

## Micro and Nanometric Wear Evaluation of Metal Discs Used on Determination of Biodiesel Fuel Lubricity

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The contact of diesel fuel with engine subsystems demands a good wear resistance. Lubricity is an important feature for integrity of injection system and the sulphur composites are primarily responsible for lubrication of the injector nozzle. Biodiesel is responsible for partially restoring the lubricity of diesel fuel that presents low levels of sulphur composites and, furthermore, it causes less pollution than diesel fuel. The lubricity is measured through the wear scar diameter following the ASTM D 975 standards. However, the friction and wear with light loads of micro/nanocomponents are highly dependent on surface interactions that can be evaluated by microscopy techniques. This study aimed to measure and to analyze the biodiesel lubricity and their blends (B5, B20) with diesel by observing the wear scars of discs using the scanning electronic microscopy (SEM), atomic force microscopy (AFM) and micro roughness techniques. The fuels performance was evaluated using HFRR tribometer. The tests conditions were based on standard ADTM D-6079-04. The coefficient of friction was measure during the test. After the test, the worn ball and disc were analyzed by SEM, AFM and profilometer. The results showed that the addition of biodiesel in diesel improve the tribological performance of fuel. Also, the just WSD value is not sufficient to evaluate the lubrication ability of a fuel. Analysis of the worn disc surfaces proved to be compatible with WSD number and also more sensitive to these kinds of fuels, showing mainly the form and intensity of the wear.

**Keywords:** *AFM, WSD, roughness, biodiesel, lubricity, HFRR*

### 1. Introduction

Biodiesel fuel is an environmentally friendly alternative, which is obtained by transesterification of vegetable oils producing alkyl esters of long chain fatty acids<sup>1,2</sup>. It is an environmentally and economically interesting option to generate technology and incomes to Brazil. These fuels are transesterified vegetable oils of soybean, sunflower, castor and palm<sup>3</sup>, whose main importance of use is related to the needs of reducing the pollutant gases that are present in the combustion emissions during engines use<sup>4</sup>.

Blends of biodiesel promote the formation of better fuels than diesel oil, because of its low sulfur content, high flashpoint and low aromatic content. Besides, engines using biodiesel as an energy source emit fewer pollutants for the atmosphere<sup>5,6</sup>, containing 78% and 98% less CO<sub>2</sub> and sulfur, respectively. Other advantages of biodiesel when compared to conventional diesel include biodegradability and national source<sup>7</sup>.

In order to reduce the emission of pollutants from diesel oil, biodiesel is added to it, which can also increase its lubricity. From the tribological point of view, the lubricity of biodiesel and the lifetime of fuel supply line are correlated<sup>8</sup>. The lubricity is defined by the ability to reduce friction and wear on surfaces under load and relative motion. The most common method to evaluate fuel lubricity is described by ASTM D-6079. This standard determines the lubricity

by evaluation of wear scar diameter (WSD) in  $\mu\text{m}$ , as measured in the x and y axis, produced on the ball surface due to reciprocating sliding against the pressure plate, both immersed in fluid<sup>9</sup>.

Generally, smaller wear scar signifies greater lubricity that ensures the effectiveness of interfacial lubricant fuel film on the separating action of these surfaces<sup>10</sup>. This thin film is formed by adsorption of polar molecules of fuel on metal surfaces, i.e., there is a high affinity to metallic surfaces forming a thin protective metal-metal contact. The maximum permitted WSD by American and European standards is 520  $\mu\text{m}$  (ASTM D 975-10) to 460  $\mu\text{m}$  (EN 590 -10) to 60° C, respectively<sup>11</sup>.

The lubricity issue is significant because of the advent of low-sulfur petrodiesel fuels and, more recently, ultralow-sulfur diesel (ULSD) fuels, as required by regulations in the United States, Europe, and elsewhere. This can promote failure of engine parts such as fuel injectors and pumps, because they are insufficient lubricated by the fuel. The reason for poor lubricity of ULSD is not the removal of sulfur-containing compounds, but rather that polar compounds with other heteroatoms such as oxygen and nitrogen are also reduced in this petrodiesel<sup>11-13</sup>.

Most papers refer to lubricity just as a function of WSD (wear scar diameter). Hu et al.<sup>14</sup> developed a study about the refined and unrefined biodiesels to improve the

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lubricity of diesel (S166 ppm) blended with 2% wt/wt of biodiesel. They could note that all the unrefined biodiesels showed improved lubricity properties over all the refined biodiesels, WSD (351–429  $\mu\text{m}$ ) were lower than 460  $\mu\text{m}$  of EN590. Bućinskas<sup>15</sup> investigated the tribological properties of biodiesel fuel and its mixtures. They concluded that regular diesel fuels have more stable properties, although pure biodiesel showed the lowest coefficient of friction.

Muñoz et al.<sup>16</sup> evaluated the lubricity of diesel and the mixtures of biodiesel with diesel fuel, using HFRR method. Different biodiesel blends were used to compare their lubricant responses on the wear scars. Diesel fuel with 50 ppm of sulphur (S50) without lubricant additive promoted an approximate wear scar of 600  $\mu\text{m}$ . Nonetheless, when this diesel included small percentages of biodiesel, lubricity got closer to the one of a conventional diesel fuel (wear scars of 283  $\mu\text{m}$  and 312  $\mu\text{m}$  with 10% (B10) and 5% (B5) biodiesel, respectively, compared with 314  $\mu\text{m}$  developed with conventional diesel fuel).

The lubricity of numerous fatty compounds was studied by Knothe and Steidley<sup>7</sup>. The effects of blending compounds found in biodiesel on petrodiesel lubricity were also studied. Lubricity was determined using the high-frequency reciprocating rig (HFRR) test. They concluded that fatty compounds possess better lubricity than hydrocarbons, because of their polarity-imparting O atoms. Also, Lubricity improves somewhat with the chain length and the presence of double bonds. An order of oxygenated moieties enhancing lubricity ( $\text{COOH} > \text{CHO} > \text{OH} > \text{COOCH}_3 > \text{CdO} > \text{C-O-C}$ ) was obtained from studying various oxygenated C10 compounds. These authors evaluated lubricity just in function of WSD.

Pehan et al.<sup>17</sup> studied the influence of B100 rapeseed biodiesel fuel on roughness of some components of injection system in controlled diesel engine. According to these researchers, the surface roughness at the pump plunger head is not as important as the roughness at the pump plunger skirt; and after biodiesel usage, the surfaces showed better lubrication conditions than the diesel usage, whereas Ra (arithmetic roughness) parameter was of 0.45 to 0.40  $\mu\text{m}$ .

The WSD does not provide sufficient information in case of critical markets and diesel fuels. Possible approaches for improvements are disclosed in this article. The HFRR method is kept as intended, but complemented by additional evaluation methods, e.g. by micrographic and topographic analyses and measurement of worn disc surfaces for a better understanding of the tribological processes happening in the contact zone (ball-fuel-disc).

This work aimed to establish other parameters to measure the lubricity and their correlations with WSD. So, the fuel lubricity was evaluated by the AFM (contact mode), SEM and microroughness techniques, analyzing the disc scars used in HFRR testing of soybean and sunflower biodiesels and their B5 and B20 blends with diesel S1200 (1100 ppm sulfur).

## 2. Materials and Methods

### 2.1. Ball and disc characterization

In HFRR test, the tribological couple is composed by ball (quenched and tempered) and disc, both made of AISI 52100 steel (SAE 52100), whose chemical compositions, by X-Ray Fluorescence technique, are shown on Table 1.

The dimensions of the tribological couple are: hard polished ball of 6 mm and smooth polished disc of 10 mm of diameter and 3 mm of height, according to ASTM D 6079-04<sup>9</sup>. The Vickers microhardness tests are performed for both ball and disc surface which consisted by applying the Vickers indenter (diamond pyramid with square base and apical angle of 136°) on the sample surface during 15 seconds with the following loads: 50 gf or 0.49 N ( $\text{HV}_{0.05}$ ), for disc surfaces; and 200 gf or 1.96 N ( $\text{HV}_{0.2}$ ), for ball surfaces. The Vickers microhardness values showed average range of 174 to 190  $\text{HV}_{0.05}$  to disc surfaces and 585 to 677  $\text{HV}_{0.2}$  to ball surfaces to the non-worn condition surface, as can be seen on Table 2.

### 2.2. Fuel samples preparation

A total of seven fuel samples were evaluated in this work. Diesel (mineral conventional diesel fuel, 1100 ppm sulfur) was obtained from Petrobras S.A., which was used as the comparison fuel. Biodiesels were obtained by the ethylic transesterification process of commercial soybean and sunflower oils with potassium hydroxide catalyst and ethanol 99.5 %, synthesized in the NUPEG II Laboratory of the Federal University of Rio Grande do Norte. Besides diesel and biodiesel, some blends of these fuels were evaluated, in 5 % and 20 % volumetric concentration of biodiesel (B5 and B20). Table 3 describes the blends and their abbreviations.

### 2.3. Tribological test

Lubricity of the fuels was evaluated using the HFRR from PCS Instruments®, as shown in Figure 1. It is a ball-on-disc test to measure friction and wear under boundary lubrication conditions using a highly stressed ball-on-disc

**Table 1.** Chemical composition by weight (% p.) from the AISI 52100 steel disc.

Fe	C	Mn	Cr	S	Si	Al	Ca
Bal.	0.900	0.413	1.567	0.127	0.546	0.105	0.154

**Table 2.** Microhardness HV averages of the non-worn ball and disc surfaces.

Avg. Values	B0-Diesel	B100-SB	B20-SB	B5-SB	B100-SF	B20-SF	B5-SF
$\text{HV}_{0.2}$ (Ball)	585±42	614±119	644±101	677±153	670±80	585±55	600±41
$\text{HV}_{0.05}$ (Disc)	187±10	190±25	183±18	183±33	174±7	174±8	175±7

contact. A hard steel ball slides on a softer steel disc under the fully submerged fuel condition ( $2.0 \pm 0.2$  mL) at normal load of  $1.96 \pm 0.01$  N and a  $1.00 \pm 0.02$  mm stroke length at a frequency of  $50 \pm 1$  Hz for 75 min. Fuel temperature was kept at  $60 \pm 2$  °C, according to the ADTMD-6079-04<sup>9</sup>, where the heating of contact is measured at 1.7 mm distance of the ball-on-disc contact.

The repeatability of the data (coefficient of friction and wear scar diameter) provided in the HFRR tests was evaluated using seven replicates for each fuel. In order to minimize any outside interference during the tests, humidity and temperature were controlled. COF (coefficient of friction) was measured by a piezoelectric force transducer. At the end of the test, the ball is removed from HFRR to measure the WSD (wear scar diameter) at the optical microscopy with magnification of 100 times. The resulting scar size, WSD was corrected to normalize the vapor pressure to 1.4 kPa (WS 1.4 number), established by ISO 12156<sup>18</sup>.

#### 2.4. Techniques of surface analysis

The wear scar of discs was analyzed by micro and nanometer scales through rugosimeter, SEM and AFM techniques. The dominant wear mechanisms and surface

topographies of the worn discs were studied with a SEM. The microroughness tests carried out by mechanical stylus method used Taylor Hobson Surtronic 25 rugosimeter to verify new and worn disc (perpendicular to sliding direction on worn surfaces). To evaluate the developed changes in topography during HFRR tests, SEM and AFM equipments were used. Before observation, the disc specimens were ultrasonically rinsed with ethyl alcohol. The SEM was operated at accelerating voltages of 30 kV. Representative SEM micrographs of the wear tracks were obtained at 100x and 1000x magnifications.

### 3. Results and Discussion

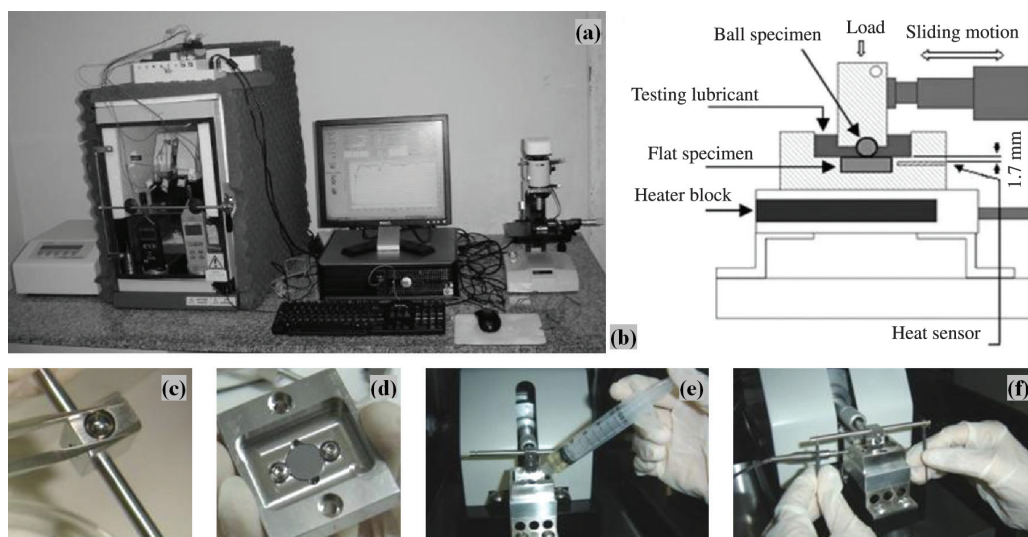
In this section are presented the lubricity results obtained in function of WSD number, as proposed by standards, and also considering other parameters such as coefficient of friction and topographic analysis of wear tracks by roughness, AFM and SEM. These data were obtained by considering seven repetitions of HFRR test.

#### 3.1. Lubricity: wear scar diameter (WSD) and coefficient of friction (COF)

The WSD and COF average data are exhibited in Figures 2 and 3, respectively. The COF and WSD are effective correlated parameters to evaluate the lubricity of biodiesel. According to ASTM D975:2010<sup>19</sup>, the WSD number (or WS1.4) is the main parameter to measure the diesel/biodiesel lubricity and it is compared to the European regulation (DIN EN 590)<sup>20</sup>, which establishes a maximum WSD of 460  $\mu$ m. Figure 2 shows WSD values obtained by optical microscopy, with 100 x magnification, it was used to examine the wear scar of the ball surfaces after each test. Based on these results, B0-Diesel presented highest values ( $345 \pm 15$   $\mu$ m) and, consequently, a smaller lubricity than the biodiesel fuels and their blends, however it was smaller than the maximum value of 460  $\mu$ m, requirements defined in the World Fuel Charter World Fuel Charter.

**Table 3.** Description of fuels on ball-disc contact.

Fuels	Description
B0-Diesel	Mineral conventional diesel fuel, 100 % of diesel oil, S1100
B100-SB	100 % ethyl ester of soybean oil
B20-SB	20 % ethyl ester of soybean r oil + 80 % B0-Diesel
B5-SB	5 % ethyl ester of soybean oil + 95 % B0-Diesel
B100-SF	100 % ethyl ester of sunflower oil
B20-SF	20 % ethyl ester of sunflower oil + 80 % B0-Diesel
B5-SF	5 % ethyl ester of sunflower oil + 95 % B0-Diesel



**Figure 1.** HFRR tribotester: a) picture of equipment; b) schematic diagram; c) and d) are the ball and disc with their supports; application of e) fuel and f) load in mechanical HFRR unit.

Thus, the lubricity tests demonstrated that incorporating of biodiesels in small (5%) or medium (20%) percentage, without a conventional lubricity additive, improves the lubricant properties of the fuel, which their wear scars were around 200  $\mu\text{m}$ . Similar results were observed by<sup>16,21-23</sup>. Lapuerta et al.<sup>23</sup> when they studied the lubricity of ternary fuel blends (ethanol-biodiesel-diesel). They verified that the addition of small biodiesel concentrations (2 %wt/wt, approximately) improved the lubricity much more than adding 30 % wt/wt (WSD of 257  $\mu\text{m}$ ). Also, Muñoz et al.<sup>16</sup> measured the WSD of biodiesel made from vegetable oil previously used for frying and purified in the laboratory. The blends with 5, 10 and 100% of biodiesel showed WS1.4 of 312  $\mu\text{m}$ , 283  $\mu\text{m}$  and 322  $\mu\text{m}$ , respectively.

It is also possible to conclude that WSD is an approximated measure and it is susceptible to high variations depending on the measurement method, as it can be observed in Figure 2. Due to this fact, this paper analyses the lubricity

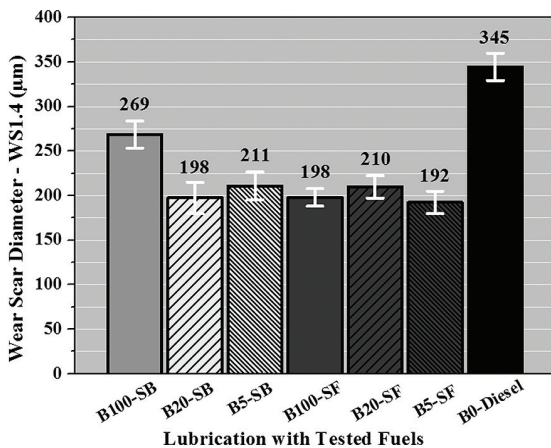


Figure 2. WS1.4 number after 225,000 cycles of lubricity HFRR.

based on tribological properties and microscopy techniques. According to Figure 3, the coefficient of friction decreased with an increase in the content of the ethyl esters; the lowest values were found for pure biodiesels (B100-SB and B100-SF). The initial values are high until first  $25 \times 10^3$  cycles for the lubricated tests by B0-Diesel and B100-SB and 100-SF, while the blends of both biodiesel fuels offered the highest stability of friction than these other fuels. In this graph, the medium values of COF were higher to B0-Diesel (0.122) than the soybean (0.079) and sunflower (0.078) biodiesel fuels and their respective blends with 20% (0.088 and 0.086) and 5% (0.099 and 0.097). Furthermore, it should be considered that these biodiesel fuels have greater ability to protect the surfaces of pieces than B0-Diesel (S1100), due to their high contents of oxygenated compounds and fatty acids. Thus, the oxygen present in biodiesel can accelerate the generation of  $\text{Fe}_3\text{O}_4$  film, which is a good lubricant<sup>24</sup>.

### 3.2. Worn steel disc surface analysis

Figures 4 and 5 show representative SEM micrographs of wear tracks on disc specimens lubricated with mentioned fuels using HFRR test. The wear tracks were generated by ball rubbing against each disc. The first column presented the micrographs with 100 times magnification of full scar and its length value; the arrows indicate the direction of ball movement. The second and third columns show wear tracks with 1000 times of the center (area a) and lateral prow (area b) of the scars. The morphologies demonstrated that the dominant wear mechanisms were adhesion and abrasion.

The abrasion wear is noted by prow formation and ploughing on disc specimens, while the adhesive wear is represent by materials transfer resulting from strong metal-to-metal contact with these fuels. Crockett et al.<sup>25</sup> found in their experiments with commercial diesel fuel, using the HFRR test, which the iron required for decomposition of the hydrocarbons must come from the wear particles formed during sliding. Abrasive wear was generated by

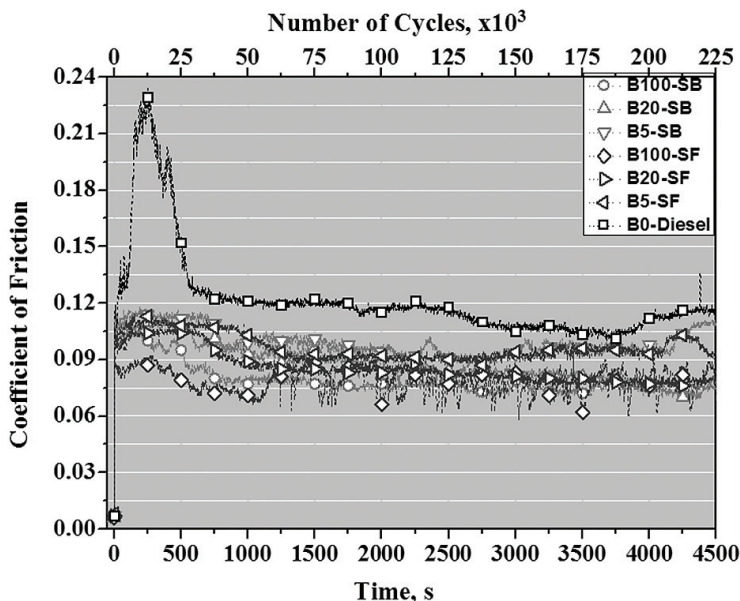
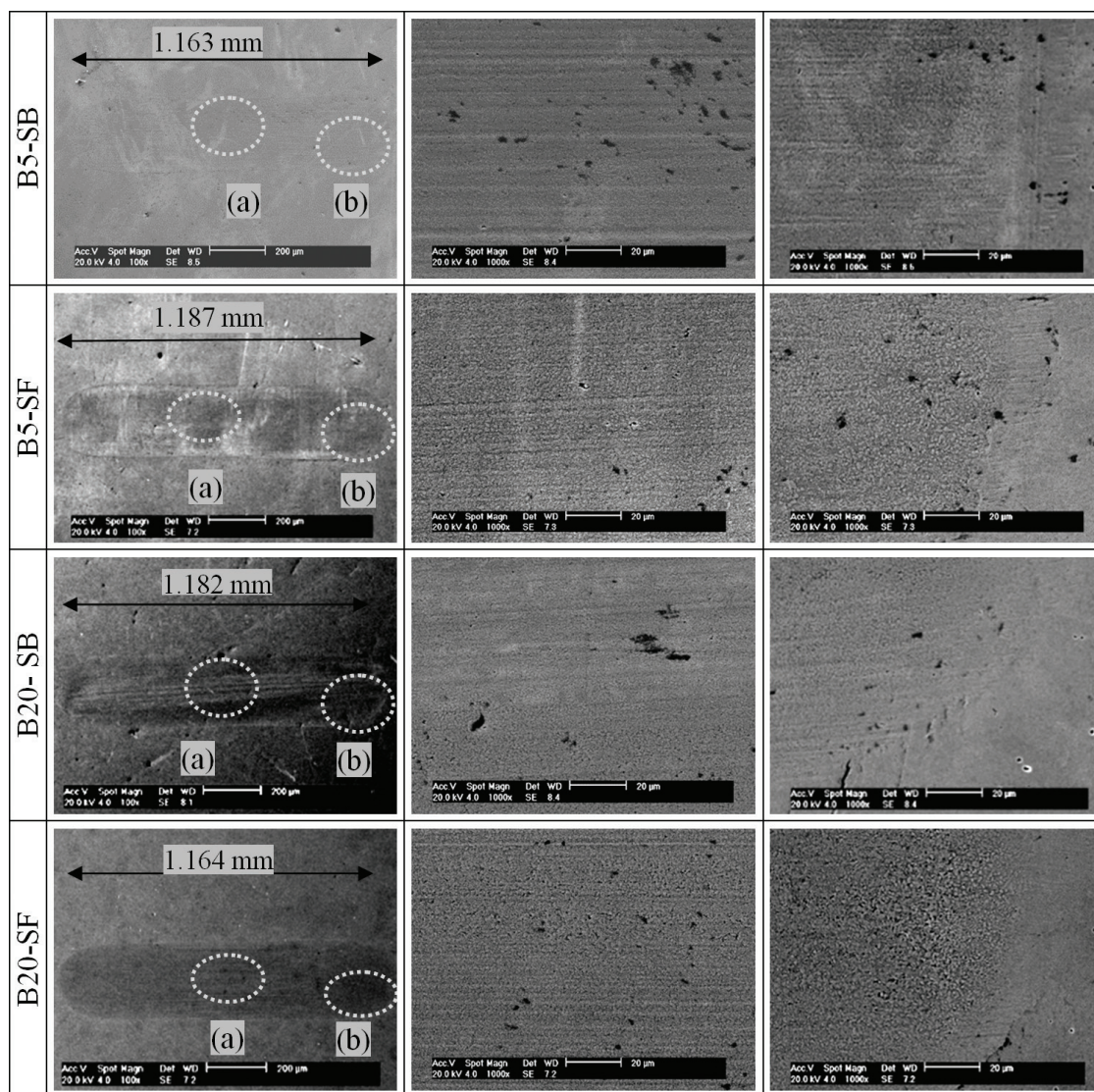


Figure 3. COF of the ball-disc contact during HFRR test.





**Figure 4.** SEM of wear scar after lubricity test of biodiesel blends: a wear track is on the left; a zoom of area (a) is in the centre and the lateral prow (area b) is on the right.

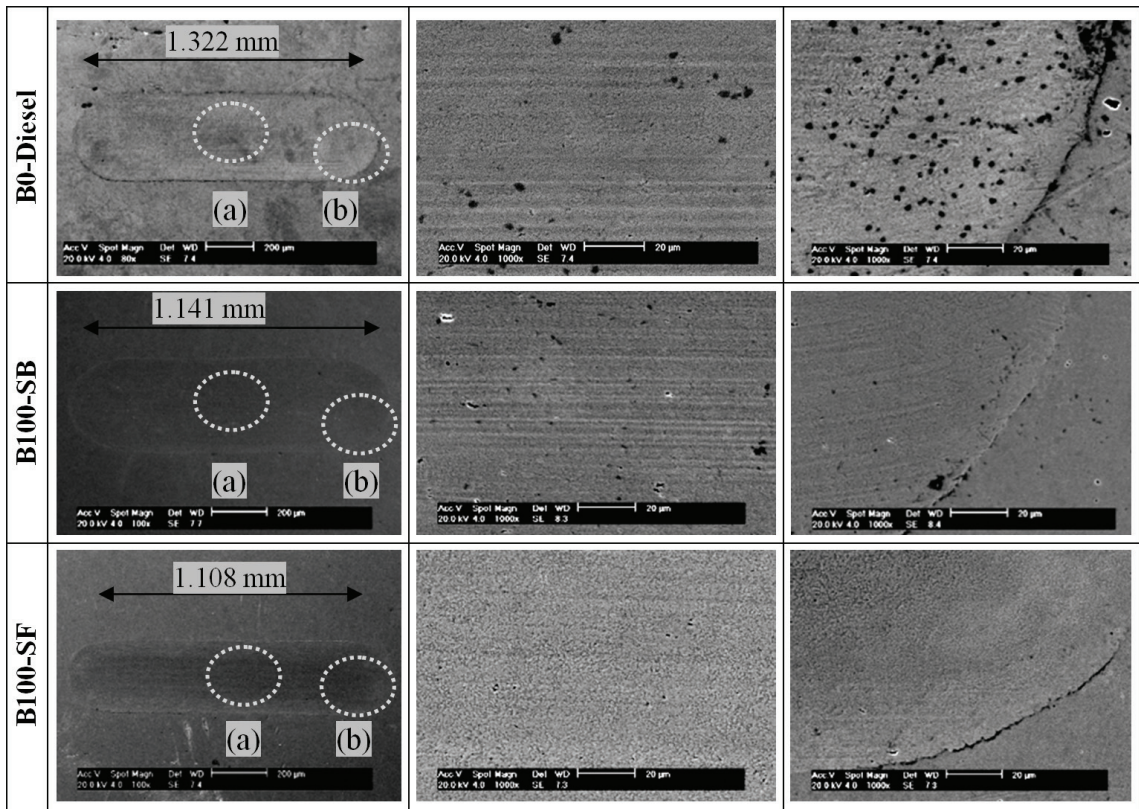
difference between hardness of ball and disc and lubrication conditions. When the difference on hardness is greater than 20% (see Table 2), the abrasion can occur; and its intensity depends on the lubrication conditions, i.e., viscosity, sliding speed and normal load. So, increasing the normal load on the contact, decreasing the sliding speed or decreasing the lubricant viscosity all tend to reduce film thickness, and consequently, abrasion<sup>26</sup> is greater.

From the micrographs obtained (Figures 4 and 5), diesel fuel produces more deposits (black points) when compared with biodiesel and their blends fuel. Nevertheless, according to Arifin et al.<sup>27</sup>, is not only the fuel type that can affect the fuel deposition, other factors are impingement interval, hot surface temperature, and heat transfer of deposits. These factors depend on adhesion force, which arises mainly from Van der Waals and capillary forces acting between two contacting surfaces and it depends on surface reactivity and affinity to fluid of the interacting surfaces. Sukjit et al.<sup>28</sup>

employed the energy dispersive spectrometer (EDS) to report the main chemical composition of almost all the black residues on the test disc was carbon. According to them, carbon formation is a result of the heat generated during fretting between the specimen surfaces which leads to acceleration of the adsorption process from the chemical reactions of the hydrocarbons in the fuels, which are good lubricating properties when the fuel can be adsorbed onto the worn surfaces.

Comparing the effect of biodiesel additives, it is noticed that the use of biodiesel blends promoted almost similar length of track and morphology, as seen in Figure 4. Their lengths were greater than lubricated discs with B100-SB and B100-SF. These biodiesel fuels showed the greatest lubricity. However, all biodiesel blends were significant to improve lubricating performance, with wear reduction. The B0-Diesel (S1100) presented the greatest length scar; and addition of 5% (B5-SB and B5-SF) is sufficient to





**Figure 5.** SEM of wear scar after lubricity test of diesel and biodiesel fuels: a wear track is on the left; a zoom of area (a) is in the centre and the lateral prow (area b) is on the right.

promote a reduction of about 12% on length of wear scar. Komvopoulos et al.<sup>29</sup> used the micrographs analysis to study the tribological performance of the tribofilms and their association with wear mechanisms. According to their observation, the increasing in the wear resistance of the steel surfaces depends strongly on the type of additives, tribofilms composition, and temperature.

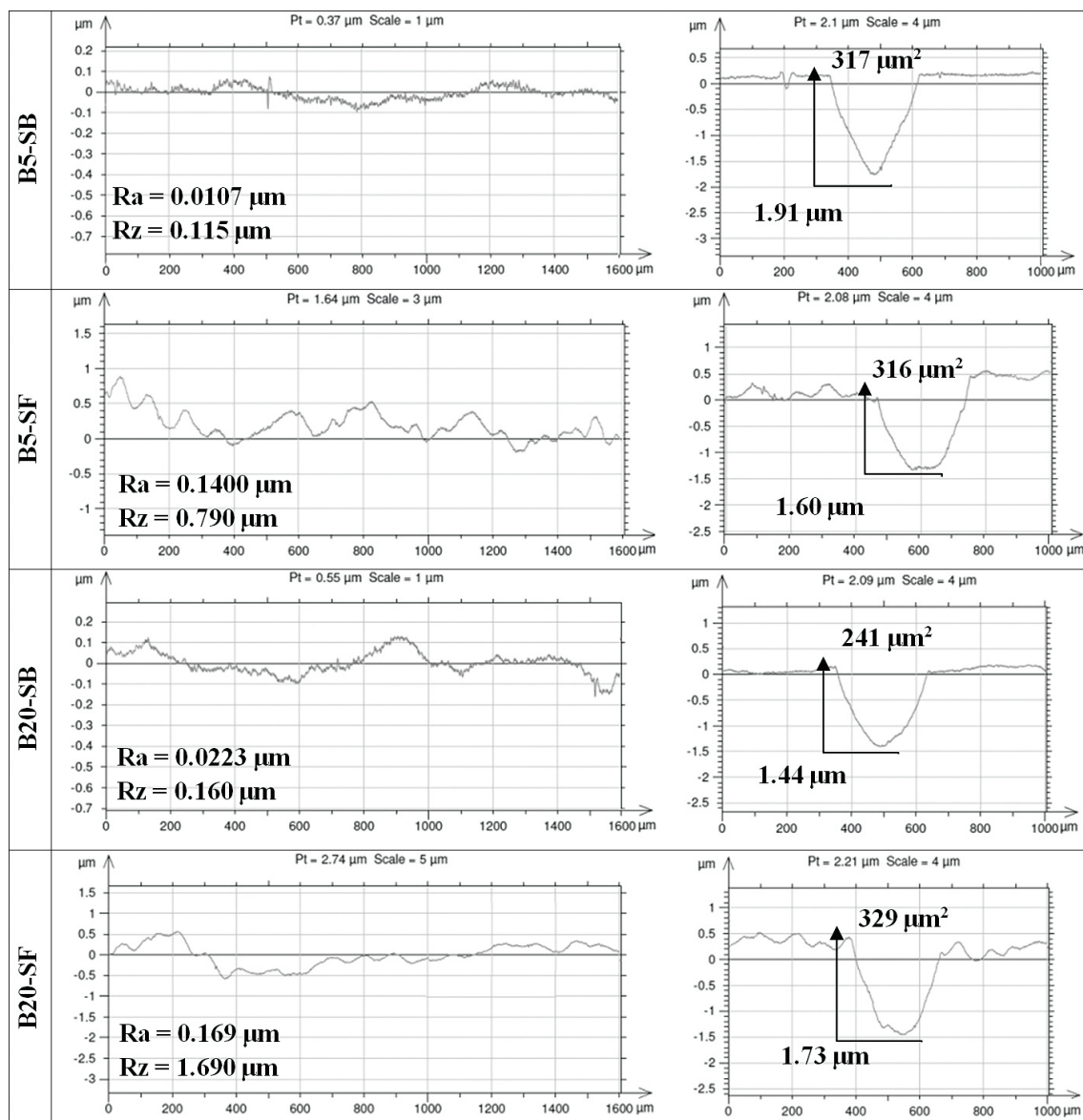
Sulek et al.<sup>22</sup> suggested that wear can be characterized by analyzing the profile of the wear scar, by such measures it can be confirmed that the wear is not a monotonic function of the concentration of ester. Figures 6 and 7 show the superficial roughness of these discs, with non-contact region (on the left) and worn condition, i.e., wear profiles measured perpendicular to the friction path (on the right). The roughness profiles are presented with their Ra and Rz parameters for non-contact region, and maximum depth and area of scar after lubricated tests with studied biodiesel/diesel fuels. Ra is an arithmetic roughness average and Rz is an average peak-to-valley height.

According to the profiles in Figures 6 and 7, the positive influence of biodiesel in the wear can be seen due to the lowest values of “maximum depth” and “area” of the scar presented in the profiles (on the right). So, for all cases, it was noted that the region of the worn disc lubricated with B0-Diesel offered the highest maximum depth and area of scar, respectively 4.45  $\mu\text{m}$  and 1191  $\mu\text{m}^2$ . These results indicated that abrasion under the B0-Diesel was larger than that of the biodiesels and their blends, which were conformed to the results of SEM.

So, these results confirmed the previous analysis (WS1.4 averages values, Figure 2). Surface roughness played an important role on the abrasion characteristics. The Table 4 summarizes the values of disc scar obtained by SEM and roughness analyses and their comparison with average WS1.4. According to these results, low values of the maximum depth and area of the disc scars indicate better fuel lubricity. The last line is used to classify the fuel performance. It appears that ester blends in fuel oil considerably reduces the depth of a wear scar compared to the B0-Diesel. Therefore, the use of B20-SB presented the best lubricity; at the other extreme, it is confirmed that the B0-Diesel offers the worst among the investigated lubricity fuels. However, B100-SB offered the second worst performance; this corroborates with the WSD values (Figure 2).

Figures 4 and 5 showed that numerous plowing grooves parallel to the sliding direction were observed on the wear tracks; however only 2D images are not sufficient to show the intensity of wear; so, the topographic images are necessary to a detailed wear observation. Asperities are referred to peaks in a profile (two dimensions) and in a surface map (three dimensions). Nano and microroughness include those features intrinsic to the production process. These are considered to include traverse feed marks and other irregularities within the limits of the roughness sampling length<sup>30</sup>.

The atomic force microscopy (AFM) was employed to evaluate the changes in topography after the lubrication



**Figure 6.** Roughness profile after lubricity tests with biodiesel blends: on the left, new disc; on the right, role area of scar.

tests. Figures 8 and 9 show topographic images with textures of wear tracks of steel discs using areas of  $30\ \mu\text{m} \times 30\ \mu\text{m}$  obtained by contact mode of separation distance between 10 to 100 nm of the cantilever and analyzed surface. The presented line segments were used to calculate the nanoroughness parameters showed in Table 5. These data have a direct correspondence with the intensity of wear of these areas.

In Figures 8 and 9 are presented homogeneous areas and with the predominant ploughing wear form; abrasion is the main mechanism observed in the prow formation and in track surface. Therefore, the topographic image of disc, that was lubricated by B0-diesel oil, exhibited peaks and valleys repeated along the friction direction. After the B0-diesel test, it was also observed that the scuffing phenomena

occurred to the disc, and then the maximum roughness of disc was found to be increased up to 212 nm. However, after the B100, B20 and B5 blends tests, it was clearly observed that the texture images were changed because of biodiesel concentrations in the blends. Smoother and shallower peaks and valleys were observed for tested discs with biodiesel blends, mainly for B20-SB and B20-SF.

According to Table 5, the Ra and Rz nanoroughness values of these disc surfaces initially decreased with increasing biodiesel content in the blends. The B100-SF exhibits the smaller Ra value, while B0-diesel shows the highest Ra values. The addition of 20% of biodiesel in the diesel improves the results of roughness significantly. This result is according to the previous analyses (WS1.4, SEM and roughness evaluation).

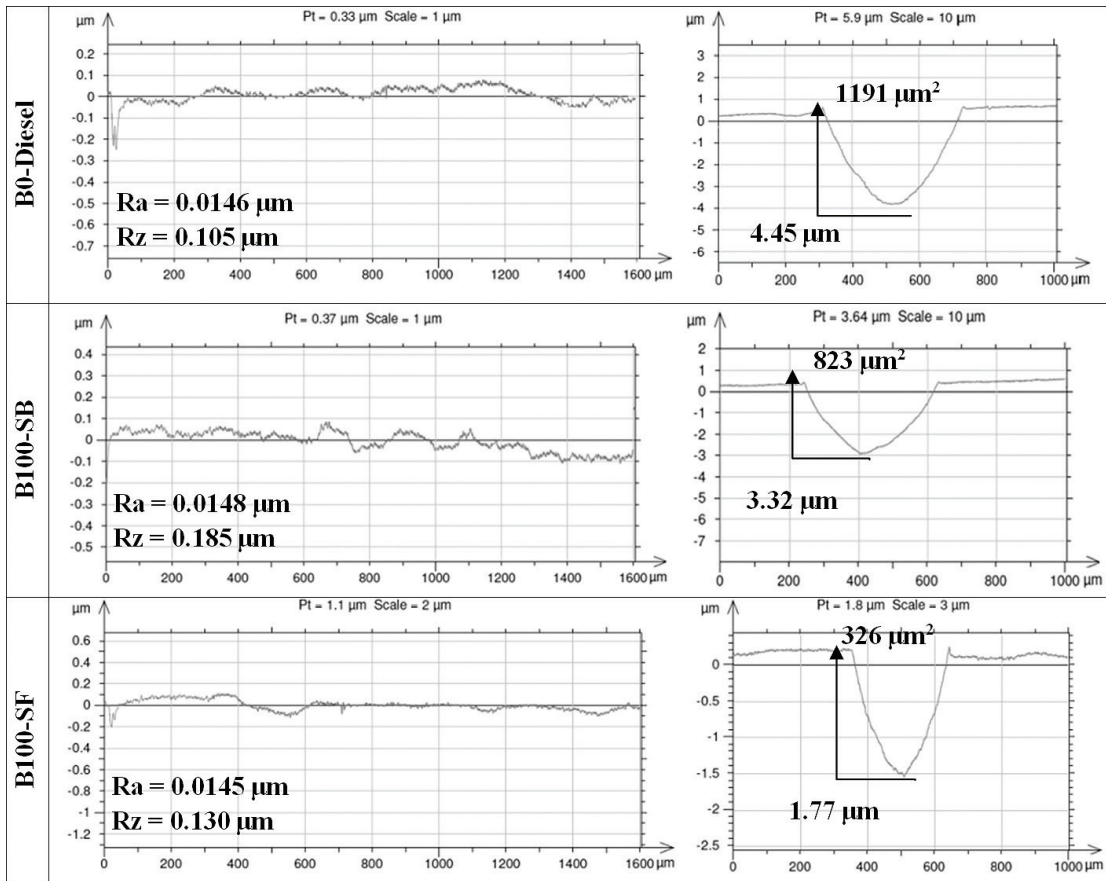


Figure 7. Roughness profile after lubricity tests with diesel and biodiesel fuels: on the left, new disc; on the right, role area of scar.

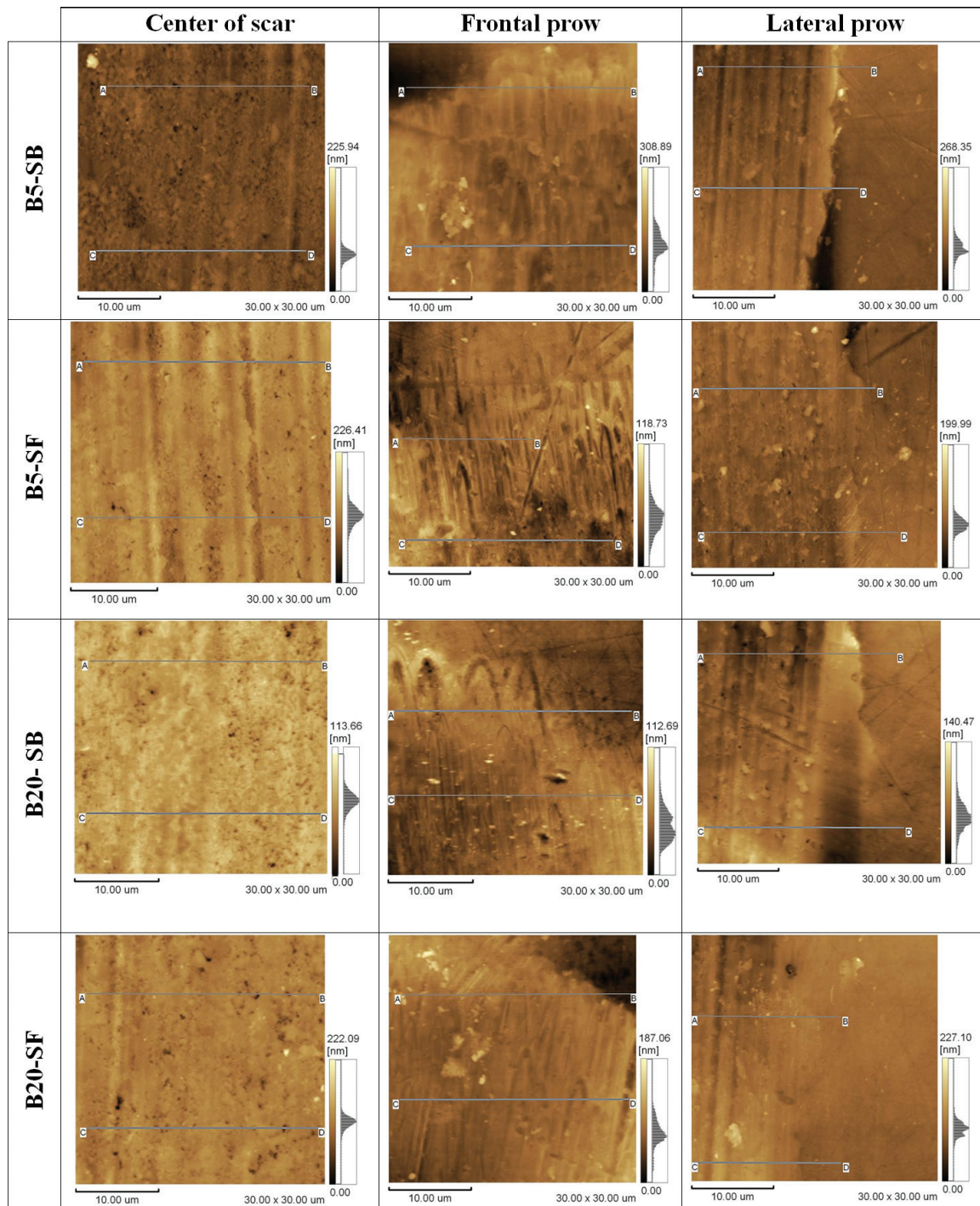
Table 4. Analysis of lubricity performance by the roughness and SEM techniques.

Scar values	Disc lubricated with						
	B5-SB	B5-SF	B20-SB	B20-SF	B100-SB	B100-SF	B0-Diesel
Max. Depth ( $\mu\text{m}$ )	1.91	1.60	1.44	1.73	3.32	1.77	4.45
Area ( $\mu\text{m}^2$ )	317	316	241	329	823	326	1191
Length (mm)	1.163	1.187	1.182	1.164	1.141	1.108	1.322
WS1.4 <sub>(ball)</sub> ( $\mu\text{m}$ )	211	192	198	210	269	198	345
Better Lubricity	5°	2°	1°	4°	6°	3°	7°

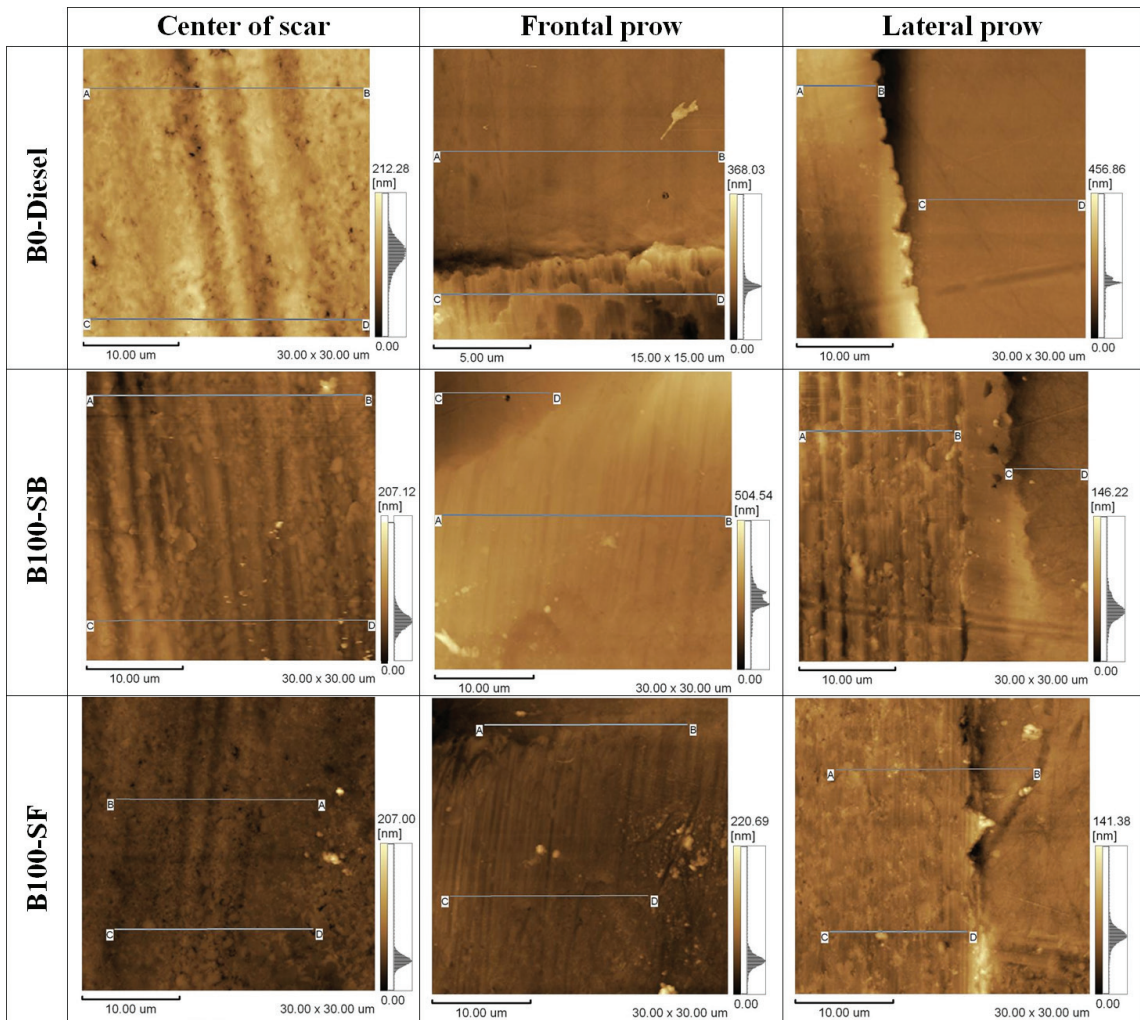
Table 5. Ra and Rz microroughness parameters by AFM analysis.

Fuel	Location	Ra (nm)		Rz (nm)		Fuel	Location	Ra (nm)		Rz (nm)	
		A-B	C-D	A-B	C-D			A-B	C-D	A-B	C-D
B20-SB	Center	6.55	5.28	47.31	32.62	B0-Diesel	Center	17.19	19.17	113.71	106.82
	Frontal	10.18	10.25	57.15	44.85		Frontal	5.57	30.63	31.12	143.75
	Lateral	15.53	14.88	68.25	60.87		Lateral	23.12	2.02	112.55	17.87
B5-SB	Center	9.18	6.63	68.29	54.77	B100-SB	Center	12.44	12.19	73.53	81.13
	Frontal	40.21	15.03	181.45	78.26		Frontal	19.6	26.89	82.18	114.11
	Lateral	22.37	10.68	141.7	78.58		Lateral	7.89	6.32	51.79	26.64
B20-SF	Center	8.9	9.73	73.65	108.87	B100-SF	Center	4.94	4.87	32.2	32.12
	Frontal	14.97	9.45	102.65	57.59		Frontal	11.23	6.05	46.21	41.4
	Lateral	9.29	16.48	75.4	65.22		Lateral	8.84	4.94	75.12	59.52
B5-SF	Center	12.01	10.52	88.92	81.51						
	Frontal	6.65	13.11	34.99	72.31						
	Lateral	4.89	11.2	36.64	91.89						





**Figure 8.** Topographic disc scar images by AFM after lubricated contact with biodiesel blends: on the left, center of track; in the middle, frontal prow; and on the right, lateral prow of track.



**Figure 9.** Topographic disc scar images by AFM after lubricated contact with diesel and biodiesel: on the left, center of track; in the middle, frontal prow; and on the right, lateral prow of track.

#### 4. Conclusion

Based on results obtained in this research, some conclusions can be drawn:

- To determine the lubricity just as function of WS 1.4 don't demonstrate the real fuel lubrication performance, because it is susceptible to high variations due to the measurement method;
- The coefficient of friction shows that biodiesel pure are more effective on friction reduction, indicating a better formation of lubricant film. This result is not compatible with WS1.4 analyze that presents high values;
- It was possible to note that the maximum depth and area of scar showed proportional relationship with the WS1.4 number. The small values can be observed for use of biodiesel blends (5-20%);
- SEM and AFM techniques are good tools to evaluate tribological performance of different fuel. They give about intensity and nature of wear. The adhesion and abrasion were mainly wear mechanism observed in

the HFRR test. When diesel was used as fuel, the severe wear was observed, however the biodiesel addition decrease the wear and give a smooth surface;

- The use of the HFRR for studies in diesel fuel performance can be significantly increased when profile and surface evaluation is performed. The standard evaluation method delivering WS1.4 value turned out to be insufficient to evaluate the tribological performance.

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