higher than that of the initial surface. For v=0.38 m/s and v=0.69 m/s, Sa has a visible increase for the highest load (F=300 N). This could be explained by a mild abrasive process at start and stop, proportional to load, as the average values of friction coefficient suggest a fully fluid film.

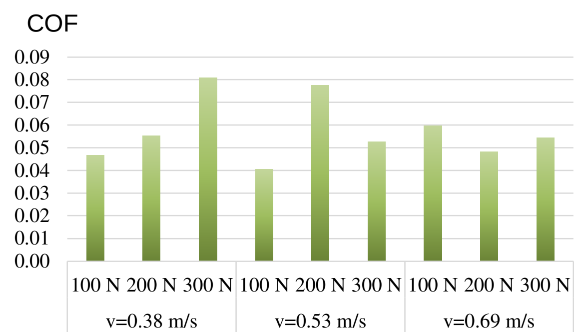
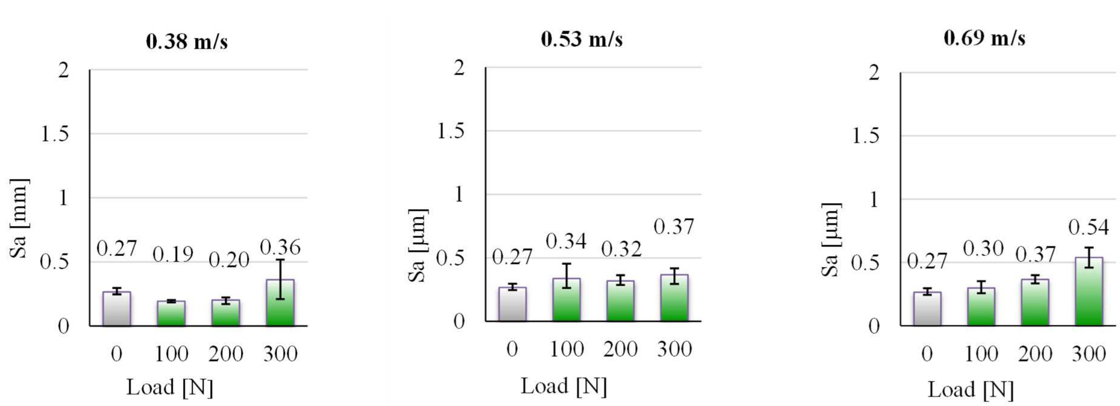


Fig. 5. The average of friction coefficient (COF) for two tests under the same conditions, for rapeseed oil tested on four-ball machine (test duration 1 h).

Sku value is a measure of the sharpness of surface asperities. Analyzing the plots in Fig. 7, one may notice values above 3, meaning a spiked height distribution, similar to lathe cutting process, this being also visible on images of the wear scars in Fig. 10. It was noticed no evidence of dependence of this parameter both to sliding velocity and load.



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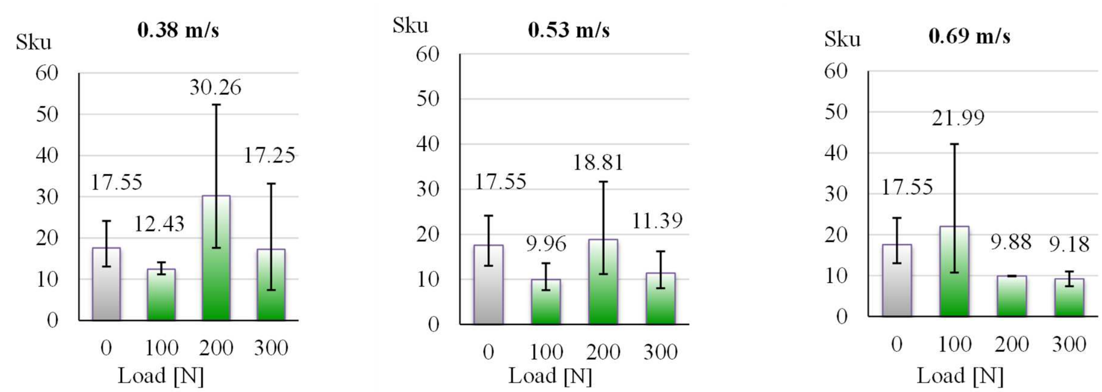

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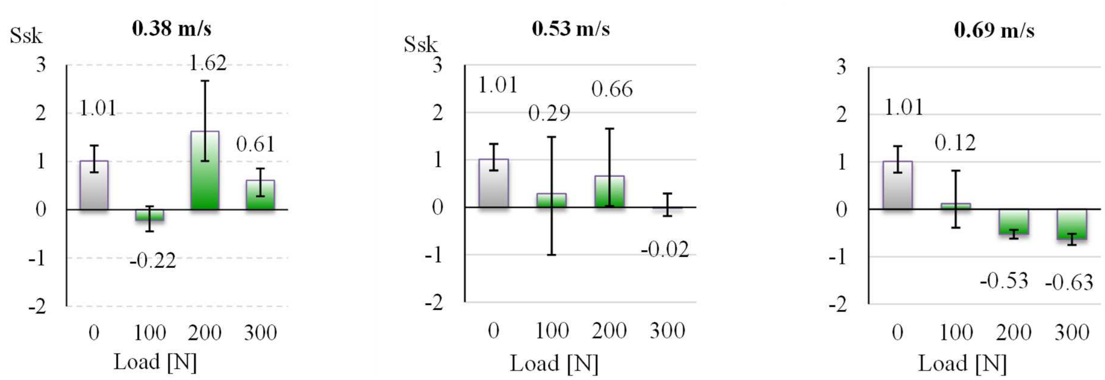

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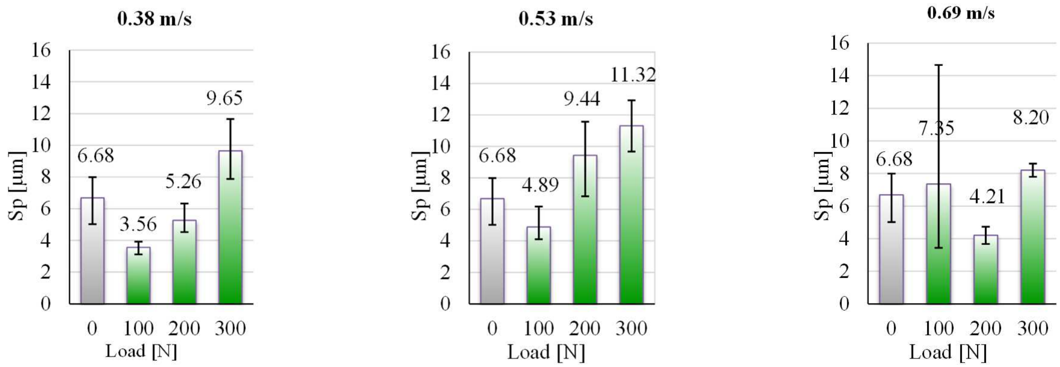
Ssk represents the bias of the roughness shape. For the initial surface, this value is positive, meaning that height distribution is biased below the reference (or mean) plane, but for the wear scars, this parameter is difficult to be related to the test regime (Fig. 8).

Points on an wear scar, z(x,y) is a function the heights of the surface relative to the fitting plane (alfer leveling the spherical surface the wear scar is generated on).

St is an important parameter in tribology, especially for lubricated contacts, because big asperity heights, even if very rare, cause the lubricant film failure and may change the regime, from an EHD regime to a boundary or mixt regime, leading to a sudden increase in the friction coefficient. If asperities are sharp and rare, they may break or deform plastically and the EHD regime may regenerates if the surface texture has not become too rough through breaking or deformation of asperities. The values for St are given in Fig. 9c.

The maximum value of Sp (Fig. 9a) suggests that this is a singularity that could disrupt the fluid film. Under low velocity (v=0.38 m/s) and moderate load (F=100-200 N), this parameter decreases, meaning that asperities' peaks are cut or sheared, this process being beneficial for generating the fluid film (if debris are small and few). The abrasive process of the texture is more intensive for F=300 N, Sp and St being higher that their initial values. Sv (Fig. 9b) decreased for all tests, meaning that initial micro pits on the ball surface are less deep because of the loss of the material in the upper part of the texture. St higher than the initial one means an intensive abrasive wear that modify the superficial layer by abrasive or adhesive wear.



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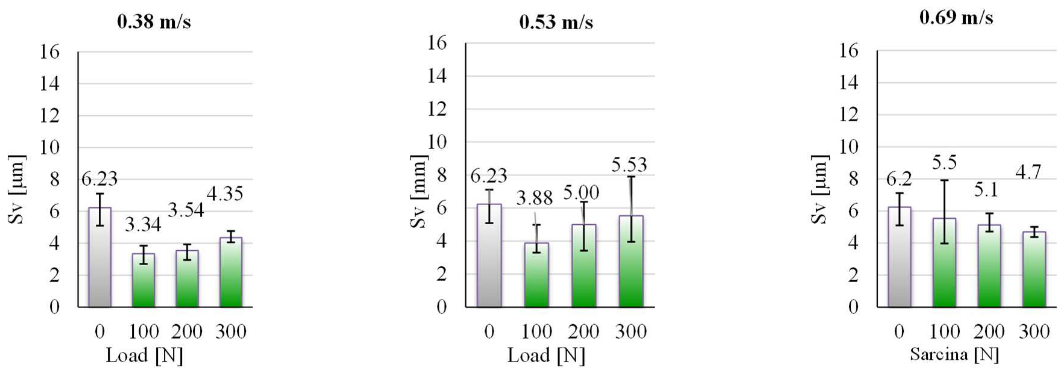

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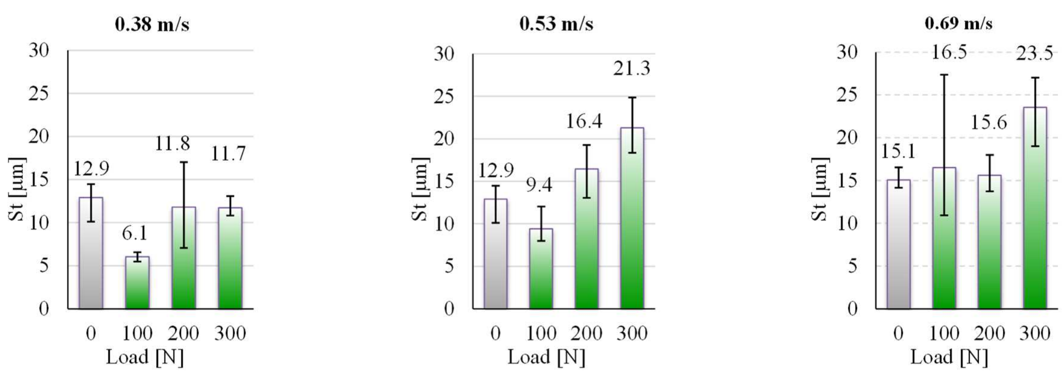

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Table 2.

Values of parameters St, Sa and the ratio St/Sa for the rapeseed oil as lubricant

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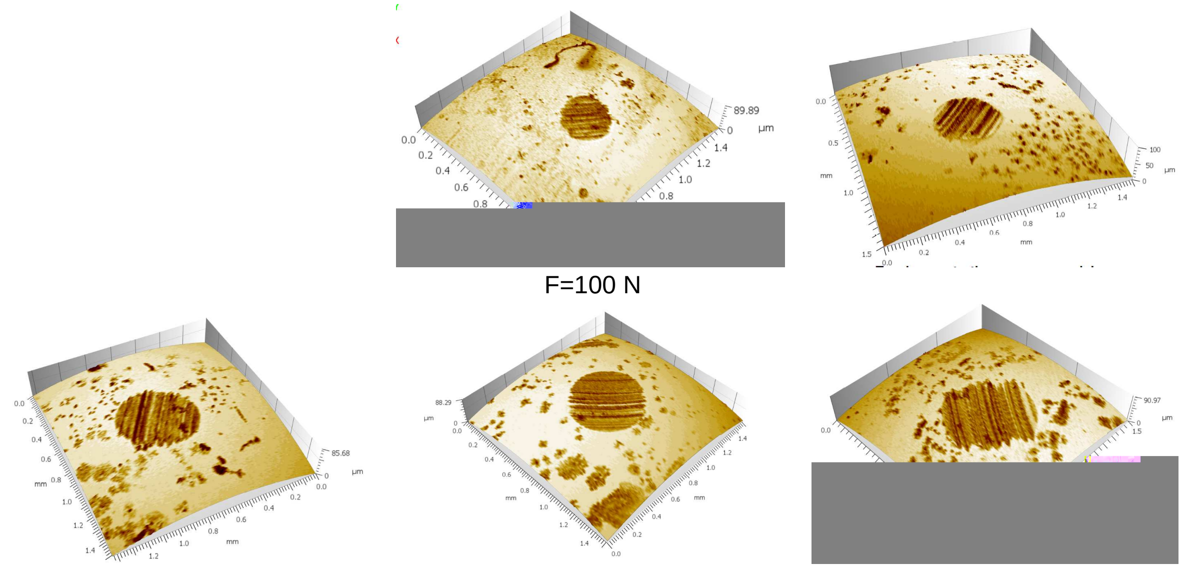


Fig 10. Images of the wear scars from different test conditions (F, v)
Each image has its own scale

Sa does not provide information about spatial structure and does not distinguish between valleys and peaks of surface texture. Malburg [27] appreciated the surface quality by the ratio $x_{(Sa,St)}$, defined as:

— (3)

Analyzing the values of 3 in Table 2, no obvious tendency could be noticed for the dependence of this parameter on load, for the same sliding velocity.

Although for the initial surface, similar ratios were obtained as for the worn surfaces, if one studies the virtual images of the non-worn surfaces and other parameters, it is observed that the initial surfaces give high values of the parameters St and Sv, but the values of the parameter Sp are low, i.e. there are micro-pits on the surface of the finely-machined balls, not micro-peaks, as is the case on surfaces that have undergone abrasive wear. From these results, it may be concluded that the analysis of surface quality should not be done by a single parameter and the values of the set of parameters should be corroborated with each other.

For the non-worn surfaces of the balls, the value of parameter is !" # $ %" $& ' ()$') .

Figure 11 presents the graph of WSD (with the scale in the left) and two amplitude parameters, Sa and Sq (their scale being in the right). If the distribution of asperity heights is normal, the relationship between the parameters Sq and Sa becomes Sa 0.8Sq. But worn surfaces could have different distributions as compared to the normal ones, thus, the proportionality between Sa and Sq is qualitatively maintains for worn surfaces, but the differences between these two parameters increases with load.

The extreme values for Sv, Sp and St for wear scars characterizing a particular test regime are presented in Fig. 12, together with the wear scar diameter, WSD. St has values between 8 mm and 12 mm, but not in a clear dependence both on load and sliding velocity, meaning that it could have an initial value, but during start and stop, this singularity may be cut or become greater (due to abrasive or/and adhesive wear), but without a relationship to either load or velocity.

Analysis of functional parameters includes Spk, Sk and Svk and two figures are of interest, Figures 13 and 14.

Spk is the reduced height of the peaks, Sk is the relative height of the core (middle area) of the surface and Svk is the reduced depth of the deepest valleys of the analyzed surface.

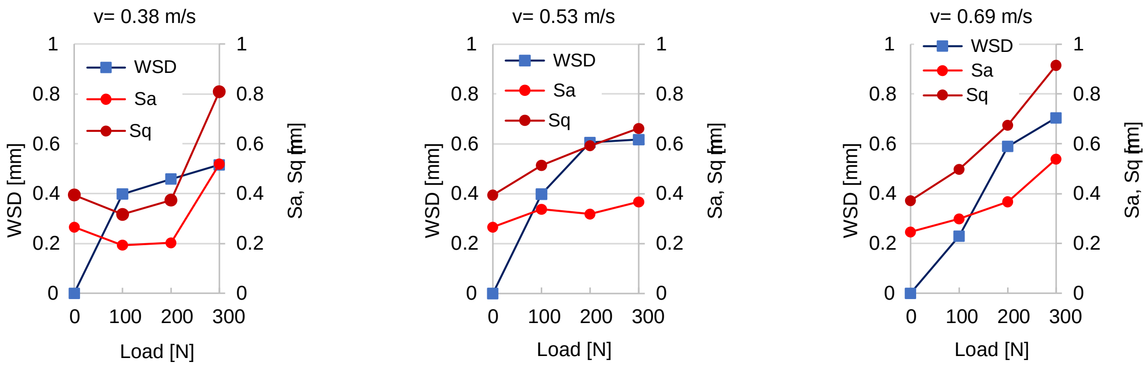


Fig. 11. Plots of WSD and two amplitude parameters, Sa and Sq, for each sliding veloci

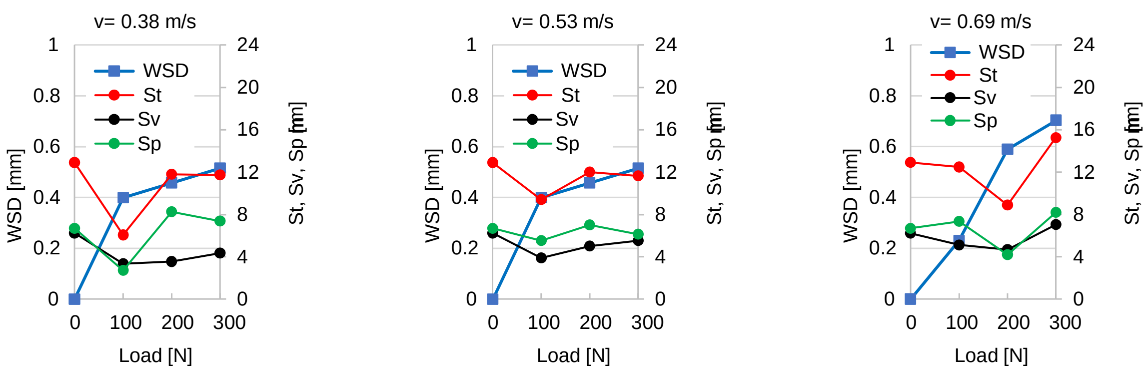


Fig. 12. Plots of WSD and three amplitude parameters, St, Sv, Sp, for each sliding veloc

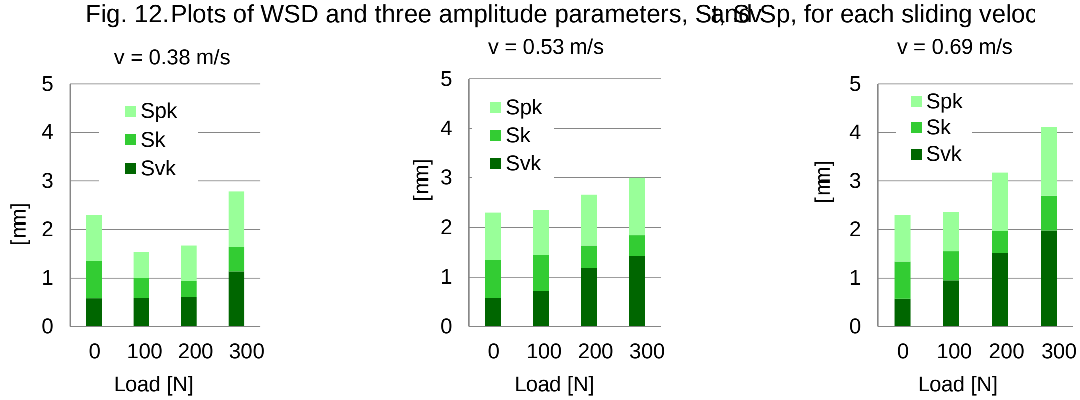
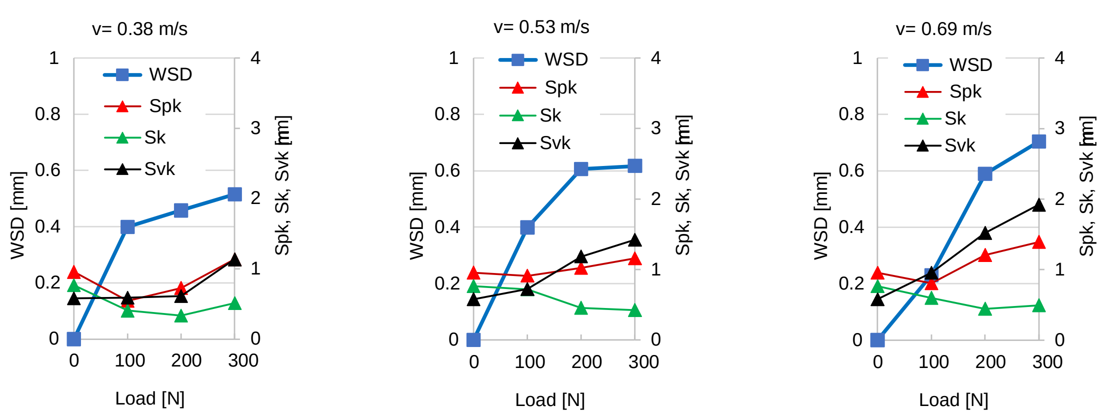


Fig. 13. The sum of functional parameters (Spk+Sk+Svk) as a function od load for each tested sliding velocity (load F=0 is for the initial surfac



a) b) c)

Fig. 14. Functional parameters and wear scar diameter (WSD) as a function of loa

In Figure 13, the analyzed functional parameters are represented as the sum of Svk+Sk+Spk; the value 0 represents the initial, non-worn surface of the ball.

The analysis of these parameters is important because it indicates how the texture components evolve (the peak area which is also the light wear area, the core or resistance area and the area for the lubricant reserve in contact).

An increase in Spk indicates abrasive wear, a decrease in Sk means a decrease in the strength of the surface layer and an increase in Svk indicates that wear has extended to the bottom of the texture.

When lubricated with rapeseed oil, a linear increase of the sum of the functional parameters, with higher slope towards higher velocity, is observed. At low velocity, v=0.38 m/s, the increase of this sum is very small up to 200 N. The proportion of parameters in this sum is not strongly modified compared to the proportion of non-worn texture. At high loads, however, a pronounced increase of Spk is observed. If the sum has a lower value as compared to the initial non-worn surface, that means abrasive wear is similar to a running-in process, the higher asperities being cut, without disturbing the bottom of the texture. This process is visible especially for F=100 N. When load increases, the sum increases too, meaning a more severe wear that enlarges the functional parameters related to peaks and valleys and reduce the texture core (that is mainly supporting the load), represented by Sk. Based on these observations, the authors suggest that volume parameters (void volume, core void volume, peak material volume, core material volume) [16] would be of interest in studying the evolution of the texture and their implication on contact durability.

Figure 14 presents the wear parameter, WSD, against functional parameters Spk, Sk and Svk in order to point out any correlation among them. Each plot is drawn for a specific sliding velocity as the value of this test input implies a different sliding distance. For each velocity and F=100 N, these functional parameters are close to the initial ones, meaning the texture change for these test inputs are minor. The tendency of Sk is to decrease as the load increases (except for v=0.38 m/s and F=300 N) meaning the surface core is reduced, due to abrasive wear. Svk and Spk have increased values as compared to the initial ones, meaning the abrasive wear affected both the peaks and valleys of the texture.

4. CONCLUSIONS

The association of wear with surface quality may help evaluate the durability of the contact of interest, help selecting a more effective lubricant that reduces wear and keeps the surface quality acceptable for further running.

When comparing worn surfaces to the initial non-worn curved surfaces, especially using 3D parameters, it is recommended to consider surfaces similar in size (and geometry).

The conclusions to be drawn from this study are the followings.

At low loads, the wear is acting on the top of the profile.

When correlating WSD with the amplitude parameters (Sa, St), for the tested regime, agreement was obtained in that both parameters have the same trend, generally increasing with load.

In order to assess the quality of a surface as close as possible to reality, using 3D parameters, the profilometer step should be as fine as possible and the area of investigation as large as possible. For this study, the entire worn scars on the fixed ball was investigated and the roughness parameters were calculated for this area.

The Sku parameter tells us if the surface has large isolated peaks, and Ssk “tells” if the peak frequency is high.

For worn surfaces, the values of amplitude parameters St and Sp are of interest, because high peaks affect the tribological behaviour.

The authors proposed the analysis of the sum of functional parameters (Spk+Sk+Svk). When using rapeseed oil as lubricant, this sum is proportional to load, at the same sliding velocity, but the sensitivity of the curve slope is strongly influenced by velocity. The modification of this sum takes place especially at start and stop, if th e oil generates a fully fluid film. For the rapeseed oil, in the sum of functional parameters, Spk increases very much and Sk changes very little. In contrast, Svk increases especially at high speed and load, reflecting an increase in abrasive wear.

For wear scars obtained with rapeseed oil as lubricant, the wear surface texture parameters can be grouped into:
- parameters that are proportional to WSD: Sa, Sq, St, Spk, Svk, meaning they reflect an increase of wear of the balls,
- parameter that was inversely proportional to the wear, as Sk, meaning that the core of the texture is reduced by wearing,
- parameters less sensitive with WSD: for instance, Sv, at least for the test campaign presented in this study;
- parameters that could not be related to test conditions, as Ssk, Sku. It is worthy to mention that l c was fixed at large values and this could influence the relevance of these parameters in studying their correlation to wear.

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Analiza parametrilor 3D de rugozitate pentru urmele de uzură obţinute pe testerul cu patru bile, lubrifiat cu ulei de rapiţă

Acest studiu îşi propune să sublinieze faptul că, în special în cazul suprafeţelor uzate, un singur parametru de rugozitate (de obicei Sa) nu este suficient pentru a stabili influenţa parametrilor de testare şi a lubrifiantului asupra comportamentului tribologic al tribosistemului. Scopul studiului este de a identifica care dintre parametrii de rugozitate 3D analizaţi ar putea fi corelaţi cu caracteristici tribologice precum coeficientul de frecare şi uzura reprezentată de diametrul urmei de uzură în testele cu patru bile. Asocierea uzurii cu calitatea suprafeţei ar putea ajuta la evaluarea durabilităţii contactului de interes, la selectarea unui lubrifiant mai eficace, care reduce uzura şi să menţină o calitate a suprafeţei acceptabilă pentru continuarea funcţionării. Această analiză poate fi calitativă, prin imagini, dar şi cantitativă prin valorile măsurate şi calculate ale parametrilor şi funcţia de dependenţă dintre acestea. Au fost investigate urmele de uzură pe bile testate pe o maşină cu patru bile, folosind ca lubrifiant uleiul de rapiţă. Parametrii de testare au fost: sarcina la arborele principal al maşinii cu patru bile (100 N, 200 N şi 300 N), viteza de alunecare (1000 rpm, 1400 rpm şi 1800 rpm). Au fost discutaţi parametri de amplitudine şi parametri funcţionali, măsuraţi sau calculaţi pentru întreaga urmă de uzură.

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