Evaluating lubricating capacity of vegetal oils using Abbott-Firestone curve

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Abstract. The paper presents the change of functional parameters defined on the Abbott-Firestone curve in order to evaluate the surface quality of the balls from the four ball tester, after tests done with several vegetable oils. The tests were done using two grades of rapeseed oil (degummed and refined) and two grades of soybean oil (coarse and degummed) and a common transmission oil (T90). Test parameters were 200 N and 0.576 m/s (1500 rpm) for 60 minutes. For the refined rapeseed oil, the changes in shape of the Abbott-Firestone curves are more dramatic, these being characterized by high values of $Spk$ (the average value for the wear scars on the three balls), thus being 40% of the sum $Svk + Sk + Spk$, percentage also obtained for the soybean oil, but the value $Spk$ being lower. For the degummed soybean oil, the profile height of the wear scars are taller than those obtained after testing the coarse soybean oil, meaning that the degumming process has a negative influence on the worn surface quality and the lubricating capacity of this oil. Comparing the surface quality of the wear scars on fixed tested balls is a reliable method to point out the lubricant properties of the vegetable oils, especially if they are compared to a “classical” lubricant as a non-additivated transmission mineral oil T90. The best surface after testing was obtained for the soybean oil, followed by T90 oil and the degummed grades of the soybean oil and rapeseed oil (these three giving very close values for the functional parameters), but the refined rapeseed oil generated the poorest quality of the wear scars on the balls, under the same testing conditions.

Introduction
Since 1933, when Abbott and Firestone had defined the ‘bearing area curve’, this has been a useful instrument to evaluate not only the surface texture, but also the changes in surface quality as the shape and parameters related to this curve reflect the modifications in the superficial layer consistency.

The curve has been used to quantify the surface quality in metal cutting and finishing processes [1], [2], [3] (especially for engine cylinders, segments and bearings), in medicine (mainly for femoral stem wear [4] and dentistry [5]) and tribological systems [6]. More recently, it has been used to describe teeth surfaces and worn surfaces (regardless the type of wear, adhesive, abrasive, erosion etc.) [7].

The bearing curve represents the material distribution related to the profile height. Initially, this distribution had a 2D interpretation: the cumulative distribution of the lengths of individual plateaux, normalised by the total assessment length of the investigated profile. Now, due to performant equipment to record the surface texture, the curve is related to a 3D interpretation of the material distribution on the texture height [8], [9].
Even the authors, in previous works [10] have been suggested that the bearing curve would describe better the initial and worn surfaces than Ra, a conclusion also sustained by Torrance [11]. A process (tribological or technological) may remove the peaks, thus, a different texture may be superimposed on the resulting plateaux; the deep valleys may remain or not unaffected, influencing, for instance, the lubricating capability of the surfaces in contact.

The bearing curve could measure the influence of a synergic process, like the tribological ones, when different types of wearing are overlapping. Studying this curve during the triboelements exploitation may offer information on the tendency of the surface changing in the immediate future.

2D studies of the bearing area curve were done by Sosa et al. [12] for studying the texture quality of gear tooth. In another paper, Sosa et al. [13] pointed out the differences in the peak zone (0...30%) of the 2D Abbott-Firestone curves after investigating the running-in process of the tooth, concluding that the valleys seem to remain unchanged while the asperity peaks are worn off.

Affatato et al. [4] characterized the worn surface by comparing Abbott-Firestone curves for unaffected and affected zone of the femoral head made of advanced ceramics.

In 2015, Franco and Sinatona [14] proposed a correlation between Skq and the volume Vmp (material volume in the hill zone), discussing that it is not correct to designate Skq as the average height of the protruding peaks above the core surface, as stated in the standard ISO 25178-2:2012 and Sk should be maintained, but that the new volume parameters, through their relationship to the “k series”, make it possible to discard Skq and Svk. Skq does not reflect isolated maximum heights of the texture, but this zone of the Abbott-Firestone curve is affecting the tribological behavior.

Stoica et al. [15] presented an interesting study on surfaces of some polyimides, after being rubbed against a cotton velvet and a velvet of cellulose diacetate, using Abbott-Firestone curves and the 3D functional parameters calculated from Abbott–Firestone curves for pointing out the improvements in surface adhesion after rubbing.

Vehmeyer et al. [3] used Abbott-Firestone curves to compare processed surfaces to virtually generated ones and to get optimal feed speed and width of cut of metallic elements.

In a consisting review of the commonly used in vitro methods for measuring surface loss and surface change of teeth, after analysing 69 papers, Field et al. [5] reported that no single technique provides a comprehensive assessment of the remaining tooth surface and each technique has peculiar limitations. Despite a variety of in vitro tests for measuring surface changes, the roughness average (Ra) is still the main reported parameter in dentistry studies. The authors of this review proposed to report bearing area parameters as they will allow for a more useful description of the tooth surface quality.

This paper presents the change of functional parameters defined on the Abbott-Firestone curve in order to evaluate the surface quality of the balls from the four ball tester, after tests done with several vegetable oils.

**Testing Methodology**

The tests were done using two grades of rapeseed oil (degummed and refined) and two grades of soybean oil (coarse and degummed) and a common transmission oil (T90). Degumming and refining processes are done at the firm “Prutul” in Galati, Romania. Tests were done under a load of 200 N and a sliding speed of 0.576 m/s (1500 rpm), for 60 minutes.

The balls, as delivered by SKF, are lime polished, made of chrome alloyed steel balls (steel grade EN31), having 12.7 ± 0.0005 mm in diameter, with 64-66 HRC hardness.

The sample oil volume required for each test was 8 ml ± 1 ml.

The test method used to investigate wear preventive characteristic was that presented in EN ISO 20623:2003 Petroleum and related products. Determination of the extreme-pressure and anti-wear properties of fluids - four ball method.

The surface investigations were done with the help of the profilometer Laser NANOFOCUS μSCAN from "Stefan cel Mare" University of Suceava, with an access zone of 150 mm × 200 mm,
vertical range of 1.00 µm to 18 mm and a vertical resolution of 25 nm. The measuring step was 5 µm and the distance between lines was also set at 5 µm. The parameters were calculated for raw profiles.

**Results and comments**
Figure 1 presents the significance of functional parameters, discussed for evaluating the surface quality of the wear scars. Functional parameters are calculated according to SPIP roughness parameters [16].

The horizontal lines in figure 1b are drawn for bearing area percentage of 5% and 80%, respectively.

![Diagram showing functional parameters](image)

(a) calculation of the reduced summit height ($Spk$), the core roughness depth ($Sk$) and the reduced valley depth ($Svc$)

![Diagram showing Abbott-Firestone curve](image)

(b) calculation of surface bearing index ($Sbi$), core retention index ($Sci$) and valley fluid retention index ($Svi$)

**Figure 1.** Functional parameters on Abbott-Firestone curve [16].

Figures 2 to 6 present typical Abbott-Firestone curves obtained for the entire area of the wear scars for a tested oil, an original method proposed by the authors, allowing for studying the entire surface of the wear scar. Other studies present only analysis on samples of surface texture, this asking for a statistical approach of the texture quality, including the probability of avoiding high isolated peaks.

Using the bearing area curve, the following parameters may be analyzed. The surface bearing index, $Sbi$, is defined as

$$Sbi = \frac{Sq}{Z_{0.05}}$$

where $Z_{0.05}$ is the height from the top of the investigated surface (the top of Abbott-Firestone curve) to the line marking 5% of the bearing area. For a Gaussian height distribution, $Sbi$ approaches 0.60. Large values indicate good bearing properties. Analyzing the values of this parameter from Table 1,
one may notice that the values are in the range 0.167...0.310, the greater value being obtained for the degummed coarse soybean oil.

The core retention index, $Sci$, is calculated as:

$$Sci = \frac{V_h(h_{0.05}) - V_h(h_{0.80})}{(M-1)(N-1)\delta x \cdot \delta y} \cdot \frac{1}{S_q}$$  \tag{2}

where $V_h(h_{0.05})$ is the area on Abbott-Firestone curve representing the void volume over the bearing area from 0 to $h_{0.05}$ and similarly, $V_h(h_{0.80})$ is the area representing the void volume till $h_{0.80}$. For a Gaussian height distribution $Sci$ approaches 1.56. Large values of $Sci$ indicate that the void volume in the core zone is large and this is not recommended because sharp asperities will be broken under higher loads. The values of this parameter (1.567...1.75 for the wear scars - see table 1) are around the value for Gaussian surfaces that are characteristic for turned surfaces, but also for surfaces bearing an abrasive wearing process, as it happens when the contact has a boundary or mixt lubrication (abrasive traces are evident on the wear scars in figure 6).

The valley fluid retention index, $Svi$, is defined as:

$$Svi = \frac{V_h(h_{0.80})}{(M-1)(N-1)\delta x \cdot \delta y} \cdot \frac{1}{S_q}$$  \tag{3}

For a Gaussian height distribution $Svi$ approaches 0.11. Large values of $Svi$ indicate large void volumes in the valley zone. In relations (2) and (3), $M$ and $N$ are the number of investigated lines and the number of points on a line, respectively. As $Svi$ for the initial surface is small (0.089), higher values mean that abrasive wear takes places over the entire height of the surface texture.

![Figure 2](image1.png)

**Figure 2.** Typical Abbott-Firestone curves obtained for the entire area of the wear scars when using coarse degummed rapeseed oil as lubricant.

![Figure 3](image2.png)

**Figure 3.** Typical Abbott-Firestone curves obtained for the entire area of the wear scars when using refined rapeseed oil as lubricant.

For the refined rapeseed oil (figure 3), the Abbott-Firestone curves reveal a dramatic change in the range of 0...10% of the material ratio, especially for the $Spk$ zone, meaning that there are high and rare peaks that increase the risk of direct contact and to scratch the mating surface. In addition, the shapes
of the curve are quite different for each ball, meaning that the wear process is not uniform, probably due to the lower lubricating capacity of this oil.

Figure 4. Typical Abbott-Firestone curves obtained for the entire area of the wear scars when using coarse soybean oil as lubricant.

Figure 5. Typical Abbott-Firestone curves obtained for the entire area of the wear scars when using degummed soybean oil as lubricant.

Figure 6. Typical Abbott-Firestone curves (up) and virtual images of the worn surfaces (down) obtained for the entire area of the wear scars when using non-additivated transmission oil T90 as lubricant.
The value of the ratio \( \frac{Spk + Sk + Sv k}{St} \) gives a measure of the sharpness of the top of the Abbott-Firestone curve (\( St \) is the height difference between the highest and the lowest point of the investigated zone). For higher values of this ratio, the surface has very high rare peaks that give the risk of the direct contact between surfaces. The smallest value for this ratio was obtained for the coarse soybean oil, thus, this vegetable lubricant has a better tribological behavior at least from the point of view of the quality of the worn scars.

### Table 1. Values as average calculated for the wear scars on the three fixed balls from a test.

| Oil                                | Code | \( Sa \) (\( \mu m \)) | \( \frac{Spk + Sk + Sv k}{St} \) | Hybrid parameters |
|------------------------------------|------|------------------------|---------------------------------|-------------------|
| Non-additivated transmission oil   | T90  | 1.09                   | 0.4841                          | 0.281 1.567 0.115 |
| Coarse soybean oil                | SB   | 0.79                   | 0.349                           | 0.167 1.75 0.089  |
| Degummed coarse soybean oil       | SBD  | 1.10                   | 0.4851                          | 0.310 1.429 0.135 |
| Degummed coarse rapeseed oil      | RBD  | 1.21                   | 0.483                           | 0.263 1.673 0.104 |
| Refined rapeseed oil              | RR   | 1.06                   | 0.468                           | 0.198 1.601 0.09  |
| Unworn ball (initial surface)     | -    | 0.43                   | 0.398                           | 0.171 1.915 0.089 |

The increase of \( Sbi \) as compared to the value of the initial surface may suggest that only the top of the very high peaks are cut, thus improving the bearing properties of the superficial layer.

*Figure 7. Average values and spread ranges of the functional parameters.*
Figure 7 presents not only the average values of the functional parameters Spk, Sk and Svk, but also their spread ranges.

For all tested oils, Svk is higher than the value of the unworn surface of the ball (0.558 µm), increasing the capability of having more lubricant on the surface.

![Figure 7](image)

Figure 8. The sum of the functional parameters Spk + Sk + Svk.

Figure 8 makes the authors to pay attention that the height of the surface texture of the wear scars increased more than double the initial values of the balls for all the tested oils, the lowest value being obtained for the soybean oil and the highest for the refined rapeseed oil. For the other three tested oils (T90, degummed soybean oil and coarse degummed rapeseed oil), the sum was in a very narrow range. A small value of this sum correlated with small values for Spk means a better lubricating capability, but high values of this sum correlated with high value for Skp characterize a poorer lubricating capability. The values represented in figure 8 are the average values obtained for the three wear scars on the fixed balls of the tribotester.

**Conclusions**

The authors evaluated the lubricating capability of several vegetable oils in comparison to a non-additivated transmission oil T90 by the quality of surfaces of the worn scars generated on the four ball tribotester. As far as the authors search the literature, no study of the surface topography was reported for the entire surface of the wear scars produced on the balls.

Analyzing the Abbott-Firestone curves, the authors formulated the following conclusions.

Even if the Spk parameter does not reflect the shape of the Abbott-Firestone curves for the first 5% of the bearing ratio, for the tested oils, its magnitude, but also its percentage from the sum Spk+Sk+Svk, help the engineer to rank the oils. Based on this criterion (the lowest sum and lowest value for Spk), the best oil among the tested ones would be the coarse soybean oil. The degummed rapeseed oil, the degummed soybean oil and the non-additivated T90 generate a texture quality in narrow ranges for the functional parameters, the worst behavior being attributed to the refined rapeseed oil.

For the refined rapeseed oil, the changes in shape of the bearing curves are more dramatic, these being characterized by high values of Spk, its values being 40% of the sum Svk + Sk + Spk, value also obtained for the soybean oil, but the value Spk being lower.
For the degummed soybean oil, the profile heights of the wear scars are taller than those obtained after testing the coarse soybean oil, meaning that the degumming process has a negative influence on the worn surface quality.

Comparing the surface quality of the tested balls is a new reliable method to point out the lubricant properties of the vegetable oils, especially if they are compared to a “classical” lubricant as the non-additivated transmission mineral oil. The best surface after testing was obtained for the course soybean oil, followed by T90 and the degummed grades of the soybean oil and rapeseed oil (these three giving very close values for the functional parameters), but the refined rapeseed oil generated the poorest quality of the balls, under the same testing conditions.

References
[1] Lipa Z and Tomanícková D 2011 Utilisation of abbott-firestone curves characteristics for the determination of turned surface properties Annals of Faculty of Engineering Hunedoara - International Journal of Engineering IX (3) 223-226
[2] Corral I B, Calvet J V and Salcedo C M 2010 Use of roughness probability parameters to quantify the material removed in plateau-honing Int J Mach Tool Manuf 50 621–629
[3] Vehmeyer J, Piotrowska-Kurczewski I, Bohmermann F, Riemer O and Maß P 2015 Least-squares based parameter identification for a function-related surface optimisation in micro ball-end milling Procedia CIRP 31 276-281
[4] Affatato S, Ruggiero A, De Mattia J S and Taddei P 2016 Does metal transfer affect the tribological behaviour of femoral heads? Roughness and phase transformation analyses on retrieved zirconia and Biolox ®Delta composites Compos Part B-Eng 92 290-298
[5] Field J, Waterhouse P and German M 2010 Quantifying and qualifying surface changes on dental hard tissues in vitro J Dent 38 182–190
[6] Moshkovich A, Perfiliev V, Lapsker I and Rapoport L 2014 Friction, wear and plastic deformation of Cu and a/ß brass under lubrication conditions Wear 320 34–40
[7] Las Casas E B, Bastos F S, Godoy G C D and Buono V T L 2008 Enamel wear and surface roughness characterization using 3D profilometry Tribol Int 41 1232–36
[8] Stout K J and Blunt L 1994 Three-Dimensional Surface Topography (London: Penton Press)
[9] Dong W P, Sullivan P J and Stout K J 1993 Comprehensive study of parameters for characterising three-dimensional surface topography II: Statistical properties of parameters variation Wear 167 9-21
[10] Tomescu L, Ripa M and Georgescu C 2001 Analyzing abbott curve for composites with polymeric matrix and fibbers Tribology in Industry 23 65-71
[11] Torrance A A 1997 A simple datum for measurement of the Abbott of a profile and its first derivative Tribol Int 30 239-244
[12] Sosa M, Björklund S, Sellgren U and Olofsson U 2015 In situ surface characterization of running-in of involute gears Wear 340-341 41–46
[13] Sosa M, Sellgren U, Björklund S and Olofsson U 2016 In situ running-in analysis of ground gears Wear 352-353 122–129
[14] Franco L A and Sinatoria A 2015 3D surface parameters (ISO 25178-2): Actual meaning of Spk and its relationship to Vmp Precis Eng 40 106–111
[15] Stoica I, Barzic A I and Hulubei C 2013 The impact of rubbing fabric type on surface roughness and tribological properties of some semi-alicyclic polyimides evaluated from atomic force measurements Appl Surf Sci 268 442–449
[16] The Scanning Probe Image Processor SPIP™ Roughness parameters 2016 available at http://www.imagetec.com/WebHelp6/Default.htm#RoughnessParameters/Roughness_Parameters.htm#kanchor778 (6.02.2016)