Evaluating lubricant performance by 3D profilometry of wear scars

C Georgescu 1, L Deleanu1 and C Pirvu2

1Department of Mechanical Engineering, “Dunarea de Jos” University, Galati, Romania
2INCAS, Bucharest, Romania

E-mail: constantin.georgescu@ugal.ro

Abstract. Due to improvement in analysing surface texture and optical instruments for investigating the texture surface, the authors propose to evaluate the lubricant performance by analysing the change in several 3D parameters in comparison to an analysis on 2D profile. All the surface of the wear scar generated on the four ball machine is investigated and the conclusion is that from the tribological point of view, the 3D parameters reflect better the surface quality evolution after testing. Investigation was done on the wear scars generated on the three fixed balls, for five lubricants: a non-additivated transmission mineral oil (T90), two grades of rapeseed oil (coarse degummed and refined) and two grades of soybean oil (coarse and degummed).

1. Introduction

The interest in testing vegetable oils as future solution as lubricants becomes more and more pregnant among researchers as these oils, even taking into account their shortcuts, are friendly with the environment and are obtained from renewable resources.

An estimative consumption of the lubricants is of 40 millions tons/year, mainly based on mineral oils but these one are challenged by two categories: the synthetic lubricants and those based on renewable resources - the vegetable ones [1], [2], [3], [4], [5]. The latest are not yet suitable enough for the most performant technical systems because of their set of characteristics that includes, besides desirable ones, others like low values for viscosity (even if they have a very good viscosity index) [6], [7], [8], tendency for oxidising [9], [10], [11], [12], [13] and narrow range of temperature in exploitation, the awareness for environment preservation makes the vegetable oils the subject of an intense research [14], [15], [16], [17], [18].

Tests done on a four ball machine are easier to be compared and many tribologists have reported results obtained on this tribotester [19], [20], [21]. The four ball machine is easy for using to characterize lubricants and to rank them [22], for improving additivation [23], [24], [25], [26], [27], [28], for limiting carrying capacities [13], [22].

Zeng et al. [29] reported that good results on the four ball tester for the rapeseed oil: a wear scar diameter (WSD) of 0.66 mm under 396 N, for running 30 minutes at 1420 rpm and 0.56 mm after testing at 196 N, but adding additives, the tribological behavior of this vegetable oil improved.

Gu et al. [30] evaluated the tribological properties of rapeseed oil with an additive based on La-TiO2 and, based on four-ball tests, concluded that the anti-wear and friction-reducing capacities of this vegetable oil were improved.

At 1200 rpm, Cheenkachorn [31] obtained 0.360 mm for wear scar diameter when using conventional soybean oil, but for a load of 12.5 kg for 30 minutes of running.
Even if the four ball tester becomes more used for characterising the tribological behavior of lubricants, the test parameter combinations are so diverse that it is hard to perform a comparison as the test parameters are not the same or, at least, closer. Thus, the interpretation of data from literature has to be done carefully and the conclusions are sustainable for limited ranges of test parameters.

Due to improvement in analysing the texture and optical instruments for investigating the surface [32], [33], [34], [35], the authors propose to evaluate the lubricant performance by analysing the change in several 3D parameters.

The aim of this study is to make a comparison between a 2D profilometry analysis on the wear scars and an analysis of the homologous 3D parameters as obtained for the entire surface of the wear scars generated on the fixed balls of the four ball tribotester. The texture parameters were related to the other tribological parameters, namely, the average friction coefficient for the last 10 minutes of running and the wear volume calculated with the average values of the wear scar diameters. An efficient tribological behavior could not be the excellent value for only one parameter, but a set of parameters in acceptable ranges for a particular application.

2. Methodology and tested lubricants

The tested oils are: coarse degummed rapeseed oil (RBD), refined rapeseed oil (RR), coarse soybean oil (SB), coarse degummed soybean oil (SBD) and a non-additivated transmission oil - T90 for comparison reason. The vegetable oils are obtained by cold pressing and the content of fat acids is given in table 1 for coarse grades. One may notice the high content in non-saturated fat acids of these two vegetable oils, many specialists making a correlation between this content and the tribological and rheological behaviour of these oils [36], [37]. The degumming and refining process of the rapeseed oil and the degumming process for soybean oil is done at Prutul SA Galati and prevent oil to form gum deposit and to ferment [38].

The test method for investigating the lubricating capacity was EN ISO 20623:2003 Petroleum and related products - Determination of the extreme-pressure and anti-wear properties of fluids - four ball method [39]. The test balls are polished, made of chrome alloyed steel (table 2), having 12.7 ± 0.0005 mm in diameter, with 64-66 HRC hardness. The sample oil volume required for each test was 8 ml.

| Fat acid C14:0 | C16:0 | C16:1 | C17:0 | C18:0 | C18:1 | C18:2 | C18:3 | C20:0 | C20:1 | C22:0 |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Rapeseed oil  | 0.05  | 4.84  | 0.06  | 0.14  | 0.14  | 62.73 | 22.4  | 7.50  | 0.50  | 1.25  | 0.30  |
| Soybean oil   | 0.11  | 12.7  | 0.13  | 0.05  | 5.40  | 21.60 | 52.40 | 5.70  | 0.25  | 0.20  | 0.50  |

Table 1. Fat acid composition for the tested rapeseed oil, % [7].

| Element | C | Cr | Mn | Si | S | P |
|---------|---|----|----|----|---|---|
| Steel grade EN31 | 1.0 | 1.3 | 0.5 | 0.35 | 0.05 | 0.05 |

Table 2. Chemical composition of the steel the balls are made of (wt%).

The test parameters were: the normal load 200 N and the rotational speed of the main axe of the four ball machine 1500 rpm, corresponding to a sliding speed of 0.576 m/s and a test time of 60 minutes. Before starting a new test, four new balls and ball cup elements were cleaned with a solvent and wiped using an industrial fabric. The initial oil temperature was 20...23ºC.

Wear volume, \( V_{wear} \) was calculated as the volume of a calotte (see Figure 1):

\[
V_{wear} = \pi \cdot h^2 \left( R - \frac{h}{3} \right) = \pi \cdot R^2 \left[ 1 - \frac{1}{4} \left( \frac{D}{R} \right)^2 \right] \left[ 1 - \frac{1}{3} \left( 1 - \frac{D}{R} \right) \right] \]

(1)
where $R$ is the nominal radius of ball ($R = 6.35 \text{ mm}$), $D$ – wear scar diameter, calculated as the average of the six measurements (two on each ball, one along the sliding direction and one perpendicular to it), $h$ is calculated knowing the ball radius, $R$, and the wear scar diameter, $D$.

![Figure 1. Geometry for calculating the wear volume.](image)

For evaluating the surface texture, using the dedicated software SPIP [40], an ellipse having the same axes with the measured wear scar diameters was cut from an investigated area of 500 $\mu\text{m} \times 500$ $\mu\text{m}$, on each ball. All 3D measurements were done with a step of 5 $\mu\text{m}$. The distance between lines was also 5 $\mu\text{m}$. The 3D parameters are calculated for all the values $z(x,y)$, measured on the elliptic area. Values of 3D parameters are the average values obtained from the set of three fixed balls. For calculating 2D parameters there was selected a primary profile filtering with mean form removal [40].

3. Results and discussion

Studies [25], [41] suggested that free fatty acids can improve the boundary lubrication properties of vegetable oils. From table 1, one may notice that both tested oils have a high content in non-saturated fat acid and this could be a actual reason of good results.

A discussion about texture quality of the worn surfaces has to be related to other tribological parameters and the author take into account the following parameters:

- the friction coefficient as an average of the last 10 minutes of running;
- the wear volume, calculated with the average of the diameters obtained on the three fixed balls.

![Figure 2. The average value of the friction coefficient.](image) ![Figure 3. Average of wear volume.](image)

Analysing only these two tribological parameters, one may notice that soybean oil had the most favourable values for the wear volume and the friction coefficient was the lowest (for coarse oil) and the highest for the degummed coarse soybean oil, close to that obtained for the transmission oil.

Except the refined rapeseed oil, the other three grades of vegetable oils have the wear volume less than that obtained with T90 as lubricant, meaning that, at least for the tested regime (200 N and 0.576 m/s), these vegetable oils have a better tribological behaviour than T90.

Table 3 presents the results of evaluating the wear scar surfaces (left – 2D parameters, right – 3D parameters). The last right column gives the values of 3D parameters characterising the initial surface
of the balls. All values for the worn surfaces are obtained as average of the parameter on the each worn area of the tree fix balls. The worn areas are characterized by greater values of the analysed parameters as compared to those for the initial surface. Values for 2D parameters are calculated for the raw profile, using a average mean line. Values for 3D parameters are calculated for raw profiles, after a general levelling of the investigated surfaces (500 µm x 500 µm).

### Table 3. Values of 2D and 3D parameters for the tested oils.

| Line profile on wear scar, perpendicular to sliding direction | Wear scar area | Initial surface of the ball |
|---------------------------------------------------------------|----------------|----------------------------|
| Parameter | RBD | RR | SB | SBD | T90 | Unit | Parameter | RBD | RR | SB | SBD | T90 | Initial surface of the ball |
| Ra | 1.184 | 1.736 | 0.707 | 1.252 | 1.096 | µm | Sa | 1.1974 | 1.609 | 0.791 | 1.104 | 1.096 | 0.473 |
| Rq | 1.487 | 2.256 | 0.961 | 1.526 | 1.356 | µm | Sq | 1.5507 | 2.322 | 1.046 | 1.415 | 1.388 | 0.667 |
| Rsk | 0.311 | 0.500 | -0.114 | -0.473 | -0.004 | | Ssk | 0.6357 | 1.054 | 0.886 | -0.276 | 0.048 | 1.486 |
| Rku | 3.194 | 4.584 | 4.360 | 2.6953 | 2.872 | | Sku | 4.5022 | 7.092 | 5.767 | 3.563 | 3.271 | 8.213 |
| Ry | 8.344 | 15.18 | 6.359 | 7.315 | 7.417 | µm | Sy | 15.954 | 22.57 | 14.27 | 13.369 | 13.25 | 7.378 |
| Rv | 3.580 | 5.827 | 3.098 | 4.055 | 3.662 | µm | Sv | 5.8664 | 7.614 | 5.810 | 6.638 | 6.029 | 2.213 |
| Rp | 4.763 | 9.352 | 3.261 | 3.259 | 3.754 | µm | Sp | 10.087 | 14.956 | 8.467 | 6.730 | 7.224 | 5.164 |
| Rpk | 2.599 | 4.510 | 2.012 | 1.430 | 1.724 | µm | Spk | 2.3641 | 4.275 | 1.879 | 1.560 | 1.677 | 1.367 |
| Rk | 3.396 | 5.082 | 1.858 | 3.513 | 3.479 | µm | Sk | 3.593 | 4.691 | 2.376 | 3.248 | 3.451 | 1.021 |
| Rvk | 1.042 | 1.902 | 1.258 | 1.811 | 1.017 | µm | Sv | 1.2589 | 1.614 | 0.734 | 1.674 | 1.287 | 0.558 |

All oils have the surface texture rougher than the initial one of the balls. Analyzing the values for both 2D and 3D parameters, the refined rapeseed oil used as lubricant generated the worst worn surface as all parameters are the highest (except Rsk or Sku). When using the grades of soybean oil (coarse and degummed coarse) and T90, the surfaces of the wear scars exhibit the lowest values and in a narrow range.

2D parameters that are clearly lower than the 3D ones are: Rku, Ry, Rp and Rv (figure 4c, d, e and f).

In tribology studies, the extreme values of the surface texture are important as they could cause the film failure and direct contact with the mating surface. Analysing Sy (see figure 4d), this have the greater value for refined rapeseed oil (22.57 µm), for the other tested oils this values being around 13...14 microns.

Except the refined rapeseed oil, the others tested oils have only a slight increase of Spk as compared to the initial (non-worn) surface, but the core of the texture, expressed by Sk, increased more than two times, the greatest value being obtained by the refined rapeseed oil.

The film generation presumes the two surfaces are completely separated. For these oils the values of the friction coefficient, the images of the wear scars and even the values of the texture parameters are arguments in the favor of a combined regime, mixt and boundary lubrication.
Analyzing figure 4a, the value of Ra oscillates up or down as compared to the value Sa calculated for the entire area of the wear scar with a percentage less than 10%.

The comparison between Rsk and Ssk is not relevant (figure 4b), reflecting only the very different appearance of the worn surface as compared to the other worn surfaces (figure 6). As the surfaces are not uniformly worn, the line profile could give information only for the analysed line and not for the entire worn area.

Sku, Sy and Sv and Sp (please, take into account that Sy = Sv + Sp) are greater than those measured on the profile perpendicular to the sliding direction (figure 4c, d, e and f). The parameter Sy is very important in maintaining an oil film on the sliding surfaces, higher values meaning that the
fluid film could be interrupted, lowering the film parameter $\lambda$ [42], even in only a point, the direct contact among asperities making to increase the friction coefficient and the wear.

![Figure 6](image)

**Figure 6.** Typical virtual images of the wear scars after lubricating the four ball tester; the profile for 2D analysis is also drawn: (a) coarse degummed rapeseed oil (RBD); (b) refined rapeseed oil (RR); (c) coarse soybean oil (SB); (d) coarse degummed soybean oil (SBD); (e) transmission oil (T90)

Virtual images may point out interesting processes obtained on the balls. For instance, for the coarse degummed soybean oil, the wear scar area have two distinct zone: a central surface with less wear as the aspect of this zone is resembling to the initial surface of the ball and two lateral zones where abrasive wear is evident and the asperities are re-shaped by a direct contact between balls. The other balls exhibit a more uniform appearance meaning the mixt or boundary lubrication is generated all over the contact zone.

Generally, the value of the same parameter is greater for the 3D evaluation as compared to the value obtained from a 2D one and the scattering range is smaller for the 3D method as compared to that resulted from the 2D one. Lower values of the amplitude and functional parameters (especially $S_y$ and $S_p$, but also for $S_a$ and $S_{pk}$) point out that lubricant is capable of protecting the balls either by film generation or by maintaining a boundary lubrication (see figure 4 and figure 5).

Even the virtual images obtained by reconstruction after profilometric investigation may point out characteristic of the wear scar that is not revealed by values of the texture parameters. For instance, comparing images for degummed soybean oil (figure 6d) to that in Figure 6a for degummed rapeseed oil, one may notice the relatively uniform abrasive marks on the balls tested with degummed rapeseed oil and the wear scars with two very different regions, as obtained after testing with degummed soybean oil.
4. Conclusions
The tested oil involved in this study may be grouped in two classes, at least for the test parameters involved in this study:
- lubricants that increase very much the amplitude and functional parameters (the rapeseed oil grades, refined and coarse degummed),
- lubricants that give a better quality of the worn surfaces, with less increase in the analysed parameters (the two grades of soybean oil, coarse and coarse degummed).

This grouping is sustained by both parameters, 2D and 3D, but values are different from those obtained by a 3D analysis on the entire wear scar.

As the recent designed instruments, like that used in this analysis (profilometer Laser NANOFOCUS μSCAN), are more performant, an analysis on the entire wear scars on the balls from the four ball tester are more suitable to characterize the surface quality after tests and to rank the lubricant capacity of an oil depending on a set of parameters, including amplitude parameters, spatial parameters and functional ones.

Texture parameters could be included into two groups:
- less sensitive to the type of analysis (2D or 3D), like Ra (and Sa), Rpk (and Spk), Rk (and Sk),
- with higher sensitivity to the type of analysis: Rvk, Ry, Rv, Rp, Rsk and Rku.

This conclusion has to be related only to the experiments the authors have done and included in this study.

As far as the authors know from the available specialized literature, it is for the first time that all the surface or the wear scar generated on the four ball machine is investigated and the conclusion is that from the tribological point of view, the 3D parameters reflect better the surface quality evolution after testing.

5. References
[1] Gebig F A, Helman B, Gebig Y and Haefke H 2002 A comparative study of the tribological properties of vegetable oils Proceedings of 2nd World Tribology Congress 2002 paper A-21-08-159
[2] Honary L and Richter E 2011 Biobased Lubricants and Greases: Technology and Products (Chichester: John Wiley & Sons Ltd)
[3] Luna F M T, Rocha B S, Rola Jr E M, Albuquerque M C G, Azevedo D C S and Cavalcante Jr C L 2011 Assessment of biodegradability and oxidation stability of mineral, vegetable and synthetic oil samples Industrial Crops and Products 33 pp 579–583
[4] Murilo F T L, Rocha B S, Rola Jr E M, Albuquerque M C G, Azevedo D C S and Cavalcante Jr C L 2011 Assessment of biodegradability and oxidation stability of mineral, vegetable and synthetic oil samples Industrial Crops and Products 33 pp 579–583
[5] Nagendramma P and Kaul S 2012 Development of ecofriendly/biodegradable lubricants: An overview Renewable and Sustainable Energy Reviews 16 pp 764–774
[6] Esteban B, Riba J R, Baquero G, Rius A and Puig R 2012 Temperature dependence and viscosity of vegetable oils Biomass and Bioenergy 42 pp 164-171
[7] Solea L C 2013 Contributions in studying the rheological and tribological behavior of biodegradable lubricants with vegetable oils as stock base oil - PhD thesis (Galati: “Dunarea de Jos” University)
[8] Yilmaz N 2011 Temperature-dependent viscosity correlations of vegetable oils and biofuel-diesel mixtures Biomass and Bioenergy 35 pp 2936-2938
[9] Castro W, Perez J M, Erhan S Z and Caputo F 2006 A Study of the Oxidation and Wear Properties of Vegetable Oils: Soybean Oil Without Additives Journal of the American Oil Chemists’ Society 83 pp 47-52
[10] Erhan S Z, Sharma B K and Perez J M 2006 Oxidation and low temperature stability of vegetable oil-based lubricants Industrial Crops and Products 24 pp 292–299
[11] Fox N J and Stachowiak G W 2007 Vegetable oil-based lubricants – A review of oxidation
Liu Z, Sharma B K, Erhan S Z, Bijwas A, Wang R and Schuman T P 2015 Oxidation and low temperature stability of polymerized soybean oil-based lubricants *Thermochimica Acta* **601** pp 9–16

Wang R and Schuman T P 2015 Oxidation and low temperature stability of polymerized soybean oil-based lubricants *Thermochimica Acta* **601** pp 9–16

Adhvaryu A, Erhan S Z and Perez J M 2004 Tribological studies of thermally and chemically modified vegetable oils for use as environmentally friendly lubricants Wear **257** pp 359–367

Biresaw G and Bantchev G B 2013 Pressure Viscosity Coefficient of Vegetable oils *Tribology Letters* **49** pp 501-512

Campanella A, Rustoy E, Baldessari A and Baltunas M 2010 Lubricants from chemically modified vegetable oils *Bioresource Technology* **101** pp 245-254

Erhan S Z 2005 *Industrial Uses of Vegetable Oils* (Champaign: AOCS Press)

Ing A 2009 Biobased Lubricants: A Viability Study *Proceedings of the 53rd Annual Meeting of the International Society for the Systems Sciences*

Georgescu C 2015 *Using the vegetable oils to obtain ecological lubricants - postdoctorale report* (Galati: Dunarea de Jos University)

Shahabuddin M, Masjuki H H, Kalam M A, Bhuiya M M K and Mehat H 2013 Comparative tribological investigation of bio-lubricant formulated from a non-edible oil source (Jatropha oil) *Industrial Crops and Products* **47** pp 323–330

Syahrrulal S, Ani F H and Golshkouh I 2013 Wear Resistance Characteristic of Vegetable Oil *The 2nd International Conference on Sustainable Materials Engineering* pp 44-47

Spanu C, Ripa M, Stefanescu I and Deleanu L 2007 A comparison of standardized methods for lubrication failure determination *The Annals of “Dunarea de Jos” University of Galati Fascicle VIII Tribology* **XIII** pp 99-103

Ji X, Chen Y, Wang X and Liu W 2012 Tribological behaviors of novel tri(hydroxymethyl)propene esters containing boron and nitrogen as lubricant additives in rapeseed oil *Industrial Lubrication and Tribology* **64** pp 315–320

Kumar Dubey M, Bijwe J and Ramakumar S S V 2015 Nano-PTFE: New entrant as a very promising EP additive *Tribology International* **87** pp 121–131

Minami I and Mitsumune S 2002 Antiwear, Properties of Phosphorous-Containing Compounds in Vegetable Oils *Tribology Letters* **13** pp 95-101

Quinchia L A, Delgado M A, Valencia C, Franco J M and Gallegos C 2010 Viscosity modification of different vegetable oils with EVA copolymer for lubricant applications *Industrial Crops and Products* **32** pp 607–612

Rico E F, Minondo I and Cuervo D G 2007 The effectiveness of PTFE nanoparticle powder as an EP additive to mineral base oils *Wear* **262** pp 1399–1406

Xianga L, Gaoa C, Wanga Y, Pana Z and Hu D 2014 Tribological and tribochemical properties of magnetite nanoflakes as additives in oil lubricants *Particuology* **17** pp 136–144

Zeng X, Li J, Wu X, Ren T and Liu W 2007 The tribological behaviors of hydroxyl-containing dithiocarbamate-triazine derivatives as additives in rapeseed oil *Tribology International* **40** pp 560–566

Gu K, Chen B and Chen Y 2013 Preparation and tribological properties of lanthanum-doped TiO2 nanoparticles in rapeseed oil *Journal of Rare Earths* **31** pp 589–594

Cheenkachorn K 2013 A Study of Wear Properties of Different Soybean Oils *Energy Procedia* **42** pp 633–639

Blateyron F 2001 3D Parameters and New Filtration Techniques available on: www.digitalsurf.fr/pressreleases/2008-06-umm-prize.pdf

McCormick H and Kwame Duho K A Brief History of the Development of 2-D Surface Finish Characterization and More Recent Developments in 3-D Surface Finish Characterization http://www.c-kengineering.com/images/pdf/product/surface%20finish/see%203di/3-
D%20Surface%20Measurement.pdf

[34] Muralikrishnan B and Raja J 2009 *Computational Surface and Roundness Metrology* (London: Springer-Verlag)

[35] Smith G T 2002 *Industrial Metrology: Surfaces and Roundness* (London: Springer Verlag)

[36] Kim J, Kim D N, Lee S H, Yo S H and Lee S 2010 Correlation of fatty acid composition of vegetable oils with rheological behavior and oil uptake *Food Chemistry* 118 pp 398-402

[37] Ting C and Chen C 2011 Viscosity and working efficiency analysis of soybean oil based bio-lubricants *Measurement* 44 pp 1337–1341

[38] Deffense E M J 2009 From organic chemistry to fat and oil chemistry *Oléagineux Corps Gras Lipides/OCL* 16 pp 14-24

[39] *** SR EN ISO 20623:2004 Petroleum and related products - Determination of the extreme-pressure and anti-wear properties of fluids - four ball method (European conditions)

[40] *** SPIP *The Scanning Probe Image Processor SPIP™, Version 6.5 2015* available on: http://www.imaginet.com/WebHelp/spip.htm

[41] Fox N J, Tyrer B and Stachowiak G W 2004 Boundary Lubrication Performance of Free Fatty Acids in Sunflower Oil *Tribology Letters* 16 pp 275-281

[42] Olaru D 2002 *Fundamentals of Lubrication* (Iaşi: Gh. Asachi)