TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

ACTA TECHNICA NAPOCENSIS

Series: Applied Mathematics, Mechanics, and Engineering
Vol. 67, Issue Special IV, August, 2024

STRIBECK CURVE FOR LUBRICANTS BASED ON RAPESEED OIL

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Abstract: This paper presents a discussion on tribological behavior of rapeseed oil, additivated or not, taking into account the Stribeck organization of information. Tests were carried out on a four-ball machine. The following parameters were analyzed: friction coefficient, average diameter of wear scars on the three fixed balls and lubricant temperature at the end of the test. Test parameters were: the normal load on main shaft of the four-ball machine from 100 N to 300 N, and the rotational speed of the main shaft (600 rpm to 2200 rpm, corresponding to a sliding velocity of 0.23 m/s to 0.84 m/s, respectively). There were plotted Stribeck curves based of Stribeck parameter (depending on velocity, lubricant viscosity and applied load). Lubrication regimes could be easily identified on these curves and, based on this information, recommendations for using rapeseed oil, additivated or not, could be formulated.

Key words: *rapeseed oil; friction coefficient; Stribeck parameter; four-ball test; wear scar diameter; hexagonal Boron nitride (h-BN), graphene*

1. INTRODUCTION

In a very recent paper, intitled “Twelve Principles of Green Tribology” [1], tribology is recognized as supporting sustainability due to its interconnectivity among many fields of activities. The authors underline that this science allows for diminishing and attenuating crises related to environmental, economic and social issues, using similar strategies. The second principle is related to reducing wear, very important in increasing durability and sustainability of the systems. Also, the economy should use the good results obtained by introducing nano-additives in bio-lubricants.

The Stribeck curve was named after its initiator, a German engineer, Richard Stribeck, which, in 1902, had described the friction coefficient in lubricated sliding bearings as a function of a parameter including normal load, lubricant viscosity and velocity [2].

Reviewing the recent literature, the Stribeck curve was plotted for

- different geometry of the tribotesters (including radial sliding bearings, pin-on-disk, ball-on-disk [3], block-on-ring and very few for four-ball machine [4]),
- different lubricants, including water [5], mineral and synthetic oils and greases; for vegetal oil only few research papers are published; also, this curve was plotted for dry contact with third body friction,
- different temperatures of lubricant or environment.

Blau J. P. [6] explained the lubricating regimes pointed out by Stribeck curve using values of friction coefficient, μ, at high pressures in contact; when lubricants have very low viscosity, and/or speed is very low, solid surfaces may touch, even locally, leading to high friction coefficients, typically $\mu > 0.5$. The plateau at the left of the curve in Figure 1 represents the boundary lubrication regime, in which friction is lower than that for unlubricated sliding contact. The drop-off in friction is characteristic for the mixed regime that refers to a combination of ”dry” regime (direct contact between solid bodies) with hydrodynamic or elastohydrodynamic lubrication. Beyond the minimum in the curve, hydrodynamic and elastohydrodynamic lubrication regimes are said to occur. Typical friction coefficients for various types of rolling bearings range between 0.0010 and 0.0018 and an order of 10^{-2} for sliding contacts.

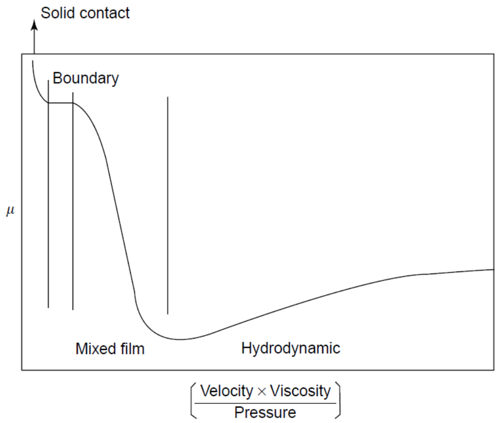


Figure 1. Typical Stribeck curve for a lubricated system [6]

Friction coefficient could be also plotted against Sommerfeld number, S, for a particular sliding bearing having the length L, the diameter D and the radial clearance C (bore radius minus bearing shaft radius):

$$S = \frac{\eta \cdot N \cdot L \cdot D}{F} \left(\frac{R}{C}\right)^2 \tag{1}$$

where F is the radial load on the bearing, η is the dynamic viscosity of the lubricant, and R is the radius of the bearing bore.

Another parameter that influences the shape of Stribeck curve is the specific film thickness or lambda ratio, usually noted with symbol λ, defined as the ratio of the minimum film thickness in contact (h) to a composed root-mean-square surface roughness, $\sigma(Rq)^*$ or $\sigma(Sq)^*$, Rq being the root-mean-square for a 2D profile and Sq being the same parameter, but calculated for an investigated surface

$$\lambda = \frac{h}{\sigma(Rq)^*} \tag{2}$$

where

$$\sigma(Rq)^* = \sqrt{\sigma(Rq)_1^2 + \sigma(Rq)_2^2} \tag{3}$$

or

$$\sigma(Sq)^* = \sqrt{\sigma(Sq)_1^2 + \sigma(Sq)_2^2} \tag{4}$$

where $\sigma(Rq)_1$ and $\sigma(Rq)_2$ are the 2D root-mean-square roughness of surfaces 1 and 2, respectively. $\sigma(Sq)_1$ and $\sigma(Sq)_2$ are values for the same parameter, but measured for both surfaces in contact. As values for $\sigma(Rq)^*$ and $\sigma(Sq)^*$ are different for the same surface, λ will be also different. Discussion of this parameter is frequently given for 2D roughness, but initiation of a discussion for λ calculated with 3D parameters is given in [7]. These values are usually measured for the non-worn surfaces, but, during the system functioning, these roughness parameters are modified and the point on the Stribeck curve could migrate.

σ^* is not simply the average roughness parameters of both surfaces, but rather involves the sum of both values, since the surfaces are contacting each other. For the boundary regime, when using Rq_1 and Rq_2, $\lambda << 1$ and for the mixed regime, $1 < \lambda < 3$. For the hydrodynamic regime, $\lambda >> 6$, and for the elastohydrodynamic regime, $3 < \lambda < 10$. It is possible to alter the shape of Stribeck curve for a bearing by changing the surface finish and the film thickness. The determination of λ requires both surface roughness data and film thickness data, the first being relatively easy to obtain from profile measuring instruments [6].

Data for evaluating the lambda ratio for the 3D roughness parameters are very few, but it could be more relevant because Sq_1 and Sq_2 could be obtained for all contacting surfaces. The λ values obtained with $\sigma(Sq)^*$ for limiting the lubrication regimes are different from those recommended for calculation with 2D roughness parameters, generally lower than those for homologous 3D parameters [7].

The estimation of film thickness is not straightforward when the bearing situation does not allow a constant film thickness to develop. Modification in the functioning regime (in velocity or/and load) can cause the characteristic point to move up or down on Stribeck curve.

Rudge E. D. et al. [3] demonstrate how different could be Stribeck curves and the sliding regimes in tests with different ball-on-disk testers (stationary rotating ball on three plates, stationary linearly sliding, reciprocating motion and rotating ball on rotating plate). In boundary regime, the friction coefficient evolutions are different as values and shape, being strongly influenced by the design of triboelements, but, in the mixed regime, there are only minor differences. The Stribeck curve and minimum film height were sensitive to the design parameters and surface roughnesses of both surfaces in contact (for instance, reflected by *Sq* parameter), the load and the material characteristics (especially elastic modulus and hardness).

Trzepieciński T. [8] reported results of using vegetal oils (neat or with boric acid as additive) in a laboratory stand replicating the cold rolling mill process of steel sheet. All tested vegetal oils (corn oil, rapeseed oil, palm oil, linseed oil, olive oil and soybean oil) with additive were effective in lowering the friction coefficient.

The additivation of vegetal oils is still in the focus of researchers, many recipes including nano and micro, friction and wear additives, as SiO_2 and TiO_2 in sunflower oil [9], or halloysite clay nanotubes in the same vegetal oil [10]; hexagonal Boron nitride (h-BN), graphene and a combination h-BN + graphene in a vegetal oil (Cuttex Syn5) gave best tribological characteristics for the additive mixture (0.6 vol% each) [11]. Tests were conducted on a pin-on-disk tribometer, pins being made of titanium alloy and the disks being made of hardened steel; sliding velocity was 1.15 m/s, for 1 hour.

This paper analyzed Stribeck curves for the friction coefficient, but also the dependence of wear scar diameter (WSD) and temperature at the test end on the same Stribeck parameter. This relatively new approach identifies acceptable working regimes with the tested rapeseed oil-based lubricants.

2. MATERIALS AND METHOD

For this study, Stribeck parameter is calculated with the relationship:

$$S = \frac{v \cdot \eta}{F} \quad [m^{-1}] \qquad (5)$$

where *v* is the sliding velocity, η is the lubricant dynamic viscosity at the temperature at the test end and *F* is the force applied on the main shaft of the four-ball tester.

According to Nosonovsky and Bhushan [12], among the 12 principles of green tribology, two are dedicated to natural and biodegradable lubrication.

This is why in authors' research centre, studies related to vegetal oils (additivated or not) were elaborated and their tribological behavior, the tests being done on a four-ball machine [13], [14].

Figure 1 presents the composition of fatty acids, characterizing the rapeseed oil used for this study. As compared to other vegetal oils, two components are in high concentration (linolenic acid and linoleic acid, two non-saturated fatty acids that are mainly responsible for the boundary lubrication).

Values of rapeseed oil viscosity were taken from [15], [16], [17], for the recorded temperatures at the test end on four-ball machine.

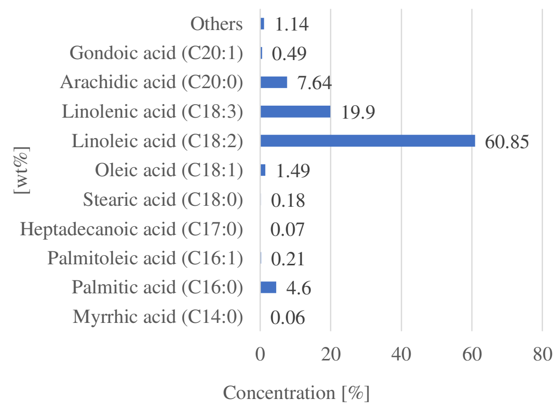


Figure 1. Fat acid concentration for the tested rapeseed oil

Graphically, the influence of temperature on the dynamic viscosity is presented in Figure 2, with the data taken from [17], for kinematic viscosity and density of the rapeseed oil.

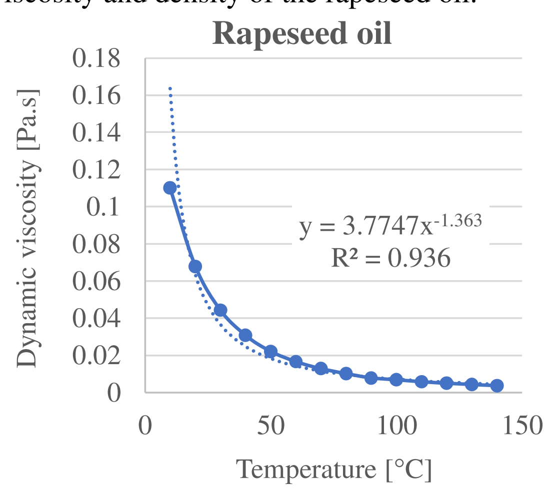


Figure 2. Viscosity of rapeseed oil depending on temperature. Dots are reported in [17]

Dynamic viscosity was calculated with

$$\eta(t) = \upsilon(t) \cdot \rho(t) \qquad (6)$$

where t is the temperature of the rapeseed oil, in °C. To calculate intermediate values for dynamic viscosity, the following regression was used

$$\eta(t) = 3.7747 \cdot t^{-1.363} \quad (7)$$

where t is the temperature in °C. It is important to underline that this is a mathematical regression, suited only for rapeseed oil and it was used to calculate the rapeseed oil viscosity at the temperature measured at the end of the test.

The viscosity of additivated lubricants was considered the same with the base oil, at the same temperature. For instance, Nik Roselina [18] reported an increase of less than 5% of the kinematic viscosity when adding 1 wt % TiO_2 in palm oil and synthetic oil. Waqas M. et al. [19] and Kananathan J. et al. [20] reported that the good thermal conductivity of h-BN nanoparticles helps evacuate the heat generated in friction, the lubricant maintaining its viscosity, which ultimately results in less metal-to-metal contact and a reduction in friction and wear. Walvekar R. et al. [21] reported tests on a blend of peanut oil and naphthenic oil, additivated with graphene nanoparticles and MoS_2; the presence of such an additivating package enhances the thermal conductivity of the lubricant and, of course, it could improve the tribological characteristics, too.

This study is based on tests on a four-ball machine, with the following parameters: normal load of 100 N, 200 N and 300 N (this is the load applied on the main shaft of the tribotester, meaning the load on all four balls arrangement), sliding velocity of 0.23 m/s, 0.38 m/s, 0.53 m/s, 0.69 m/s, 0.84 m/s, the sliding distance being kept constant L=1993 m. During the test, there were recorded the friction coefficient and the temperature of the oil the balls are immersed in.

The tested lubricants were rapeseed oil, rapeseed oil additivated with 1 wt% h-BN and rapeseed oil +1 wt% h-BN + 1 %wt graphene, respectively. The lubricant with 1%wt h-BN contains 1 wt % guaiacol (a dispersing agent) and the rapeseed oil with 1 wt% h-BN + 1%wt graphene contains 2 wt% guaiacol.

Both substances are sheet-shape particles, and they are usually added for reducing friction and wear [22]. The nano additives were supplied by the company PlasmaChem GmbH [23]:

- hexagonal Boron nitride (h-BN) (Fig. 3); powder with particle size of 100-1000 nm, mean value 500 ± 100 nm, specific area of 23 ± 3 m^2/g, purity >98.5%, nitrogen content > 55%, contents of elements, in %: O < 1; C < 0.1, B_2O_3 < 0.1,
- nano graphene: nano foils with a thickness of 1.4 nm and particle size up to 2 µm, specific area 700-800 m²/g, purity 91 at%, of the element: O < 7 at%; N < 2 at%.

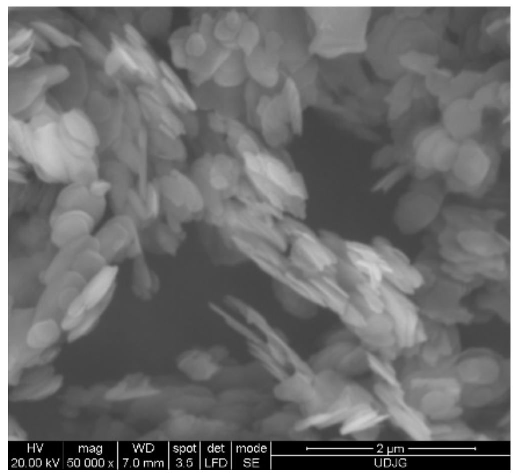


Figure 3. SEM images, at different magnification scales, of the nano additive h-BN (×50000)

Hexagonal Boron nitride was used as additive in mineral and synthetic oils [24], [25], [26], [27], [28]. Thachnatharen N. et al. [29] added 0.025 vol% of h-BN in SAE 20 W50 military grade diesel-based engine oil and tested the formulated lubricant on four-ball tribotester. The coefficient of friction (COF) and wear scar diameter (WSD) were improved as compared to the those obtained with the neat oil.

But in vegetal oils, this additivation is still at the beginning and the set of additive h-BN + graphene is still rarely reported, as in [30], and in ionic liquids [31].

Table 1. Test parameters on four-ball machine, for the tests carried out

v [m/s]	0.23	0.38	0.53	0.69	0.84
n [rpm]	600	1000	1400	1800	2200
L [m]	1933-constant				
Time [h/min/s]	2 h 20 min	1 h 24 min	1 h	46 in 40 s	38 min 12 s

Liñeira del Río J. M. et al. [30] reported a synergy when mixing h-BN and graphene with an ionic liquid in an ester base oil, tested on a ball-on-disc tester, the load being of 20 N, the sliding distance 340 m and the speed 0.10 m/s. The best results for friction coefficient and wear scar were obtained for the combination ionic liquid plus graphene.

Recently, results are presented for canola oil with graphene nano platelets (GNP) and hexagonal Boron nitride (h-BN) [32], but on a pin-on-disk tribometer and for a very small sliding distance (100 m) and low velocity (0.037 m/s). The combination h-BN + graphene kept the sum of additives as 1%wt. The increase of dynamic viscosity of additivated lubricants was less than 8% as compared to the viscosity of neat canola oil. This is the reason that, in calculating Stribeck parameters in this paper, there were introduced only values for neat rapeseed oil.

Nomède-Martyr N. et al. [33] added h-BN and graphite, separately, in Moringa oil. Tests were carried out on ball-on-disk tribotester, with reciprocating movement (2000 cycles), but under low load (10 N) and velocity (0.04 m/s) and the friction coefficient was still high (around 0.11 for Moringa oil +1 wt% h-BN and 0.09 for Moringa oil +1 wt% graphite).

Adding, separately, h-BN and graphene in a polyalphaolefin neat oil (PAO 40), a research team [34] obtained lower friction coefficients than that of neat PAO 40, the best results being for 0.5 wt% graphene and for 0.75 wt% h-BN (around 20% reduction as compared to neat PAO40). For all nano additivated lubricants (based on graphene and h-BN, respectively), the disk wear is smaller than that generated with PAO 40 lubrication.

These results encourage the authors to test the additive mixture 1 wt% h-BN + 1 wt% graphene.

The steps taken in the formulation of the tested lubricants were as follows [16]:

- mechanical mixing of the nano additive or the set of additives with an equal quantity of guaiacol (supplied by Fluka Chemica) with the formula C6H4(OH)OCH3 (2-methoxyphenol), for 20 minutes; this dispersing agent is compatible with both additives and rapeseed oil,
- continuous pouring of rapeseed oil, for obtaining 200 g of additivated lubricant,
- mixing with a magnetic homogenizing device for 1 hour,
- sonication + cooling of 200 g lubricant for five periods of 5 minutes using the sonicator Bandelin HD 3200 (Electronic GmbH & KG Berlin); during sonication the lubricants are heated to approximately 70 °C, thus there was interposed a cooling time for 1 hour. The parameters of the sonication regime were: continuous regime at power of 100 W, with a frequency of 20-500 Hz.

The balls have a diameter of 12.7 mm and were supplied by SKF, in set of four balls. Balls are made of chromium alloy steel EN 10027, 100CR6, mark 20, specially treated. The balls have a very small diameter tolerance (±0.0005 mm), a shape deviation of 0.5 μm, a diameter variation of 0.5 μm per ball and 1 μm on a set of four balls, high hardness (60- 66 HRC) and a very fine surface quality (Ra = 0.02-0.032 μm).

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 perpendicular to it). In the following analyses, the wear scar diameter (WSD) is the average of six diameter measures on the fixed balls.

The initial oil temperature was 20...23 ºC. During the test, the temperature was measured till the end of the test, with a thermocouple introduced in the ball cup, without touching the balls or the cup walls.

3. ANALYSIS OF STRIBECK CURVES

Figure 4 presents the friction coefficient for the rapeseed oil + 1 wt% h-BN in order to point out the good repeatability for two tests under the same condition.

Taking into account the lubrication regimes, as proposed by Stachowiack [35], Olaru [36], for the tested parameters, the rapeseed oil is working in a pieso-visco-elastic regime [14].

Values around 0.1 are on a slightly taped plateau for rapeseed oil, on a larger interval for S parameter, meaning a regime of boundary or mixed lubrication is obtained if the *S* parameter is varying in a certain range. Larger interval are obtained for F=100 N. But at higher values for S (S around 21×10^{-5} m^{-1}), the friction coefficient increases to 0.1, meaning a change towards a boudary or mixed regime again. This could be characteristic for this vegetal oil, very probably because of the higher temperature in contact and the decrease of oil viscosity at this temperature.

It is interesting to notice that the curves are ordered in the same way for all three tested lubricants: in the right side of the plots, the curves for F=300 N are positioned, followed by those for F=200 N and, then, those for F=100 N, towards the left side of the plots.

Comparing the plots for COF for these lubricants (Figure 5a), one may notice the followings:

- points for higher load (F=300 N) are situated to the left of the X coordinate (smaller values of Stribeck parameter), this being explained by increasing the denominator and decreasing the oil viscosity due to the higher temperature in the oil bath),

- when load increases, the points concentrate on narrower intervals of Stribeck parameter, S,

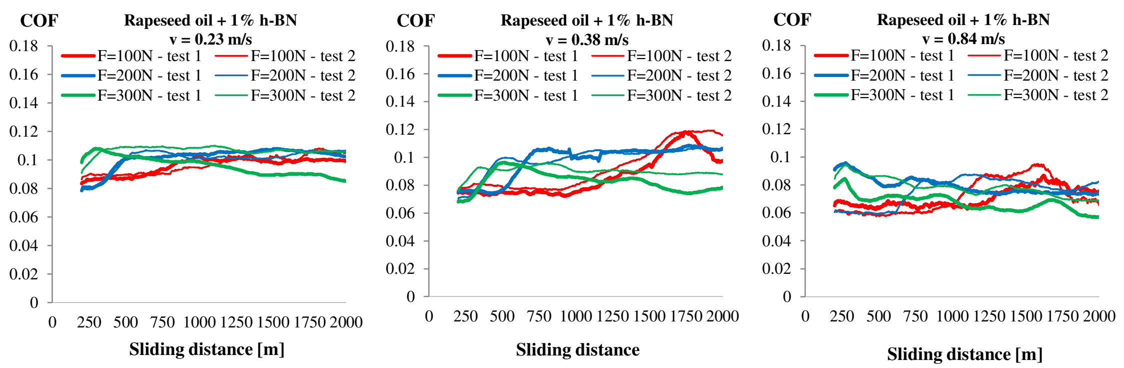
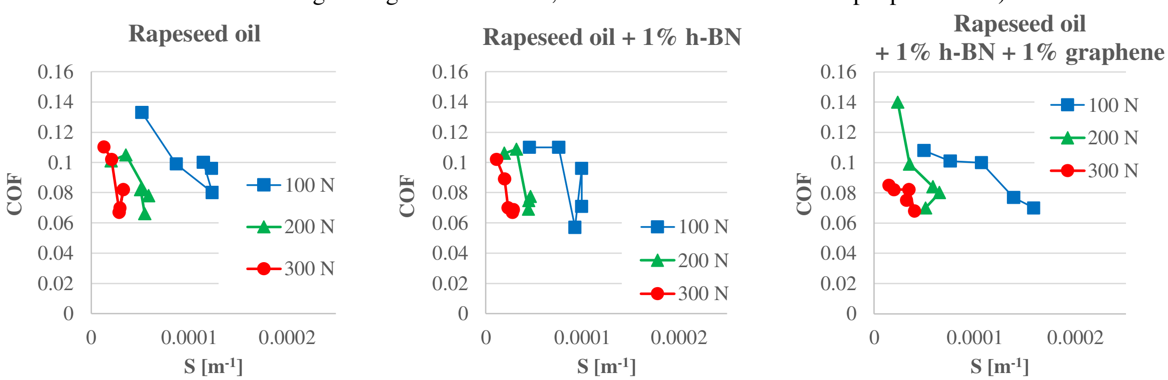
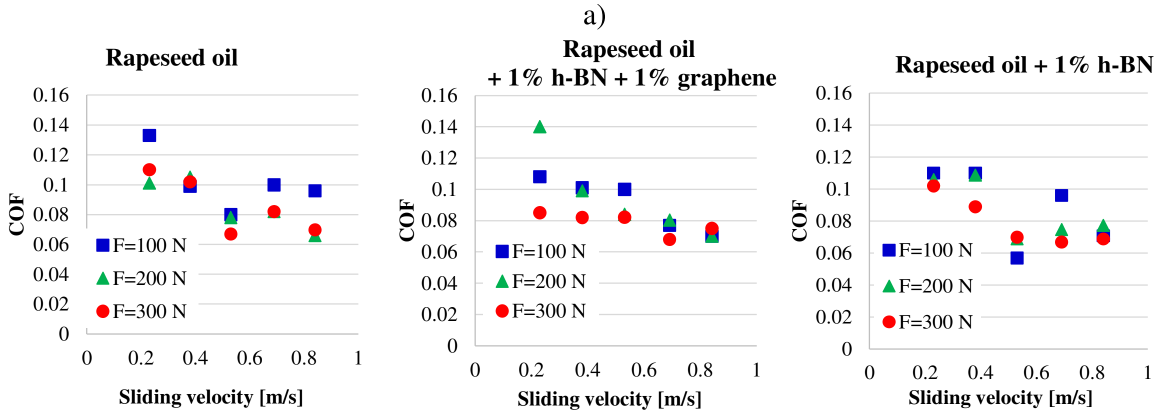


Figure 4. Friction coefficient for the lubricant rapeseed oil + 1 wt% h-BN, for three sliding velociies (lines were traced with a moving average of 100 values, there were recorded two sample per second)



a)



b)

Figure 5. Stribeck curves for the lubricant based on rapeseed oil (a color represents test with the same force, and points on the curve of the same color represents sliding velocities): a) plots using Stribeck parameter on X-axis, b) plots using sliding velocity on X-axis

- for each load, there are points situated around 0.1, meaning a very probably boundary or mixed regime,
- points under the value of COF=0.08 are similar arranged for all tested lubricants.

From this analysis, it is obvious that friction coefficient would not be a decisive criterion for selecting one of these three lubricants. The range for COF is similar for them:

for rapeseed oil: 0.133-0.066,

for rapeseed oil + 1 wt% h-BN: 0.11-0.068,

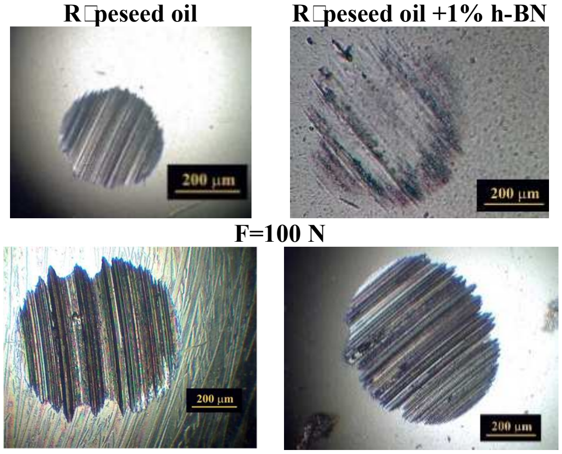
for rapeseed oil + 1 wt% h-BN + 1 wt% graphene: 0.140-0.068, meaning that adding h-BN and h-BN + graphene in rapeseed oil does not influence significantly the range of COF values, at least for the tested regime parameters (force and sliding velocity).

If the data for COF is plotted against sliding velocity, the graphs in Fig. 5b are obtained. Except for several points, (0.53 m/s, 100 N) and (0.84 m/s, 200 N), the lowest values for COF are obtained for *F*=300 N.

Figure 6 gives representative images of the wear scars, suggesting a dependence of wear scar diameter (WSD) on applied load, for the same sliding velocity, here photos being given for *v*=0.53 m/s.

Also, comparing first column to the second one, one may notice that adding nano particles of h-BN, the abrasive wear is not so severe, even if the area of wear scars are close for the same load and velocity.

Rapeseed oil **Rapeseed oil +1% h-BN**



F=300 N

Figure 6. Wear scars obtained on fixed balls, for the test with the following parameters: sliding velocity 0.53 m/s, sliding distance L=1933 m (1 hour) (each photo has its own scale)

Two other important tribological characteristics are analyzed as function of *S* parameter or as function of sliding velocity:

- the wear scar diameter (WSD) in Fig. 7,

the lubricant temperature in the ball cup, at the test end, in Fig. 8.

Analyzing the plots in Fig. 7a, the following conclusions could be drawn:

- when using *S* parameter for X axis, values for WSD are clearly grouped, depending on applied force,
- adding nanoadditives (h-BN or h-BN + graphene) makes this dependence less visible for *F*=200 N and *F*=300 N,
- at *F*=100 N, the package of nanoadditives h-BN + graphene makes WSD insensitive to increasing *S* parameter, meaning the additives play their role of reducing wear or they help the generation of a fully fluid film by their mending process.

Plotting WSD against sliding velocity, these conclusions are more obvious (Fig. 7b). For the rapeseed oil and the rapeseed oil additivated with 1% h-BN, WSD increases with load, at the same sliding velocity. Only for the rapeseed oil +1 wt% h-BN + 1 wt% graphene, WSD for *F*=300 N has lower values as compared to those obtained for *F*=200 N, meaning the nanoadditives (as a package) reduce wear.

Analyzing Stribeck curves having the sliding velocity on X-axis, it is obvious that for the tested conditions, the larger interval for low COF (under 0.08) is obtained for all lubricants, for load *F*=200-300 N. For *F*=100 N, low values of COF were obtained only around v= 0.53 m/s.

As a novelty, the wear scar diameter (WSD) and the oil temperature at the test end are plotted against Stribeck parameter and sliding velocity.

Analyzing Figure 7, the values of WSD obtained for rapeseed oil + 1 wt% h-BN +1 wt% graphene are less influenced by *S* parameter, for *F*=100 N (meaning at low load, the wear of the metallic surfaces of the balls remain almost constant due to the synergic protection of the nano additives). For *F*=200-300 N, the best wear characteristic (lower WSD) are obtained for the mixture of additives.

The better results for WSD could be explained by the roles that these two different nanoadditives (h-BN and graphene) play in contact [37], [38].

Wu H. et al. [41] proposed four lubricating mechanisms of nano additives in fluids: rolling, mending, polishing and protection. In the case of rapeseed oil nano additivated with h-BN and graphene, the nano-sheets could be rolled (especially those made of graphene) and replace the sliding motion by rolling. The deep valleys of the texture could be filled with nano additive particles and reduce the heights of the asperities, consequently, the fluid film is easier to be generate. The polishing effect could be done when nanoparticles are forced to slide against the solid bodies. In this study, the protective effect of nanoparticles against corrosion of the solid bodies could not be determined because of short time of the tests and the rapeseed oil protects the metallic surfaces, even in rest, as a very thin film of oil remains on the surfaces.

After arranging the experimental data having the sliding velocity as X-axis (Figure 8b), the data for the additive mixture seem to be less sensitive to the sliding velocity, recommending the lubricant for a variable regime.

Points of temperature at the test end form a plateau with small slope: a stable and good lower working temperature and then a sharp increase (with high slope), but the temperature is still under the oxidation temperature of the rapeseed oil (Figure 8a). For the mixture of additives, lubricant temperature is less dependent on test conditions (introduced by *S* parameter), points being grouped in the range of 40-60 °C, except for the highest test velocity (v=0.84 m/s). This may be attributed to the reduced internal friction in the lubricant due to the presence of graphene. Also, at the highest velocity, the presence of nanoparticles could generate a turbulent flow of the rapeseed oil, friction among particles, that could generate more heat in the lubricant.

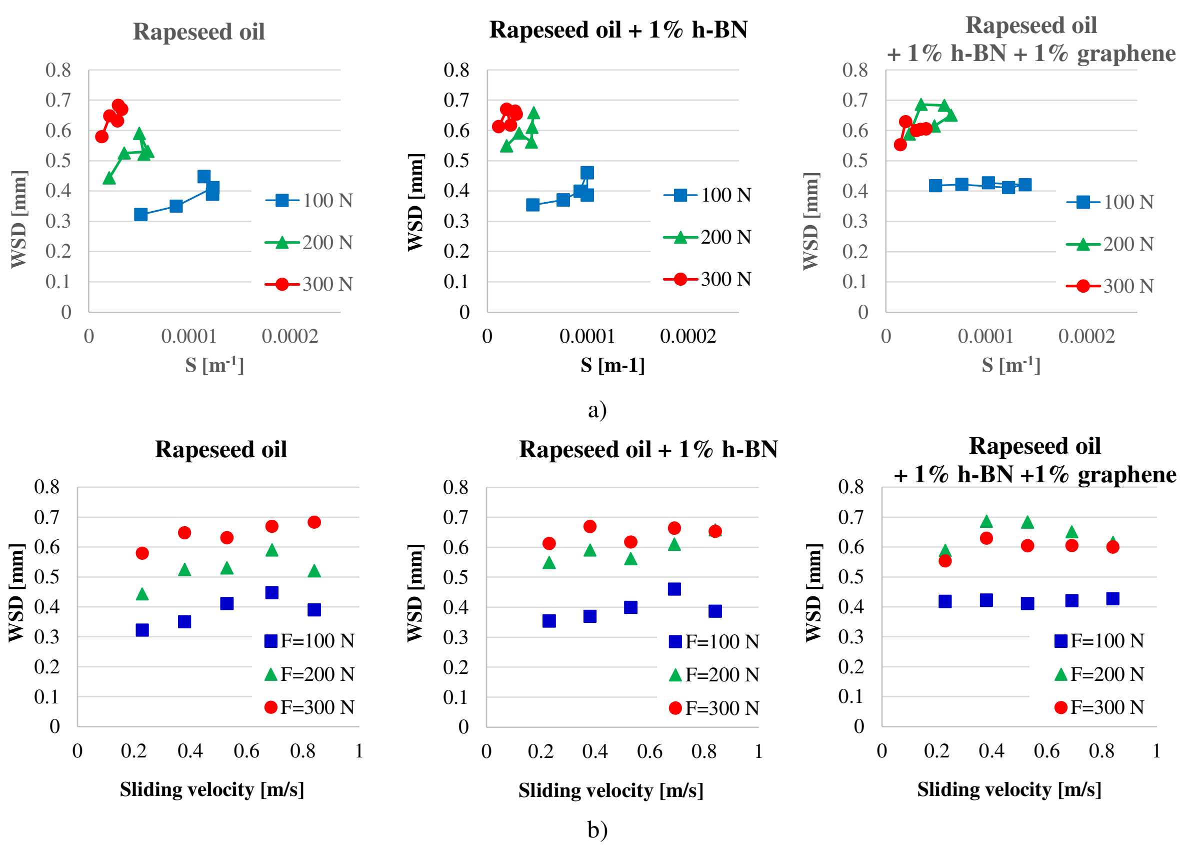


Figure 7. Stribeck curves for lubricant based on rapeseed oil (a color represents tests with the same force: a) plots using Stribeck parameter on X-axis, b) plots using sliding velocity on X-axis

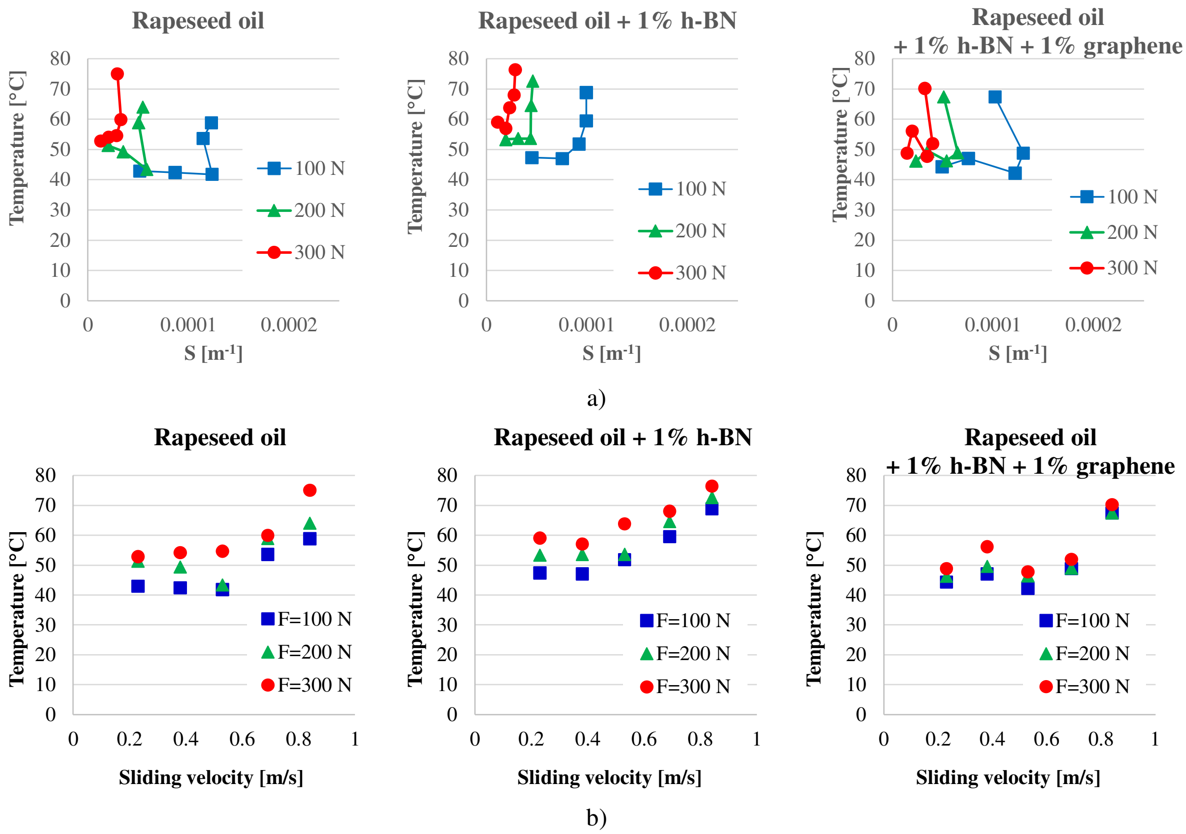


Figure 8. Stribeck curves for lubricant based on rapeseed oil (a color represents tests with the same force): a) plots using Stribeck parameter on X-axis, b) plots using sliding velocity on X-axis

Figure 8b, with velocity as X-axis, shows similar trends: the lubricant containing both additives has the temperature less sensitive to velocity. The points obtained for the other two lubricants were ordered in a resemblant arrangement. Maximum values of the temperature at the test end are recorded for *F*=300 N, but they do not reach 80 °C, meaning the rapeseed oil would not oxidize. The package of nano additives (1 wt % h-BN + 1 wt% graphene) decreases this parameter, especially for *F*=300 N, meaning the additives help removing the heat generated in contact.

4. CONCLUSION

Tests done on the four-ball machine pointed out low values of the friction coefficient as prove of a very thin lubricant film, but also values characterizing a mixt or boundary lubrication when using rapeseed oil and nano additives like h-BN and graphene in this vegetal oil.

This study shows that the rapeseed oil, even without additives, could be taken into consideration as a lubricant if the application is characterized by a well-controlled regime (low variations of velocity and load).

Analyzing the friction coefficient, the wear scar diameter and the lubricant temperature at the test end, on Stribeck curves, the rapeseed oil behaves as well as the lubricant additivated with 1 wt% h-BN, for regimes characterized by low load and velocity, but the mixture of additives (1 wt% h-BN + 1 wt% graphene) in the same vegetal oil makes the formulated lubricant to be less sensitive to the variation of test conditions, especially for WSD and the temperature at the test end, here, except for the highest tested velocity (v=0.84 m/s).

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Curba Stribeck pentru lubrifianți pe bază de uleiuri vegetale
Courbe de Stribeck pour les lubrifiants à base d'huiles végétales

Această lucrare prezintă o discuție privind comportamentul tribologic al uleiului de rapiță, aditivat sau nu, ținând cont de organizarea pe curbe Stribeck a informației. Testele au fost efectuate pe o mașină cu patru bile. Au fost analizați următorii parametri: coeficientul de frecare, diametrele urmelor de uzură pe cele trei bile fixe și temperature lubrifiantului la sfârșitul testului. Parametrii de testare au fost: sarcina normală de la 100 N, la 300 N și viteza de rotație a axului principal al mașinii de testare, de la 600 rpm la 2200 rpm, ceea ce corespunde unei viteze de alunecare de la 0,23 m/s la 0,84 m/s. Au fost trasate curbele Stribeck pe baza parametrului Stribeck (în funcție de viteză, vâscozitatea lubrifiantului și sarcina aplicată). Regimurile de lubrifiere au putut fi identificate cu ușurință pe aceste curbe și s-au putut face recomandări pentru regimul de lucru, pe baza acestor informații.

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