Mechanical Testing and Diagnosis
ISSN 2247 – 9635, 2021 (XI), Volume 4, pp. 5-14

3D AMPLITUDE PARAMETERS FOR THE WEAR SCARS RESULTED AFTER TESTING ADDITIVATED RAPESEED OILS ON FOUR-BALL TESTER

Traian Florian Ionescu[1], George Cătălin Cristea[2], Constantin Georgescu[1], George Ghiocel Ojoc[1], Larisa Chiper Titire[1], Cornel Suciu[3], Lorena Deleanu[1]

[1] ”Dunarea de Jos” University, Galati, Romania
[2] National Institute for Aerospace Research ”Elie Carafoli” - INCAS Bucharest, Romania
[3] ”Stefan cel Mare University”, Suceava, Romania

lorena.deleanu@ugal.ro

ABSTRACT

This paper presents an analysis of several 3D amplitude parameters of the texture, measured or calculated for the entire wear scar of the stationary balls used in four-ball tester: Sa, St, Sv, Sp, Ssk and Sku. The authors investigated balls tested in rapeseed oil, rapeseed oil + 1% TiO_2 and rapeseed oil +1 % ZnO in order to establish the influence of the testing regime (sliding velocity and force on the main shaft of the tester) on the surface quality at the end of the test, by the help of several amplitude 3D parameters. Qualitatively, the wear process is uniform on the balls in one test, because the spread ranges of the discussed parameters are small enough. At low force (F=100 N), corroborating the values of the studied amplitude parameters, it could be concluded that wear processes take place on the peaks of the texture. The Sa parameter is not affected by additivation for v=0.38 m/s and forces from F=100 N to F=300 N. At high sliding velocity, a slope change of both parameters is observed between F=200 N and F=300 N. If the wear is approximately the same at the test end for F=300 N, the roughness of the wear trace increases greatly when the rapeseed oil is additivated, meaning that nano particles of TiO_2 agglomerate and participate in the formation of a rougher texture. Lubricant with ZnO keeps the average roughness Sa close to that obtained with non-additivated rapeseed oil. In order to assess the quality of a surface as close as possible to reality, using 3D parameters, the profilometer pitch should be as fine as possible and the area of investigation as large as possible. However, a trade-off has to be done between the step size, the investigation area and the time to fulfill the study. The Sku parameter shows if there are large isolated peaks and Ssk indicates if the peak frequency is high. For the case of worn surfaces, the values of the parameters Ssk, Sku, St, Sp and Sv are of interest, because high peaks affect the tribological parameters. The surface quality when additivated with 1% TiO_2 is much better up to F=300 N. Additivation with 1% TiO_2 is recommended for low loads, F=100 N and F=200 N, for point contacts. The study should be completed with the same investigation in a severe regime where nano-additives should improve the seizure limit of load.

Keywords: amplitude parameter, wear scar, four-ball tester

1. INTRODUCTION

Since friction depends considerably on the topography of the contacting surfaces, both in dry and lubricated contacts, the characterization of the surface in relation to tribological properties becomes more relevant for a system function. Standard 2D roughness parameters do not provide a sufficiently good functional characterization of the surface. Therefore, the surface should be investigated with the help of 3D parameters. Studying the literature [1], [2], [3], [4], [5], [6], a conclusion is drawn: this investigation is dependent on the equipment and software the researcher uses. Another important factor is the size and shape of the analyzed items and the parameters selected for analysis.

From relevant scientific papers, two research directions are pointed out [2] [7]-[14]:

- the profilometric study should do a correlation between the texture parameter evolution and the functional parameters of the system, here including durability reliability, reflected in wear rate, friction coefficient, lubricant temperature, etc.,

- the study should be done for both surfaces in contact, especially when their materials are different.

Studies for worn surfaces are rare and the use of a set of 3D parameters instead of the well-known Ra average roughness is just the beginning. 2D measurements capture only localized surface profiles; this leads to inadequate sampling and sometimes different results based on the location of the scanned line. These surface parameters allow for a better characterization of the surface structure and a better understanding of the wear process.

The roughness along a single profile does not offer a complete image of the surface quality. The new tendency is to investigate surfaces large enough to characterize and to evidence wear mechanisms and their magnitude, but also the influence of surface evolution on the reliability and durability of the system.

These 3D parameters, developed also by Stout [14] are standardized by International Standardization Organization in the series ISO 25178.

The Gaussian robust filter separates the waviness from roughness, allowing for o better evaluation of the surface roughness and easier automatic detection of failures.

Calvo et al. measured the surface roughness with the help of the optical profilometer LEICA DCM 3 in a controlled environment (20 °C) and 45±5% humidity [15]. The scanned surface was filtered for eliminating the waviness with a standard Gaussian filter in order to evaluate the order of the roughness and to select the cut-off length adequate to the ISO standards.

Chivers şi Radcliffe described how to use profilometry as a tool for the diagnosis of surface damages in many applications: a valve for fluid flow control, identifying plastic yield as a cause of malfunctioning, a failure of a sealing system, also caused by plastic deformation, indentations due to centrifugal load, wear and oxidation evolution in order to evaluate the durability of two components in contact, very important in rails [16].

The topographic analysis done by Hyunseok [17] uses a general quadratic equation that allows for eliminating the effect or surface curvature (as for instance, balls for rolling bearings) before the quantification of surface roughness.

Wear exists for all machine components in motion and under load but researchers and engineers could reduce it and increase the reliability and durability of the components [18]. Studies mainly focus on wear performance after the contact pairs have been operating for a period of time. Studies on the evolution of surface topography and friction coefficient resulting from the wear process under mixed or full film lubrication conditions are still limited. They may have significant importance in reducing wear and improving lubricant performance and the overall system.

This profilometric study aims to point out the influence of the test regime (by force and sliding velocity) and of the nano additives introduced in rapeseed oil on the texture quality of resulted worn surfaces, measured at the end of the test, on the entire wear scars of the balls (from a four-ball tester) on a set of 3D amplitude parameters (parameters S).

2. LUBRICANTS AND TESTS

The tested lubricants were rapeseed oil, supplied by Expur Company SA from Bucharest, rapeseed oil +1% TiO_2 and rapeseed oil +1% ZnO. These two nano additives were supplied by PlasmaChem [19]:

- ZnO: average particle size ~14 nm, specific surface area ~30 m²/g,
- TiO_2: average particle size ~21 nm, specific surface area ~50 m²/ g.

The fatty acid composition of the analyzed rapeseed oil is presented in Table 1.

Table 1. Composition in fatty acids of the rapeseed oil [20]

Fat acid	Symbol	Concentration, %wt
Myristic acid	C14:0	0.06
Palmitic acid	C16:0	4.6
Palmitoleic acid	C16:1	0.21
Heptadecanoic acid	C17:0	0.07
Heptadecenoic acid	C17:1	0.18
Stearic acid	C18:0	1.49
Oleic acid	C18:1	60.85
Linoleic acid	C18:2	19.9
Linolenic acid	C18:3	7.64
Arachidic acid	C20:0	0.49
Eicosenoic acid	C20:2	1.14

The finely grinded balls, supplied from SKF, are made of chrome steel, with a diameter of 12.7 mm ± 0.0005 mm, according to the ISO standard 683-17:2014, with high hardness (62...65 HRC).

The dispersion of nano additives in rapeseed oil was done by sonication [20].

The test conditions were considered as a normal regime with the following parameters: load (100 N, 200 N and 300 N), sliding velocity (0.38 m/s, 0.53 m/s and 0.69 m/s, corresponding to rotational speeds of the four-ball main shaft of, 1400 rpm and 1800 rpm, respectively) and test time (hour ±1%).

3. METHODOLOGY FOR TEXTURE EVALUATION

The initial and worn surfaces of the balls were investigated with the help of the laser profilometer NANOFOCUS μSCAN (from ”Ştefan cel Mare” University of Suceava, Romania), its resolution being 25 nm. The results, meaning the amplitude parameters, were processed with the help of the software Mountains SPIP 8.1 [21].

3D parameters were calculated or measured for each entire wear scar of the three stationary balls, and the graphs were plotted for the average, maximum and minimum values. The distance between investigated lines was 5 µm and the step on each line was also 5 µm. For each wear scar on a ball, a surface of 1500 µm x 1500 µm was investigated, as from [20], [22] the wear scars could have dimensions of 1000 µm for the more severe regime (F=300 N, v=0.53...0.69 m/s). Parameters 3D were measured or calculated using all the values z(x,y) on the wear scar, considered as an ellipse. Figure 1 presents a wear scar from ball 1, from a test with rapeseed oil, under force (on the main shaft of the four-ball tester) F=100 N and sliding velocity v=0.69 m/s, test duration being 1 h. The wear scar was virtually built based on the aggregate z(x,y), the ellipse dimensions being as those measured after the test, with the help of an optical microscope.

For each wear scar, the diagram in Fig. 3 is followed for calculating the parameters. An important step is the levelling that brings in a horizontal plane the investigated (initially spherical) the surface.

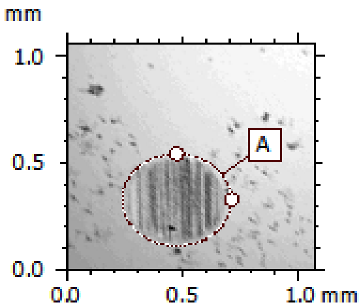


Fig. 1. Selecting the wear scar surface to be investigated

Another important step is to remove the spherical shape. The ideal spherical shape of the surface (a 6.35 mm diameter sphere) is replaced by a straight reference surface. Next, the wear trace is cropped. On this software, the wear trace is cut as an ellipse with axes equal to those measured by the optical microscope (the accuracy is of several microns). The actual wear scar does not have a perfectly regular ellipse shape and therefore it is possible that the axes of the cut-out area to differ from those measured by a few microns, which is considered to be accurate enough to reflect the texture of the worn surface.

The values of the roughness parameters depend on applied filters. For this study the following filters were applied: λs=10 µm și λc=0.25 mm.

The standard ISO 3274 (dealing with 2D parameters) recommends a diagram similar to that in Fig. 3. The extracted profile is sampled and digitilized and it represents a line on the actual surface. In both 2D and 3D analyses, the profile or the surface is levelled by the help of a polynomial function. The filter λ_s is used for eliminating the micro-roughness, usually caused by environmental or background noise. After this first filtering process, the raw profile or surface is obtained and then the filter λ_c is applied for separating the waviness from roughness.

The ends of measured profiles were not cut off, considering that, for worn surfaces, it is better not to remove the end values. The wear scar established manually on the recorded levelled surface is compared to the actual one with the help of ellipse axes. For example, for a wear scar, its size assessed on the profile is 0.4 mm and the measured value was 0.4024 mm.

4. ANALYSIS OF AMPLITUDE 3D PARAMETERS

4.1. Parameters 3D for non-worn surfaces of balls

Figure 2 shows a reconstructed (virtual) image with Mountains SPIP 8.1 software [21] of the investigated area . Surface textures were recorded for three areas of 1.5 mm x 1.5 mm, on three balls, with a step resolution of 5 µm, and line spacing of 5 µm as well. Measurement results for the parameters of interest are given in Table 1.

Analysing the information from Fig. 2 and Table 2, the ball texture is characterized by:
- rare very high asperities foarte (St=10.03 µm),
- value characteristic for fine grinded surfaces (Sa=0.206 µm),
- plateau with small unevenness and rare deeper valleys (Ssk= −0.203, Sku=19.17).

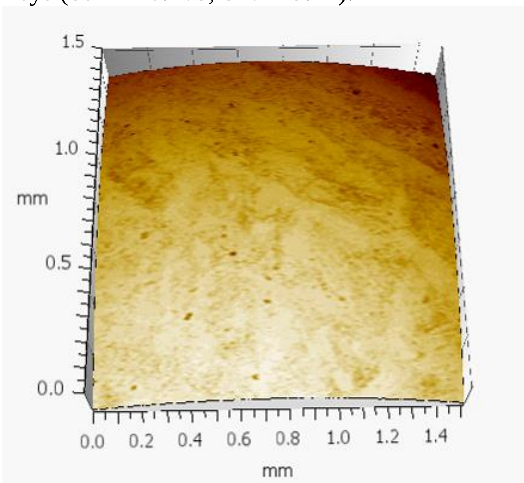


Fig. 2. Virtual image of the initial surface of a ball

Table 2. Values of the 3D amplitude parameters for the non-worn surface of the balls (average of three measurements)

3D parameter	value
Sa [µm]	0.206
Sq [µm]	0.313
Ssk	-0.203
Sku	19.17
Sv [µm]	6.027
St [µm]	10.03
Sp [µm]	4.001

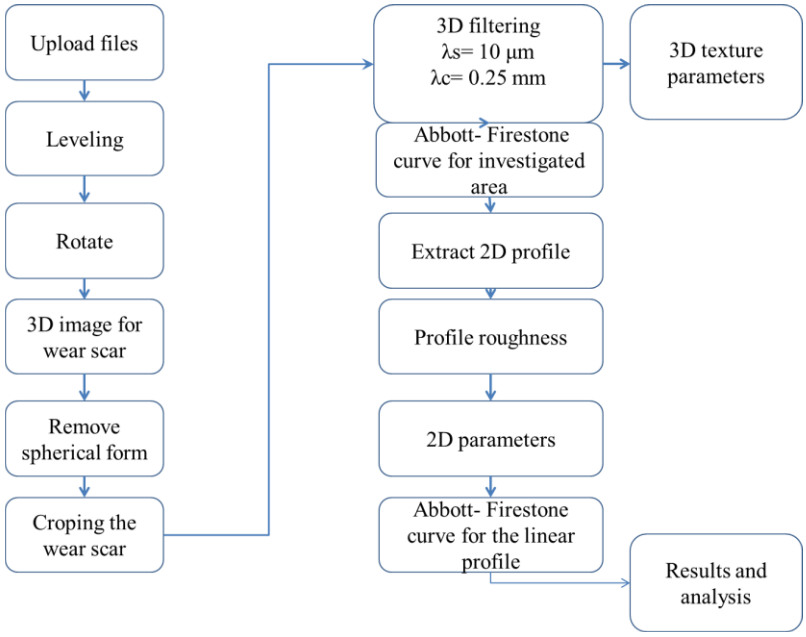


Fig. 3. Diagram of methodology for measuring and calculating the 3D amplitude parameters with the help of software SPIP 8.1.

4.2. Analysis of 3D amplitude parameters for non-worn ball surface

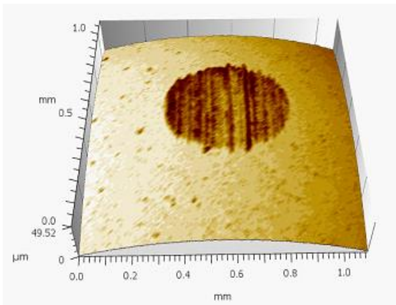
In all the following graphs, the value in grey is for the initial value, obtained on a non-worn surface. Each lubricant was represented by the same colour, light for v=0.38 m/s, normal for v=0.53 m/s and dark for v=0.69 m/s.

In Fig. 4, wear traces are given for the worn balls, as measured on the optical profilometer. These images were given in order to make a correlation between the values of the parameter Sa, for rapeseed oil additivated with 1% ZnO, at forces F=100 N, F=200 N and F=300 N, where the highest values of this parameter are observed.

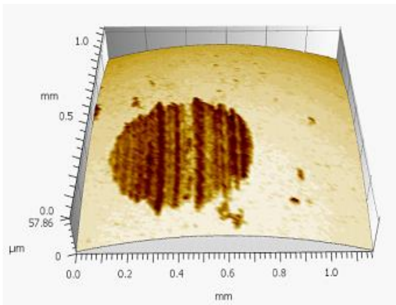
Figure 5 presents the parameter Sa for the rapeseed oil (green colours), rapeseed oil +1% TiO_2 (brown colours) and rapeseed oil +1% ZnO (blue colours). Except for the sliding velocity v=0.38 m/s, the values of these parameters seem to be linearly dependent on the applied force.

At lower velocities, the degradation of the ball surface evolves after a smaller slope for the transition from F=100 N to F=200 N. A slight increase of Sa is observed for each force and at any of the sliding speeds. At the lowest velocity (v=0.38 m/s), for non-additivated rapeseed oil and for rapeseed oil additivated with 1% TiO_2, a slight decrease is observed due to the very fine running-in (only the peaks of the asperities are removed, which is beneficial for the contact). For the other velocities and forces, the average roughness increases slightly, but the surfaces could still be used.

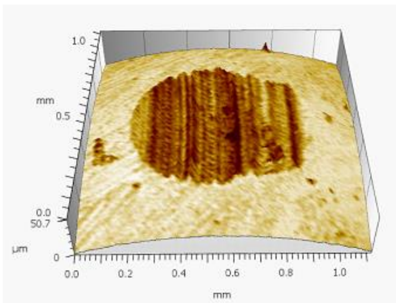
The influence of the nature of the additive and the test regime on this parameter, Sa, is shown in Fig. 5(b) and (c).



F=100 N



F=200 N



F=300 N

Fig. 4. Wear scars virtually re-bult (test with rapeseed oil + 1% ZnO, at sliding velocity v=0.69 m/s

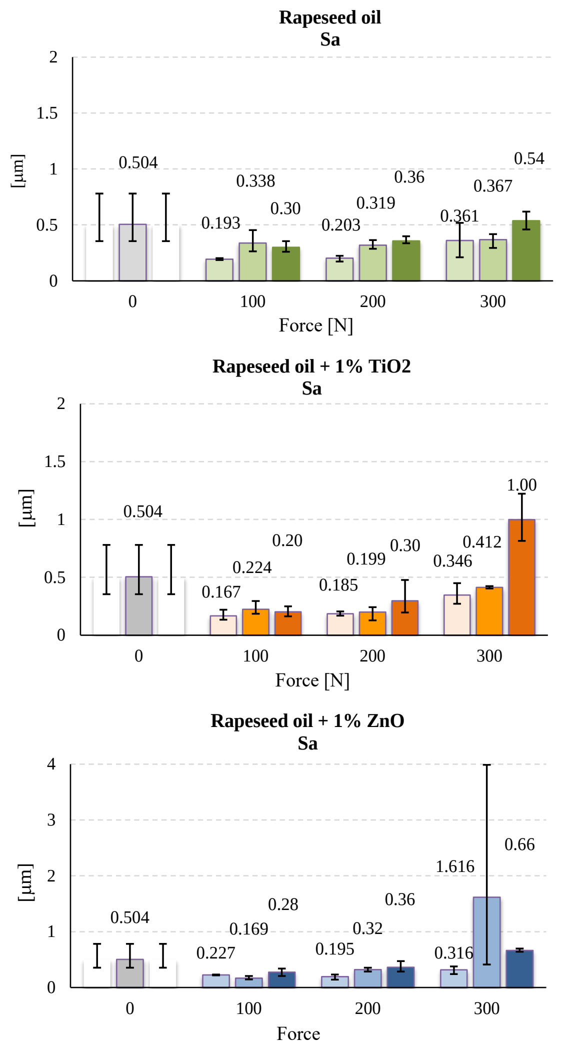


Fig. 5. Sa parameter

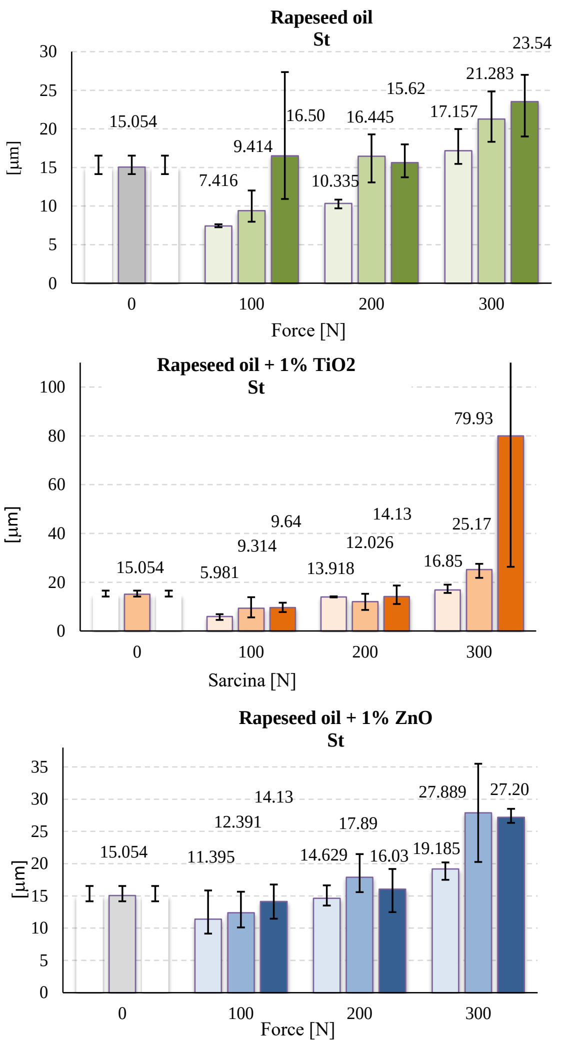


Fig. 6. St parameter

In Fig. 6 (b), for rapeseed oil additivated with 1% TiO_2, the presence of the additive produced a decrease of Sa. The additive protects the texture in contact and allows only for breaking the very high peaks. From Fig. 6 (c), an almost identical behaviour of the analysed parameter, Sa, is observed for rapeseed oil additivated with 1% ZnO. At a force of F=300 N, higher values are observed for all analysed velocities.

These graphs reflect the influence of force on this parameter, for the same velocities. The authors do not recommend making comparisons among values for different velocities as the sliding distance is not the same for each set of tests at constant velocity. In this test campaign, only the time is kept constant for all tests (1 h), the sliding distance being proportional to the sliding velocity. The test with v=0.53 m/s is close to that recommended in SR EN ISO 20623:2018 [23].

Simply using the arithmetic mean deviation of the roughness, Sa, is not sufficient to characterize the quality of surface texture. In many cases, there are surfaces that may have identical values for Sa, but they have other different characteristics that may affect the material behaviour in both dry and lubricated regimes [1], [14], [24]. This is the reason to analyze other 3D amplitude parameters. Since mathematically there is a direct, not necessarily linear, relationship between Sa and Sq, the trend of the evolution for Sq is similar to that of the parameter Sa [20]. It can be recommended that studies of worn surfaces be done on either Sa or Sq.

The greatest values of Sp (Fig. 7) were obtained for F=300 N and v=0.69 m/s for the neat rapeseed oil, but also for the rapeseed oil + 1% TiO_2 and rapeseed oil + 1% ZnO, meaning that the more severe regime generates more intense abrasive wear and the worn surface has higher peaks.

The maximum valley height Sv [µm] has higher values for tests with F=300 N, and sliding velocity v=0.69 m/s, for all lubricants. The lowest values for Sv were obtained for the neat rapeseed oil (Fig. 8). As Sv is measured with reference to the mean line, it was noticed a decrease of the deepness (Sv) of the profiles under the mean line, meaning that the material above the mean line has sharper aspect with less material as compared to that under line, very probably the shape of the valley not being modified by the wear process.

Figure 6 presents the evolution of peak-peak height, St [μm]. Under low forces (F=100 N and F=200 N), the values of St for additivated rapeseed oil are lower than those obtained for F=300 N, for all sliding velocities. St is an important parameter for tribology, especially for lubricated contacts, because the high asperities, even rare, could destroy the lubricant film and could change the regime, from an elastohydrodynamic (EHD) regime to a mixt or boundary one, implying a suddenly increase of the friction coefficient. The rare and sharp asperities could be broken or plastically deformed. These processes could re-generate the EHD regime if the surface texture is not becoming rougher.

The Sku parameter for the worn surfaces (Fig. 11) has a tendency to decrease. The lowest values were obtained for F=300 N, for all tested sliding velocities and for all tested lubricants as compared to the value obtained on the non-worn surface of the ball.

The clearest decreasing trend of Sku values is observed for rapeseed oil with 1% ZnO additive, at a sliding velocity of 0.69 m/s, for all loads. The obtained high values indicate the existence of a rough surface with very high peaks, typical of surfaces where abrasive wear occurs. The lowest values for Sku were obtained for non-additivated rapeseed oil (Fig. 11), which means that the additives favoured the appearance of high peaks or maintained them

Sa does not offer information on the spatial structure of the asperities and it does not differentiate between valleys and peaks of the surface texture. Malburg [25] also appreciated the surface quality by the help of the ratio $\xi_{(Sa,St)}$, defined as:

$$\xi_{(Sa,St)} = \frac{St}{Sa} \tag{1}$$

Figure 10 gives the value for $\xi_{(Sa,St)}$, for all tested lubricants, forces and sliding velocities. A low value of this ratio may indicate a good quality of the worn surface, thus, a good functioning of the tribosystem in the future.

Big values may characterize a surface with peaks and/or valleys (rare or not), but they vary in height, which means an aggressive wear process, at least in the area of existence of the singular maximum of the roughness heights.

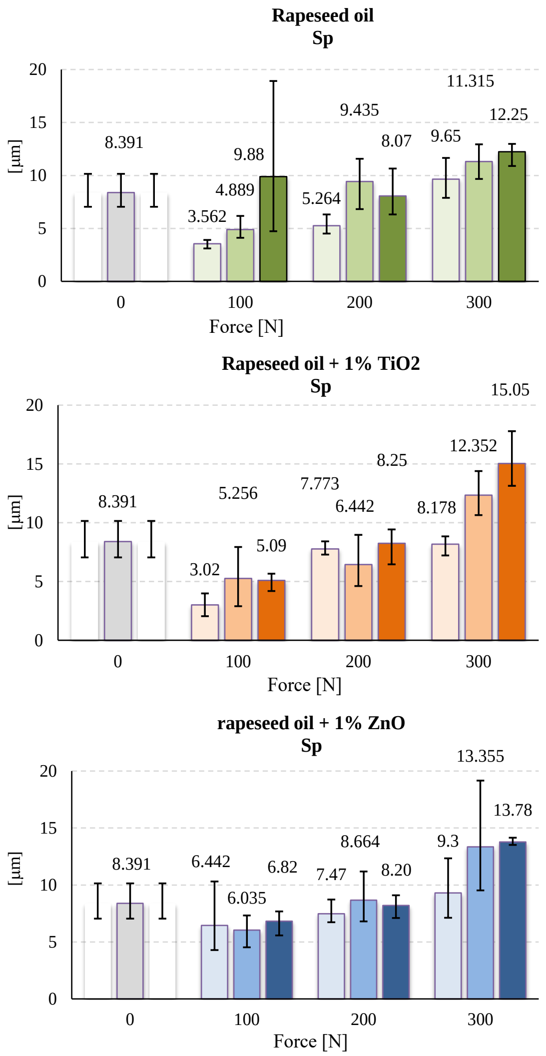


Fig. 7. Parameter Sp

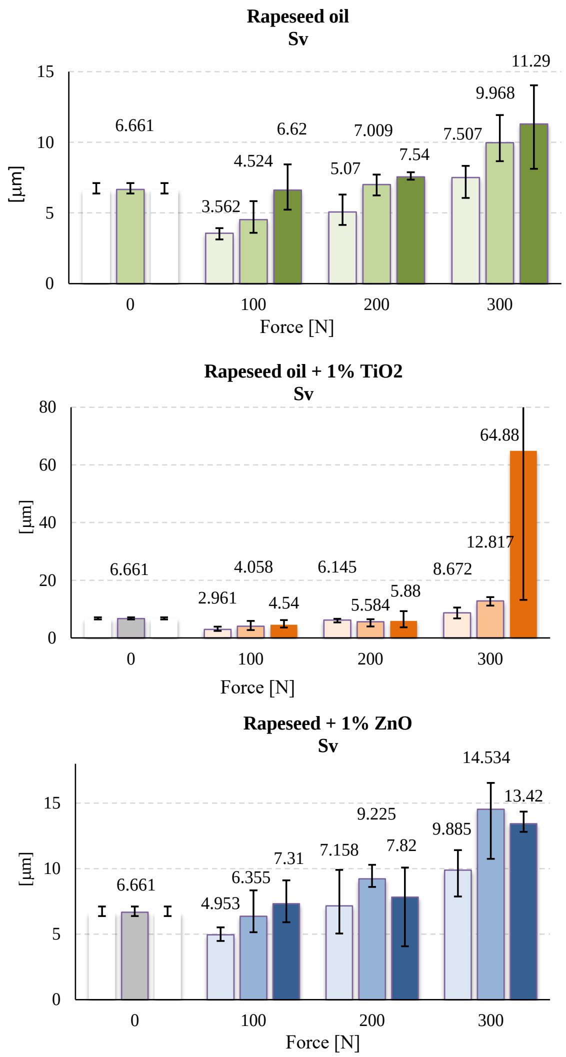


Fig. 8. Parameter Sv

A lower value of the parameter ξ (Sa,St) was obtained for non-additivated rapeseed oil, at F=200 N and v=0.69 m/s. For TiO_2 and ZnO additivated rapeseed oil, the lowest value was obtained at F=300 N and v=0.69 m/s.

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, such as Ssk and Sku, 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 beads, not micro-peaks, as it happens on surfaces that have undergone abrasive wear. From these results, it can be concluded that the surface quality analysis should not be done by a single parameter and the values of the parameter set should be corroborated with each other and qualitatively analysed together with the image recorded on the 3D profilometer.

Analysing Fig. 10 for ξ, a decreasing trend of the parameter is observed for the higher velocity, but the values cannot be clearly fitted into a velocity- and load-dependent relationship.

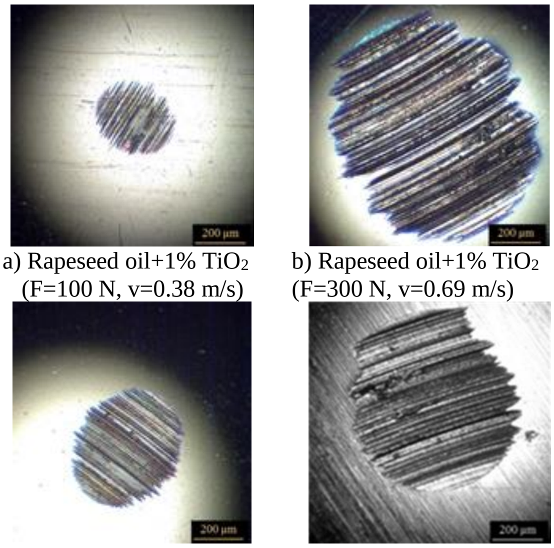
For the non-worn ball, it was calculated the value of parameter ξ,

$$\xi_{(Sa,St)} = \frac{St}{Sa} = \frac{10.3}{0.206} = 48.68 \qquad (2)$$

Figure 9 presents an image of the wear scars with the lowest and highest values for the parameter Sku. They were obtained by the help of an optical microscope.

Ssk is presented in Fig. 12 for the tested lubricants. Its tendency to depend on force can be noticed, and even on sliding velocity even if the sliding distances increase with velocity as the test time is the same. When additivating the rapeseed oil with 1% ZnO, a tendency to keep positive Ssk values is observed. Ssk represents the degree of symmetry of surface heights above the median plane, and the sign of Ssk indicates the predominance of peaks if positive, or valleys if negative.

The Sku parameter indicates the presence of random peaks and valleys for Sku > 3, or lack of them if Sku<3. If surface heights are normally distributed (Gaussian), then Ssk=0 and Sku=3. Surfaces described as gradually varying without extreme peaks or valleys will tend to have Sku<3. Ssk is useful in characterizing honed surfaces and for those bearing wear processes. Sku is useful for indicating defects with large, deep valleys or peaks. As the calculation of Ssk and Sku involves higher order powers for the z(x,y) coordinates, there must be sufficient measurements to satisfactorily evaluate these two parameters. It is observed that the initial surface has a relatively small but negative Ssk. The Ssk values do not reflect a clear dependence on the regime parameters (force or sliding velocity); they range from negative to positive values in the range (-0.8...2).



a) Rapeseed oil+1% TiO_2 (F=100 N, v=0.38 m/s)

b) Rapeseed oil+1% TiO_2 (F=300 N, v=0.69 m/s)

c) Rapeseed oil +1% ZnO (F=200 N, v=0.38 m/s)

d) Rapeseed oil +1% ZnO (F=300 N, v=0.69 m/s)

Fig. 9. Examples of wear scars

Ssk values should be interpreted by qualitatively analysing the wear scars' surfaces. The difference between the values of the Ssk parameter shows that at force F=100 N, the surface has only slight traces of abrasion (Fig. 12), whereas, at F=300 N, the negative value reflects a strongly "ragged" surface with deeper valleys and sharp peaks, even if they are rare.

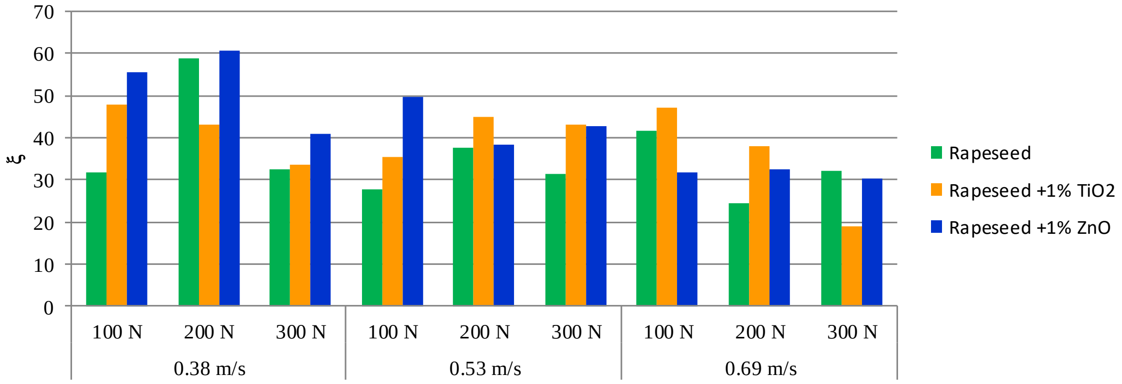


Fig. 10. Parameter $\xi_{(Sa,St)}$

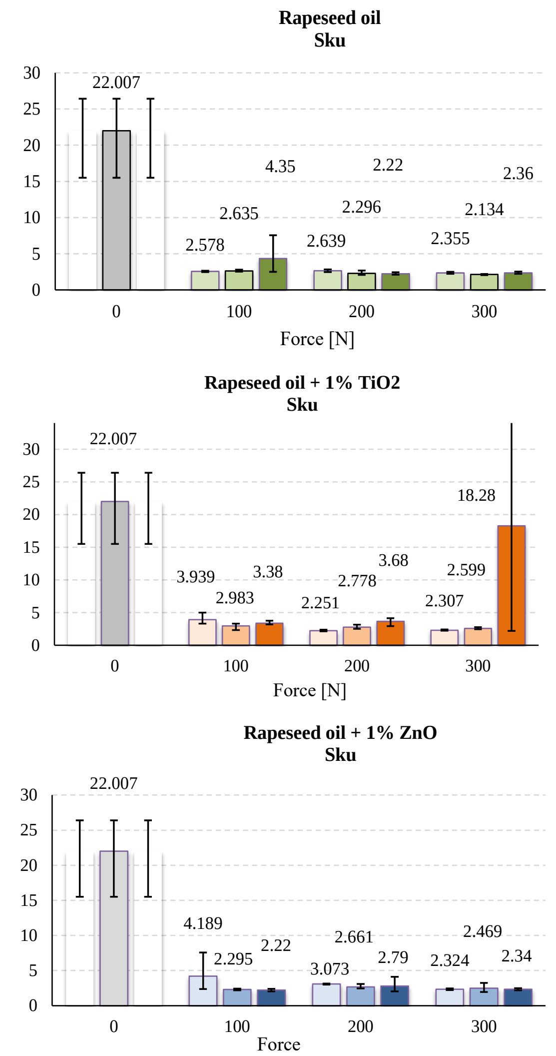


Fig. 11. Parameter Sku

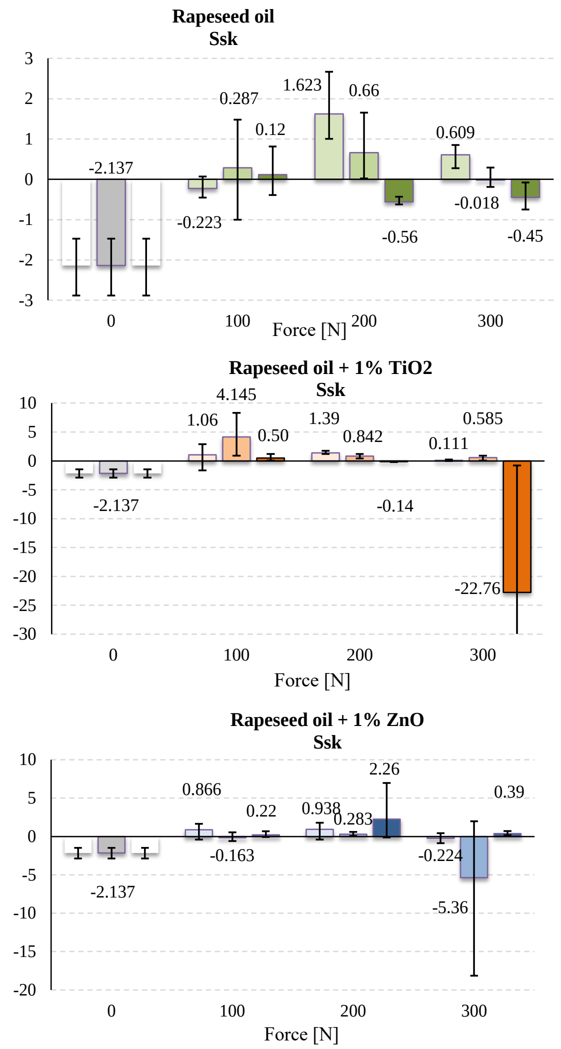
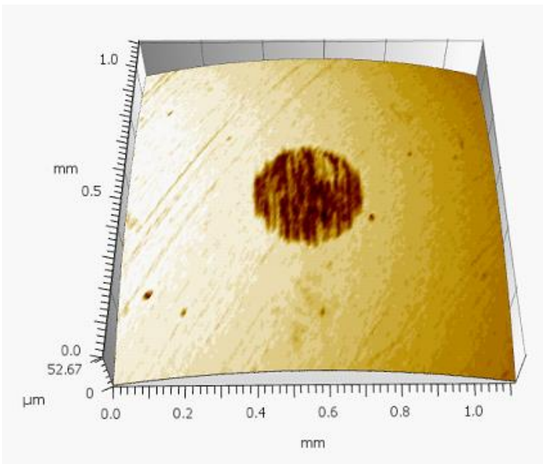
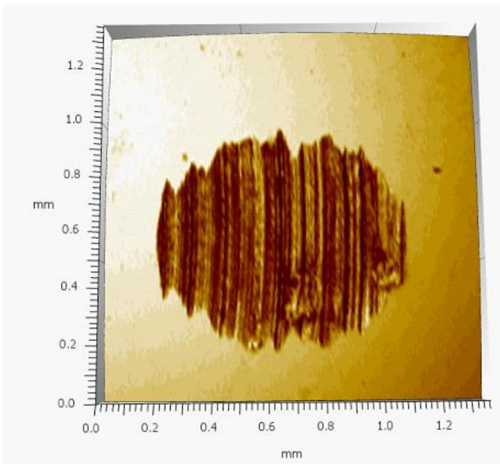


Fig. 12. Parameter Ssk



a) F=100 N, v=0.69 m/s



b) F=300 N, v=0.69 m/s

Fig. 13. Wear scars on stationary ball, virtually built with Mountains SPIP 8.1, after being tested with rapeseed oil + 1% TiO_2

CONCLUSIONS

The association of wear with surface quality can be qualitative, through images, but also quantitative through the obtained values of a set of roughness 3D parameters and the dependence function between them.

Tribologists are interested in functions like that f(v,F,t,WSD, texture parameter)=0, from which an optimization or delimitation of the working regime on wear and surface quality criteria can be evaluated.

In conclusion, when comparing worn surfaces and initial non-worn curved surfaces, it is recommended to consider surfaces similar in size (and geometry) and to do an investigation on the entire worn surfaces (if possible).

The conclusions that emerge from this study are written bellow.

Qualitatively, the wear process is uniform on the balls in one test, because the spread ranges of the discussed parameters are small enough.

At low force (F=100 N), corroborated by the values of the studied amplitude parameters, it could be concluded that wear processes take place on the peaks of the texture.

The Sa parameter is not affected by additivation for v=0.38 m/s and forces from F=100 N to F=300 N. At high sliding velocity, a slope change of both parameters is observed between F=200 N and F=300 N. If the wear is approximately the same at the test end for F=300 N, the roughness of the wear trace increases greatly when the rapeseed oil is additivated with, meaning that nano particles of TiO_2 agglomerate and participate in the formation of a rougher texture.

ZnO keeps the average roughness Sa close to that obtained with non-additivated rapeseed oil.

In order to assess the quality of a surface as close as possible to reality, using 3D parameters, the profilometer pitch should be as fine as possible and the area of investigation as large as possible.

However, a trade-off has to be done between the step size, the investigation area and time to fulfil the study. The Sku parameter shows if there are large isolated peaks and Ssk indicates if the peak frequency is high.

For the case of worn surfaces the values of the parameters Ssk, Sku, St, Sp and Sv are of interest, because high peaks affect the tribological parameters.

The surface quality when additivated with 1% TiO_2 is much better up to F=300 N. Additivation with 1% TiO_2 is recommended for low loads, F=100 N and F=200 N, for point contacts. A study should be completed with the same investigation in a severe regime where nano-additives should improve the seizure limit of load.

For wear scars obtained with lubricants with rapeseed oil + nano additive (TiO_2 and ZnO, respectively), for the tested regimes (combinations of three forces and sliding velocities), the wear surface texture parameters can be grouped into two classes:

- parameters that are proportional to one or two of the regime variables: Sa, St,
- parameters less sensitive with these variables: Ssk, Sku.

ANNEX

The 3D amplitude parameters are explained, based on the formula given in Mountains SPIP 8.1 [21].

The roughness Average of the surface**, Sa** [µm], is defined as the arithmetic value of the heights in the sampled area

$$Sa = \frac{1}{M \cdot N}\sum_{j=1}^{N}\sum_{i=1}^{M}\left|z(x_i, y_j)\right| \qquad (A.1)$$

where $z(x_i,y_i)$ represents the height in the position (x_i,y_i) on the leveled area. Sa is the most used parameter, even on technical drawings.

The peak-peak height, St [µm], represents the distance between the peak of the maximum height and the maximum value of the deepest valley.

$$\mathrm{St} = \mathrm{Sy} = \mathrm{Sz} = \mathrm{zmin}_{\mathrm{max}} \qquad (A.2)$$

If the recorded profiles are not filtered with reference to the mean line:

$$St = (|Sp| + |Sv|) \qquad (A.3)$$

Maximum peak height, Sp [□m], is defined as the heighest peak above the mean line.

$$Sp = max(\,z(x_i, y_j)) \qquad (A.4)$$

The largest valley height**,** Sv [□m], is the maximum value of the deepest valley, under the mean line.

$$Sv = \left|min(\,z(x_i, y_j))\right| \qquad (A.5)$$

The surface skewness, Ssk, represents the measure of the surface assymetry with reference to the mean line:

$$Ssk = \frac{1}{M \cdot N \cdot Sq^3}\sum_{j=1}^{N}\sum_{i=1}^{M} z^3(x_i, y_j) \qquad (A.6)$$

Ssk described the shape of height distribution of the surface texture. The negative value is obtained when more material is above the mean line and the positive value is get when more material is under the mean line [21]. Physically, this parameter offers information about the existence of peaky characteristics on the surface.

Kurtosis, Sku [µm], represents the the "peakedness" of the surface topography

$$Sku = \frac{1}{M \cdot N \cdot Sq^4}\sum_{j=1}^{N}\sum_{i=1}^{M} z^4(x_i, y_j) \qquad (A.7)$$

A surface with a gaussian distribution of heights has Sku=3. Spiky surfaces, like those after turning, has higher value, and surface with plateaux, bumpy surfaces (like the honned ones) has lower values.

REREFENCES

1. Blateyron, F. (2006). États de surface: la norme. *Mesures*, **787**, 44-47
2. Leach, R. (2011). Optical measurement of surface topography, Springer, Berlin, Heidelberg

3. Blunt, L., Jiang, X., Leach, R., Harris, P., & Scott, P. (2008). The development of user-friendly software measurement standards for surface topography software assessment. *Wear*, **264**, 389-393
4. Cotell, C.M., Sprague, J.A., & Smidt, F. A. Jr. (2002). ASM Handbook volume 5–*Surface Engineering*, ASM International, USA
5. Dong, W. P., Sullivan, P. J., & Stout, K. J. (1994). Comprehensive study of parameters for characterising three-dimensional surface topography. III: Parameters for characterising amplitude and some functional properties. *Wear*, **178(1-2)**, 29-43.
6. Davim, J. P., & Mata, F. (2004). Influence of cutting parameters on surface roughness in turning glass-fibre-reinforced plastics using statistical analysis. *Industrial Lubrication and Tribology*, **56(5)**, 270-274
7. Stachowiak, G. W., & Batchelor, A.W. (2005). Engineering tribology, Butterworth-Heinemann, Team Lrn
8. Stachowiak, G. W., & Podsiadlo, P. (2006). Fast classification of engineering surfaces without surface parameters. *Tribology International*, **39**, 1624-1633
9. Deleanu, L., Cantaragiu, A., Bîrsan, I. G., Podaru, G., & Georgescu, C. (2011). Evaluation of the spread range of 3D parameters for coated surfaces. *Tribology in Industry*, **33(2)**, 72-78
10. Deleanu, L., Georgescu, C., & Suciu, C. (2012). A comparison between 2D and 3D surface parameters for evaluating the quality of surfaces. The Annals of "Dunarea de Jos" University of Galati, V, Technologies in Machine Building, 10-17
11. Pirvu, C., Georgescu, C., & Deleanu, L. (2013). Influence of grinding feed speed on 3D texture parameters. *Mechanical Testing and Diagnosis*, **2**, 19-28
12. Kudish, I. I., & Covitch, M. J. (2010). Modeling and Analytical Methods in Tribology, CRC Press
13. Rîpă, M., & Deleanu, L. (2006). Relevant parameters set for characterising engineered surface topography, National Conference on Applied Physics, Galati, Romania
14. Stout, K. J., Sullivan, P. J., Dong, W. P., Mainsah, E., Luo, N., Mathia, T., & Zahouani, H. (1994). The development of methods for the characterisation of roughness in three dimensions, Publication no. EUR 15178 EN of the Commission of the European Communities: Brussels-Luxembourg
15. Calvo, R., D'Amato, R., Gomez, E., & Ruggiero, A. (2019). Experimental analysis of the surface roughness in the coefficient of friction test. *8th Manufacturing Engineering Society International Conference*, 153-160.
16. Chivers, T. C., & Radclliffe, S. J. (1979). The role of surface profilometry in failure diagnosis. *Wear*, **57**, 313–321
17. Hyunseok, O., Azarian, M. H., & Morillo, C. (2015). Failure mechanisms of ball bearings under lightly loaded, non-accelerated usage conditions. *Tribology International,* 292-299
18. Pei, X., Pu, W., Zhang, Y., & Huang, L. (2019). Surface topography and friction coefficient evolution during sliding wear in a mixed lubricated rolling-sliding contact. *Tribology International*, **137**, 303-312
19. *** PlasmaChem catalog, 2008, http://www.plasmachem.com/download/PlasmaChem-General_Catalogue_Nanomaterials.pdf.old4
20. Ionescu T. F. (2021) A Tribological Study of Lubricants Based on Rapeseed Oil and Nano Additives for Reducing Friction and Wear, PhD, "Dunarea de Jos" University of Galati, Romania,
21. *** SPIP The Scanning Probe Image Processor SPIPTM, Mountains SPIP 8.1.(2019), on-line: http://www.imagemet.com/WebHelp/spip.htm.
22. Cristea G. C. (2017) Tribological Characterization of Soybean Oil Additivated with Nano Materials Based on Carbon (Black Carbon, Graphite and Graphene), PhD, "Dunarea de Jos" University of Galati, Romania
23. *** SR EN ISO 20623:2018 Petroleum and related products - Determination of the extreme-pressure and anti-wear properties of lubricants - Four-ball method (European conditions)
24. Georgescu, C. (2012). The Evolution of the Superficial Layers in Wear and Friction Processes Involving Composite Materials with Polybutylene Terephthalate, PhD thesis, "Dunărea de Jos" University of Galați, Romania
25. Malburg, M. C. (2002). Cylinder Bore Surface Texture Analysis, Digital Metrology Solutions Inc. http://www.digitalmetrology.com/Papers/CylinderBoreNoBkgd.pdf