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A Quantitative and Qualitative Analysis of the Lubricity of Used Lubricating Oil Diluted with Diesel Oil

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Abstract: Experience shows that dilution of lubricating oil with diesel oil is unfavorable to the engine, causing issues including deterioration of engine performance, shortening of oil life, and reduction in engine reliability and safety. This paper presents the verification of the hypothesis that the changes in lubricity, friction coefficient, and decreasing oil film thickness (using a relative approach, given as a percentage) are similar for lubricating oil and diesel mixtures prepared from fresh lubricating oil and used lubricating oil. To validate this hypothesis, an experiment is conducted using a high-frequency reciprocating rig (HFFR), in which the lubricity is determined by the corrected average wear scar $WS_{1.4}$, the coefficient of friction μ, and the percentage relative decrease in oil film thickness r. A qualitative visual assessment of the wear scars on the test specimens is also performed after the HFFR tests. The testing covers mixtures of SAE 30 grade Marinol CB-30 RG1230 lubricating oil with Orlen Efecta Diesel Biodiesel. The used lubricating oil is extracted from the circulating lubrication system of a supercharged, trunk-piston, four-stroke ZUT Zgoda Sulzer 5 BAH 22 engine installed in the laboratory of ship power plants of the Maritime University of Szczecin. Mixtures for the experiment are prepared for fresh lubricating oil with diesel oil and used lubricating oil with diesel oil. Mixtures of these lubricating oils with diesel oil are examined for diesel oil concentrations in the mixture equal to 1, 2, 5, 10, 15, and 20% m/m. The results of the experiment confirm the hypothesis, proving that, for up to 20% m/m diesel oil concentration in lubricating oil, the changes in the lubricity of used lubricating oil diluted with diesel oil can be evaluated based on reference data prepared for mixtures of diesel oil with fresh lubricating oil. The linear approximation of μ and r trends is made with a certain margin of error we estimated. The experiment also confirms the results of previous studies which state that oil aging products in small quantities contribute to improved lubricity.

Keywords: fresh lubricating oil; used lubricating oil; diesel oil; fuel dilution; lubricity; high-frequency reciprocating rig; HFRR

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1. Introduction

Lubricity is a characteristic of a tribological system that describes the ability of lubricant molecules to adhere to lubricated surfaces and form permanent layers on them that reduce friction. When two different oils share the same viscosity, the one with superior lubricity yields less friction loss under analogous operating conditions, thereby minimizing wear between mating parts [1]. High lubricity is crucial for engine reliability, especially during boundary or mixed lubrication scenarios—such as engine maneuvering, starting, and

stopping. In particular, marine main propulsion engines with a fixed propeller are exposed to such scenarios [2].

Lubricity refers to how effectively a lubricant reduces friction and wear. Unlike a material property, it cannot be directly measured. Instead, specific tests are conducted to evaluate a lubricant's performance within a particular system. Various types of tribometers are used to determine lubricity. In this experiment, we used a high-frequency reciprocating rig (HFFR) tribometer, and the corrected average wear scar diameter $WS_{1.4}$ test conditions were taken as a measure of wear. Both the operation of the device and the method of determining the size of the wear trace are described later in the article, and the correct wear scar diameter $WS_{1.4}$ in test conditions was taken as a measure of lubricity.

The lubricity of oils for heavy-duty internal combustion engines is achieved by using extreme pressure (EP) additives in the form of organic compounds of phosphorus, sulfur, oxygen, and other elements. Oil lubricity is also improved by natural oil aging products such as asphalt, resins, or organic acids, added in low concentrations. These contaminants contribute to the improved adhesion of oil to lubricated components of lubricating oils [1].

On the other hand, when the oil contains organic impurities above 2.1% m/m or asphaltenes above 0.15% m/m, the wear intensity of the tribological pair does not decrease [3], as shown in Figure 1. With an increase in contamination in the lubricating oil (LO), new risks of filter contamination, clogging of oil pipes, deposition of lakes and carbon deposits on lubricated surfaces, deterioration of heat transfer, galling of piston rings, and overheating of engine components occur. All these elements increase the wear and tear of engine components and shorten their life [4].

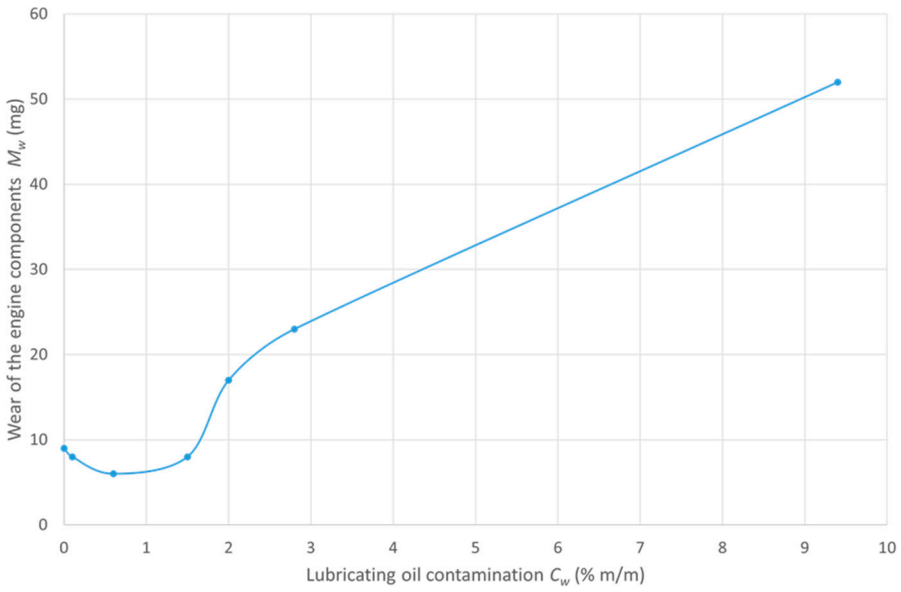


Figure 1. Relationship between the engine component wear and contaminant particulate concentration in lubricating oil (compiled based on ref. [3]).

Engine life can be influenced by an important contaminant, which is fuel that mixes with oil due to a malfunctioning injection system, drainage system, fuel leakage, and damaged or excessively worn piston rings, pistons, and cylinder liners. Experience shows that dilution of lubricating oil (LO) with diesel oil (DO) is unfavorable to the engine, causing issues including deterioration of engine performance, shortening of oil life, and reduction in engine reliability and safety [5,6]. An excessive, progressive dilution of oil with fuel can lead to significant wear and tear, and, ultimately, to serious engine failure. The analysis of such phenomena can be supported by control computational models (computational tribology) that enable the automation of the oil condition checking process using computer systems [7].

The oil film is crucial for reducing the coefficient of friction at tribological junctions. The main problem with the dilution of LO with DO is the reduced viscosity of the LO since diesel oil (DO) has a much lower viscosity than LO. Therefore, the dilution of LO can cause a deterioration of the lubricating properties of the given oil and a reduction in the strength of the oil film, which, in turn, contributes to the intensification of the wear of cylinder liners and bearings [8,9], as well as the possibility of causing premature ignition in the engine cylinder [10].

This problem becomes even more significant when lubricating oils are diluted with DO containing biocomponents, such as fatty acid methyl esters (FAME) [11,12]. In such a case, the LO/DO mixture may not only exhibit deteriorated lubricity properties [13] but also significantly reduce thermal and oxidative stability [14,15], and such a mixture may intensify the corrosion processes in the engine [16].

Some previous studies indicated that as little as 2–5% [17] or 3–5% [10] of DO in LO can pose risks to the engine, which coincides with the requirements mentioned in the literature regarding the allowable change in the viscosity value and flash point of LO in an engine during operation. According to these recommendations, the kinematic viscosity of the oil used in the engine, relative to the viscosity of fresh oil, determined at the reference temperature (40 °C or 100 °C) should not change by more than −10% to +10%, considered the warning range [18], or by more than −20% to +30% [1], taken as the alarm range (preventive action is then required). According to the 2008 CIMAC recommendation, the viscosity alert levels are −20% to +25% at 40 °C and −15% to 15% at 100 °C, while the alarm levels are −25% to +45% at 40 °C and −10% to +25% at 100 °C [19]. According to other recommendations, the kinematic viscosity of circulating LO at 100 °C should not decrease by more than 3.0 mm^2/s or increase by more than 3.5 mm^2/s relative to the value for fresh oil [20].

The dilution of LO with DO has a complex effect on changing the lubricity of the oil itself. The reasons for this are the simultaneous change in the viscosity and density of the LO/DO mixture, the change in its volatility, and its chemical composition [21]. The relatively good lubricity of today's distillation fuels makes the resulting situation even more complex due to additives to DO that improve their ability to form a boundary layer [22].

For marine distillate fuels with a sulfur content of less than 500 mg/kg (0.050% m/m), the permissible value of lubricity described as the corrected mean scar diameter of the sample during the test, $WS_{1.4}$, according to ISO 8217:2017 [23], must not exceed 520 µm when measured at 60 °C with the high-frequency reciprocating rig (HFFR) apparatus. In this instance, the DO used in the experiment contained 6.4 mg/kg of sulfur, and, as per the PN-EN ISO 590+A1:2017-06 standard [24], the local RMG [25] requirements, and the ZN-ORLEN-5:2019 [26] standard, the allowable sulfur content must not exceed 10 mg/kg. These requirements are specified in ISO 12156:2018 Part 2 [27]. On the other hand, according to the mentioned standards, the allowable value of the corrected wear scar $WS_{1.4}$ in the test sample, which is a measure of lubricity for DO, must not exceed 460 µm. In contrast, ASTM D975 [28] indicates a maximum allowable value of $WS_{1.4}$, which equates to 520 µm for DO. However, the Worldwide Fuel Charter Edition 5 [29] recommends $WS_{1.4} \leq 400$ µm for DO in categories 4 and 5 (markets with advanced requirements for emission control [30]).

Considering the factors mentioned above and the complex nature of changes in lubricity in LO diluted with DO, the authors conduct an experiment to determine the nature of these changes and the impact of oil aging and engine component wear on the results. To achieve this aim, comparative measurements of lubricity are made as a function of DO concentration in LO for mixtures of fresh and ULO. A study of DO concentrations in mixtures up to 20% m/m is undertaken, which basically covers any situation encountered in operating conditions where the dilution level usually does not exceed a few percent. The concentration range is also determined based on previously published research results by various researchers, aiming to maintain data reproducibility and enable their comparison. The lubricity measurement is further improved by determining the nature of changes

in auxiliary indicators, such as the friction coefficient and the relative reduction in the thickness of the oil film during the lubricity test of the LO and DO mixture.

Among the many different methods of evaluating lubricity, three have basically found wide industrial use [30]: the high-frequency reciprocating rig (HFFR) [31], the ball-on-cylinder lubricity evaluator (BOCLE) [32], and the scuffing load ball-on-cylinder lubricity evaluator (SLBOCLE) [33]. The HFFR method is utilized in this experiment because many fuel quality standards specify lubricity determined by the HFFR method, which has several advantages over other lubricity determination methods. Among the most important advantages of the HFFR method are factors such as [34]:

- Evaluation of the wear pattern of standardized samples only requires one measurement;
- The use of a very small amount of lubricating fluid in a single measurement;
- The low price of the samples and the ability to conveniently configure them to best replicate real friction conditions;
- Good repeatability and reproducibility of measurements;
- The ability to measure changes in electrical contact potential during a lubricity test allows for the evaluation of lubricity-enhancing additives;
- The possibility of conducting additional fretting wear tests on the same bench by using "long-strokes".

The authors proposed the hypothesis that the nature of changes in lubricity, friction coefficient, and the percentage relative decrease in oil film thickness is similar for lubricating LO/DO mixtures made from fresh lubricating oil (FLO) and used lubricating oil (ULO). The similarity concerns the possibility of presenting changes in each parameter using a linear function, where the input variable is the concentration of diesel oil considering a certain determination coefficient and an average error for each approximation.

It must be mentioned that the linear approximation of μ and r trends is just a hypothesis that we made with a certain margin of error we have estimated. There exists a possibility to build more complex models (e.g., polynomial) but with better fitting to the experimental data.

Therefore, the laboratory findings for FLO mixtures can be utilized to assess the impact of diluting ULO and, consequently, can be employed to evaluate the properties of oils collected from the circulating lubrication system during engine operation. To verify the truth of this hypothesis, a laboratory experiment is conducted to determine specific quantitative indicators and qualitatively assess the wear scar, the results of which are presented in this article.

2. Materials and Methods

The LO used in the experiment was Marinol CB-30 RG1230 [35,36] viscosity grade SAE 30 LO designed for trunk-piston marine engines and Orlen Efecta Diesel Biodiesel oil [26,37]. Samples of fresh oil and samples of ULO for testing were taken from the lubrication system of the ZUT Zgoda Sulzer 5BAH22 engine installed at the Marine Power Plant Laboratory of the Maritime University of Technology in Szczecin. The calendar operation time of the ULO at the time of collection was 2 years, and the engine operating time was 60 h.

A comparison of the basic physicochemical properties and elemental composition of the LO and DO used in the experiment is shown in Tables 1 and 2, respectively, while the contaminations present in the ULO are summarized in Table 3. All values presented in Tables 1 and 3 were determined in our laboratory using the methods given in the first column of the tables. Content of chemical elements presented in Table 2 was determined with use of ASTM D6595-17 (2022) method [38].

Table 1. Properties of tested lubricating oils (fresh and used) and diesel oil.

Parameter (Measurement Method Used in This Experiment)	Unit	Value		
		FLO	ULO	DO
Density at 15 °C (PN-EN ISO 12185:2002 [39])	kg/m^3	890.6	889.6	828.3
Kinematic viscosity at 40 °C (PN-EN ISO 3104:2021-3 [40])	mm^2/s	110.310	102.740	2.480
Kinematic viscosity at 100 °C (PN-EN ISO 3104:2021-3 [40])	mm^2/s	11.770	11.420	1.067
Viscosity index (ASTM D2270-10(2016) [41], Anton Paar calculator [42])	–	94.13	94.13	274.35
Initial boiling point (Flashpoint Pensky–Martens apparatus [43])	°C	276.0	240.5	175
Flashpoint in closed cup (PN-EN ISO 2719:2016 [44])	°C	216.0	190.0	56.0
Derivated Cetane Number (ASTM D7668(2017) [45])	–	N/A	N/A	52
Lubricity—HFFR wear scar diameter (PN-EN ISO 12156-1:2018 [27])	µm	212	149	331
HFFR friction coefficient (HFFR V.1.0.3 procedure [34])	–	0.123	0.121	0.191
Relative oil film resistance drop (HFFR V.1.0.3 procedure [34])	%	100	100	76

Table 2. Chemical composition of tested Marinol RG 1230, tested lubricating oils (fresh and used) and Orlen Efecta Biodiesel oil (measurements of 9 May 2024 with use of ASTM D6595-17 (2022) method [38]).

Chemical Element	Content (ppm)		
	FLO	ULO	DO
Fe	0.0	3.2	0.0
Cr	1.0	2.6	0.0
Pb	7.4	14.7	3.7
Cu	0.0	0.0	0.0
Sn	7.1	8.0	18.0
Al	5.8	6.0	5.3
Ni	7.5	15.2	4.6
Ag	0.7	0.6	0.3
Si	4.1	11.5	2.1
B	0.8	2.1	0.1
Na	4.9	7.4	4.6
Mg	0.1	0.8	0.2
Ca	4.8	7.3	3.1
Ba	0.0	0.0	0.0
P	0.0	0.0	0.0
Zn	1.1	4.1	0.0
Mo	2.1	2.3	1.0
Ti	0.0	0.0	0.0
V	0.0	0.0	0.0

Table 3. Content and contaminants of tested ULO (based on own measurements).

Parameter (Measurement Method Used in This Experiment)	Unit	Value
Content of DO (ASTM D8004-15 (2023) [46])	% m/m	0.01
Content of water (PN-EN ISO 12937:2005+AP1:2021-11P [47])	% m/m	0.05
Determination of total sediment (PN-ISO 10307-1:2001 [48])	mg/g	0.35
Determination of the content of the contaminant particulates (PN-ISO 4405:1994 [49])	mg/100 mL	77.1
Content of chemical elements (ASTM D6595-17 (2022) [38])	ppm	See Table 4

The experiment allowed for the testing of mixtures with concentrations of DO in LO. Samples of fresh and ULO were diluted with DO at concentrations of 0, 1, 2, 5, 10, 15, and 20% m/m. An RADWAG WPs 510/C/2 (Radom, Poland) precision laboratory balance with a minimum graduation d of 0.001 g served to prepare the samples. The calculated type-B standard uncertainties u_B [50] for the mass fractions of DO in the tested LO were C = 1% m/m—$u_B(C)$ = 0.026% by weight, C = 2% m/m—$u_B(C)$ = 0.010% m/m, C = 5% m/m—$u_B(C)$ = 0.002% m/m, and $C \geq$ 10% m/m—$u_B(C)$ = 0.001%.

Lubricity is the behavior of a lubricant during boundary friction; therefore, it is an ensemble characteristic since lubricating properties do not depend only on the parameters of the oil, but also on the mating elements (i.e., structural materials, contact geometry, and the type of movement) and their load [22]. The measurements were made with a high-frequency reciprocating rig (HFFR) tribometer, model HFFR V1.0.3 [34] (PCS Instruments, London, UK), to comply with ASTM D6079-22 [51] and PN-EN ISO 12156-1:2018 [27]. The size of the wear scar was determined using a standard optical (metallurgical) upright microscope HFR2 [52] (PCS Instruments, London, UK). The schematic diagram and laboratory setup of the HFFR device are shown in Figures 2 and 3.

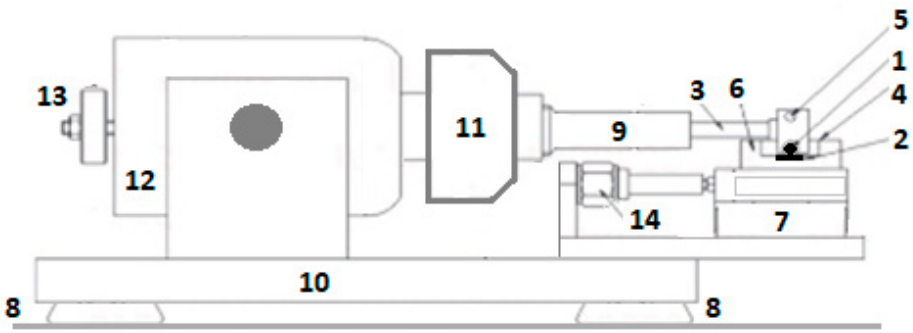


Figure 2. Schematic of the HFFR apparatus [31]: 1—test ball, 2—test plate, 3—oscillating rod, 4—test fluid reservoir, 5—test mass, 6—heating bath, 7—support, 8—controllable base, 9—elastic lock, 10—main frame, 11—elastic connector housing, 12—electromagnetic vibrator, 13—counterweight, and 14—force transducer.

During the test, the ball oscillates at a constant speed and makes a consistent stroke while the contact point of the ball with the plate is fully immersed in the liquid being tested. The test conditions, such as the metallurgical properties of the plate and ball, fluid temperature, load, oscillation frequency, stroke length, and external conditions, are specified in the standard [27]. The average wear scar diameter (*WSD*) formed on the surface of the test ball provides a measure of the lubricity properties (lubricity of the test fluid). Additionally, the device used provides information on the average value of the friction coefficient μ and the relative oil film resistance drop r, which measures the reduction in oil film thickness during the test execution.

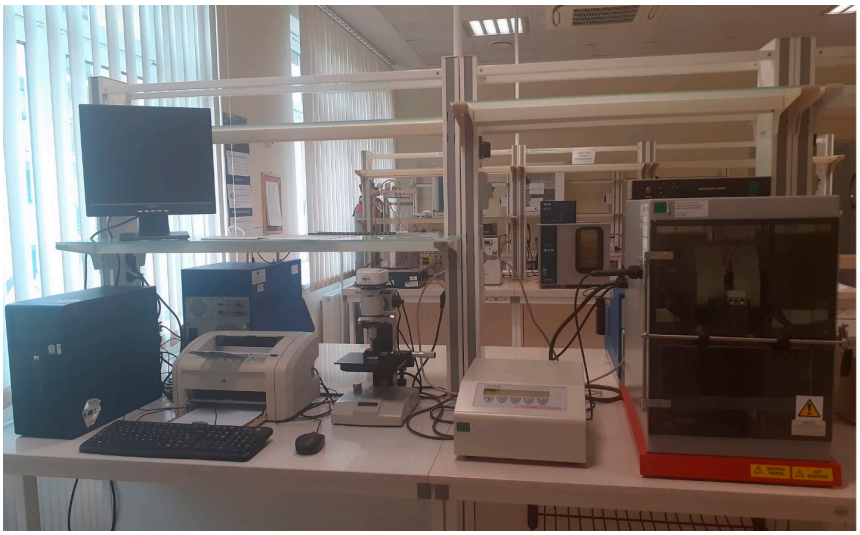


Figure 3. The PCS Instruments HFFR V1.0.3 instrument used in the experiment [53].

The average wear scar diameter *WSD* in micrometers (μm) is determined as the average value of the wear scar x (μm) measured perpendicular to the direction of ball oscillation and the wear scar y (μm) measured parallel to the direction of ball oscillation [54]. In order to be able to compare the results of the lubricity measurement in different external conditions, the standard measure of lubricity is corrected to a standardized water vapor pressure of 1.4 kPa. The wear scar diameter $WS_{1.4}$ indicator is calculated using the following formula [55]:

$$WS_{1.4} = \frac{x+y}{2} + 60 \cdot (1.4 - AVP), \quad (1)$$

where AVP (kPa) is the mean absolute vapor pressure of the tested lubricant liquid during the test [55].

$$AVP = \frac{\left(\frac{h_1 \cdot 10^{8.017352 - \frac{1705.984}{231.864 + t_1}}}{750}\right) + \left(\frac{h_2 \cdot 10^{8.017352 - \frac{1705.984}{231.864 + t_2}}}{750}\right)}{2}, \quad (2)$$

where h_1 (%) signifies the air humidity in the laboratory room at the beginning of the test, h_2 (%) is the air humidity in the laboratory room at the end of the test, t_1 (°C) is the temperature in the laboratory room at the beginning of the test, and t_2 (°C) is the temperature in the laboratory room at the end of the test.

For the measurement method used, the measurement error was not determined since lubricity is not a fundamental physical quantity and was not a property of the liquid being tested [51]. Repeatability of the lubricity measurement was ≤50 μm, and the reproducibility was ≤80 μm [51]. We repeated every measurement twice, and we further analyzed mean values of measurements. The differences in measurements we obtained for each sample did not exceed 30 μm. Taking into account the nature of the measurements in question, we consider this result to be sufficient for the research purpose adopted in the article.

Since the lubricity is not a fundamental physical parameter, and its values depend on external conditions, sample individual characteristics, and the local chemical composition of the lubricant, we had to adopt the interpretation for the coefficient of determination R^2 values for models built within our experiment, and we used the following thresholds [56]: $R^2 \geq 0.9$ is a very good fit, $0.9 > R^2 \geq 0.7$ is a good fit, $0.7 > R^2 \geq 0.5$ means a satisfactory fit, and $R^2 < 0.5$ means not a good fit.

In addition to measuring $WS_{1.4}$, the HFFR apparatus also allows for determination of the average value of the sliding friction coefficient μ and the relative oil film resistance drop r. We repeated every measurement twice, and we further analyzed mean values of measurements. The sliding friction coefficient for kinetic friction is the ratio of the frictional force F to the normal contact force N of the body on the ground (second body) during the

relative movement of these bodies (it is known as Amontons' Law of Friction or Coulomb's law of friction), i.e.,

$$\mu = \frac{F}{N}, \tag{3}$$

where F—frictional force, N—normal contact force.

The reduction in oil film thickness and its quality are determined using the parameter r, which is determined by measuring the electrical contact potential (ECP). We repeated every measurement twice, and we further analyzed mean values of measurements. After the test, the HFFR apparatus indicates the value of the relative oil film resistance drop in line with the following formula:

$$r = \frac{\Delta R}{R_1} \cdot 100\%. \tag{4}$$

where $\Delta R = R_1 - R_2$ is the absolute oil film resistance drop (Ω) from the initial resistance value R_1 to the final resistance value R_2 during the HFFR test.

If r is decreasing to a value equal to or close to zero, we assume that the metallic contact of cooperating elements has a place. On the other hand, values of the parameter r close to 100 indicate that the mating metal surfaces are separated by a film built from the tested oil [53].

As stated in the introduction, in addition the quantitative indicators mentioned, this experiment aimed to evaluate the qualitative aspects of the shape and nature of the wear observed on individual samples. In this instance, the focus was on the shape of the wear scar and the quantity and arrangement of local abrasive wear scars and grooves.

3. Results and Discussion

3.1. Quantitative Assessment of Lubricity

The corrected wear scar diameter $WS_{1.4}$ at 60 °C for the tested samples is shown in Figure 4. The $WS_{1.4}$ values for LO/DO mixtures in the concentration range studied were in the range of 163–212 µm for fresh oil mixtures and 79–217 µm for used oil mixtures. In both situations, the wear scar value decreased within the range C to 2% m/m, showing that the lubricating properties of the mixtures improve as the concentration of DO in the mixture increases. Thus, the lubricity of the mixture improves as the level of dilution with DO C increases.

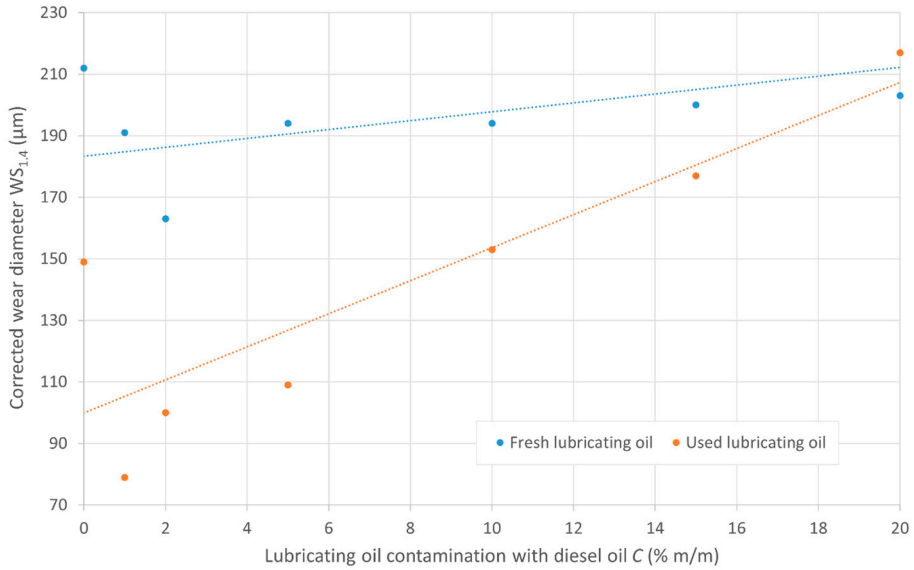


Figure 4. Variation in the corrected diameter of the wear scar $WS_{1.4}$ at 60 °C for the tested LO and diesel mixtures as a function of the DO concentration in the mixture.

Generally, the effect of LO/DO mixture on the lubricity of the mixture is complex and does not exhibit a consistent pattern of change (lubricity alternates between improvement and deterioration with increasing DO content in the LO mixture), as demonstrated in previous publications [53]. In contrast, in the present experiment for the concentration range of 2–20% m/m, the nature of changes in $WS_{1.4}$ values increased in general. The lubricity of used oil mixtures is improved compared to fresh oil because used oil contains oil aging products such as resins and organic acids, which improve the adhesion of oils to lubricated surfaces [57].

The relationship $WS_{1.4}$ = f(*C*) for FLO mixed with DO can be represented by a linear function of the following form:

$$WS_{1.4} = 1.4439\ C + 183.390, \quad (5)$$

This function is depicted in Figure 4 with a blue dotted line. The mean value of the measured $WS_{1.4}$ was 193.86 µm. The standard deviation for model (5) was 12.86 µm, and its root-mean-square error (RMSE) was 14.81 µm. The coefficient of determination for model (5) was $R^2 > 0.91$, indicating a very good model fit. For mixtures of ULO with DO, the relationship $WS_{1.4}$ = f(*C*) takes the following form:

$$WS_{1.4} = 5.3679\ C + 99.929, \quad (6)$$

This function is shown in Figure 4 with an orange dotted line. The mean value of the measured $WS_{1.4}$ was 140.57 µm. The standard deviation for model (6) was 42.98 µm, and its RMSE was 22.79 µm. The coefficient of determination of model (6) was $R^2 > 0.73$, which indicates a good fit of the model.

The graph of Figure 5 shows the average sliding friction coefficient μ of the specimen recorded during the ball wear test in the HFFR apparatus for the tested LO/DO mixtures. The values obtained exhibited some dispersion, with local fluctuations increasing and decreasing within the measured range, while the mixtures showed an overall increasing trend across the entire range studied.

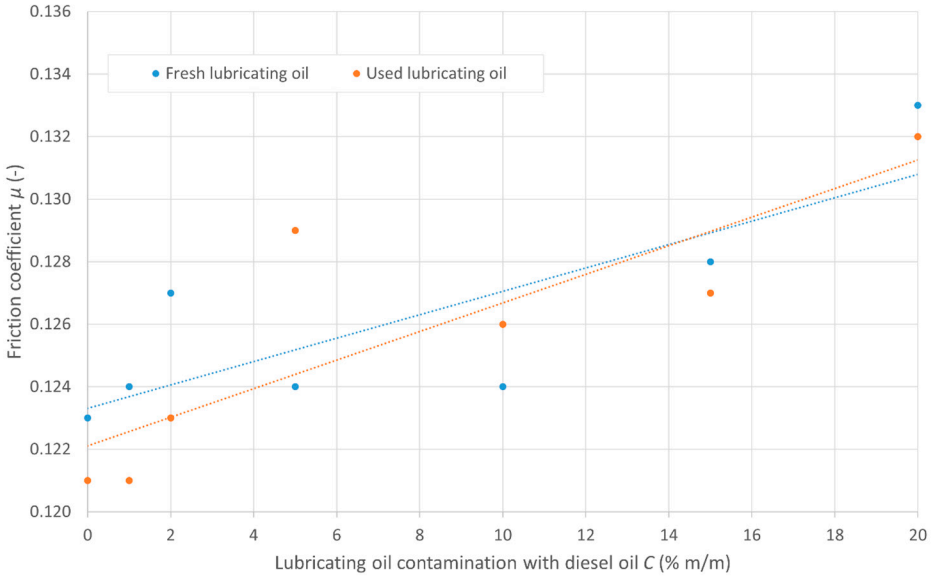


Figure 5. Sliding friction coefficient μ during the HFFR test for the tested mixtures of LO and DO varies with the concentration of DO in the mixture.

The values μ for LO and diesel mixtures in the studied concentration range fell within the range of 0.123–0.133 µm for the fresh oil mixtures and 121–132 µm for the used oil mixtures. The relationship μ = f(*C*) for both fresh and ULO mixtures can be represented as a linear function with a positive slope coefficient of the curve (showing an increasing

trend). Mixtures of FLO and mixtures of ULO can be described by similar functions since the values of these coefficients are similar for both lubricating oils.

For mixtures of FLO with DO, the relationship μ = f(*C*) can be modeled with the following function:

$$\mu = 0.0004\,C + 0.1233, \quad (7)$$

This function is shown in Figure 5 with a blue dotted line. The mean value of the measured μ was 0.126. The standard deviation for model (7) was 0.003, and its RMSE was 0.002. The coefficient of determination of model (7) was $R^2 > 0.66$, so the model fit was satisfactory. However, for mixtures of ULO with DO, the relationship μ = f(*C*) takes the following form:

$$\mu = 0.0004\,C + 0.1221, \quad (8)$$

This function is depicted in Figure 5 using the orange dotted line. The mean value of the measured μ was 0.125. The standard deviation for model (8) was 0.003, and its RMSE was 0.002. The coefficient of determination of model (8) was $R^2 > 0.71$, which indicates a good fit of the model. The linear approximation of μ trends is just a hypothesis that we made with the certain margin of error estimated above.

The obtained coefficient values of μ indicate that, as the DO content in the LO/DO mixture increases, the friction coefficient also increases. This is due to the decrease in mixture viscosity resulting from dilution with a lower viscosity component, leading to a reduction in the oil film thickness. The experiment in question did not include a detailed analysis of changes in the viscosity values of lubricating oils diluted with DO; this was presented in the articles of other researchers [58–60].

The graph of Figure 6 illustrates the percentage reduction in the thickness (resistance) of the oil film *r* recorded during the execution of the ball wear test in the HFFR apparatus for the tested LO/DO mixtures. The values obtained displayed some dispersion, with local increases and decreases within the measured range, while the mixtures exhibited a decreasing trend across the entire range under study.

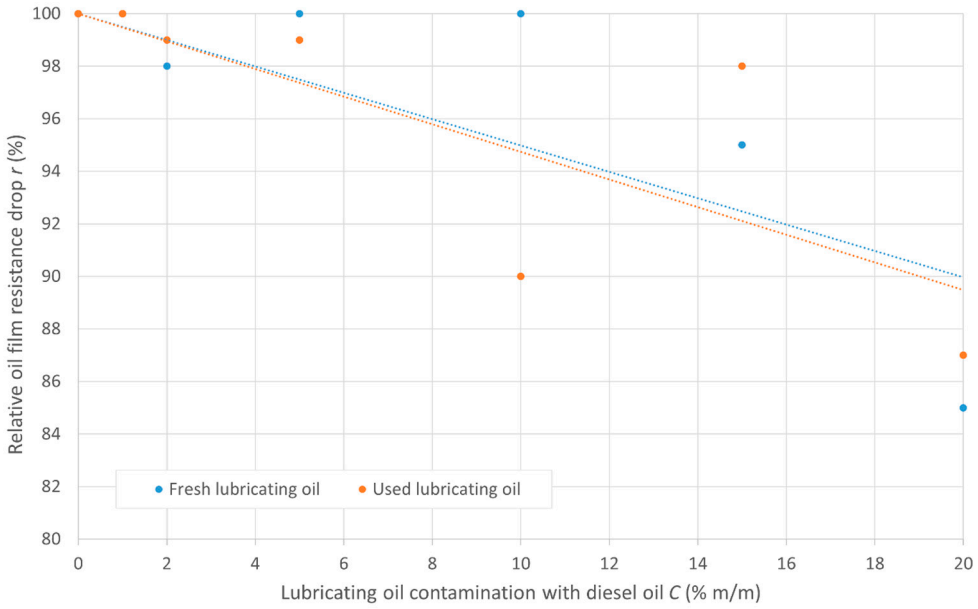


Figure 6. Coefficient of reduction in the thickness of the oil film r during the execution of the HFFR test for the tested LO and DO mixtures as a function of the concentration of DO in the mixture.

The values of *r* for LO and diesel mixtures in the tested concentration ranged from 100 to 85 µm for the fresh oil mixtures and from 100 to 87 µm for the used oil mixtures. The relationship *r* = f(*C*) for both FLO and ULO mixtures can be presented as a linear function with a negative value of the slope coefficient of the curve (a decreasing trend). Mixtures of

FLO and mixtures of ULO can be described by similar functions since the values of these coefficients are alike for both lubricating oils.

For all measurement points of the tested mixtures included in the experiment, we obtained boundary friction under test conditions. This was confirmed by the *r* indicator, referred to in other sources as the *FILM* parameter [31]. Its high values, determined during the HFFR tests and amounting to > 84, indicate that, during the lubricity measurement, there was no direct dry contact of the cooperating samples due to surfactant adsorption.

The obtained values of *r* show that, with an increase in the content of DO in the LO/DO mixture, the thickness of the oil film decreases and the risk of film breakage increases, which relates to the decrease in the viscosity of the mixture due to dilution with the lower-viscosity component.

For mixtures of FLO with DO, the relationship r = f(C) can be modeled with the following function:

$$r = -0.5020\ C + 100, \tag{9}$$

This function is presented in Figure 6 with a blue dotted line. The mean value of the measured *r* was 96.86%. The standard deviation for model (9) was 4.37%, and its RMSE was 3.02%. The coefficient of determination here was $R^2 > 0.69$, so the fit of model (9) was satisfactory. However, for mixtures of ULO with DO, the relationship r = f(C) takes the following form:

$$r = -0.5258\ C + 100, \tag{10}$$

This is shown in Figure 6 with an orange dotted line. The mean value of the measured *r* was 96.14%. The standard deviation for model (10) was 4.30%, and its RMSE was 3.08%. The coefficient of determination here was $R^2 > 0.61$, which indicates a satisfactory fit for model (10). The linear approximation of *r* trends is just a hypothesis that we made with the certain margin of error estimated above.

3.2. Qualitative Assessment of Lubricity

In addition to the standardized values of $WS_{1.4}$, auxiliary indicators μ, and *r* obtained during the HFFR test, the authors visually evaluated the wear scar on the ball surface. Table 4 presents a summary of the specific scars for mixtures of LO with diesel in mixtures with FLO and mixtures with ULO.

Table 4. A view of the sample's wear scar during HFFR tests performed with the HFR2 microscope.

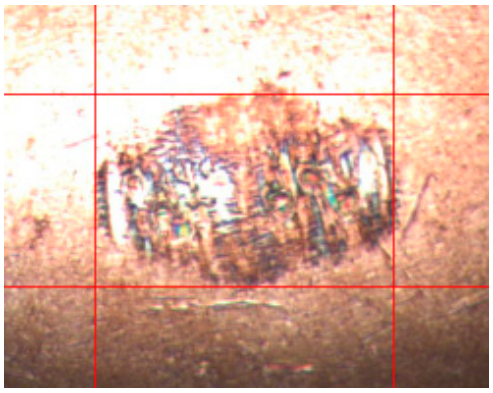
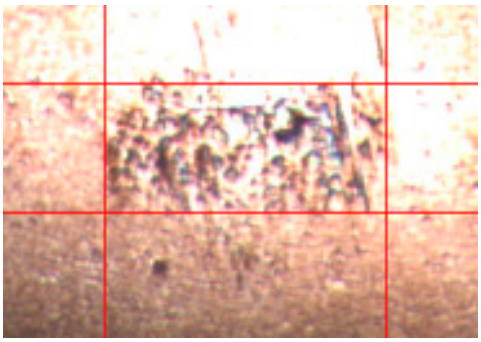
DO Concentration *C* (% m/m)	**LO Diluted with DO**	
	FLO	**ULO**
0		

Table 4. *Cont.*

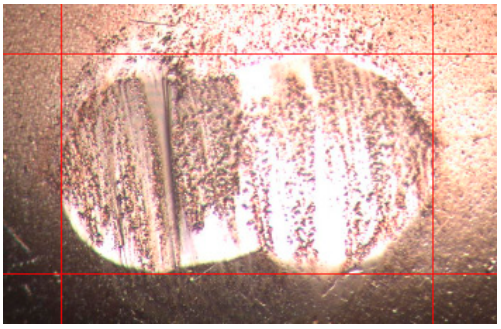
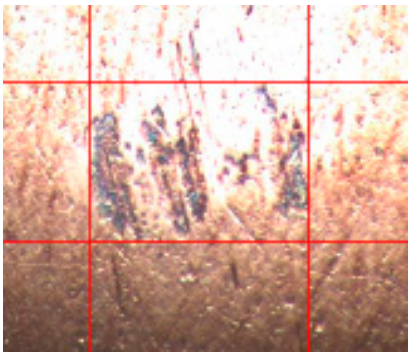
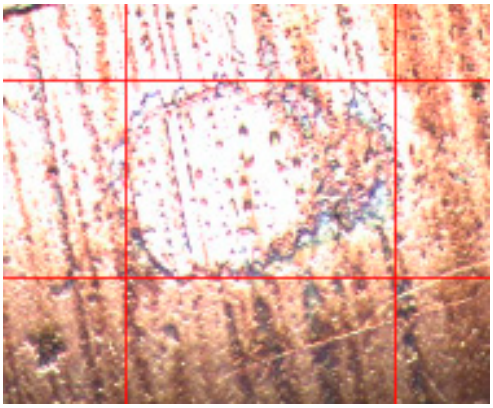
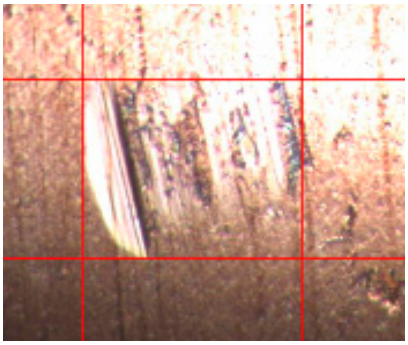
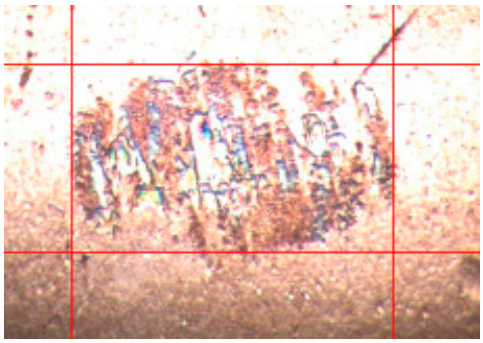
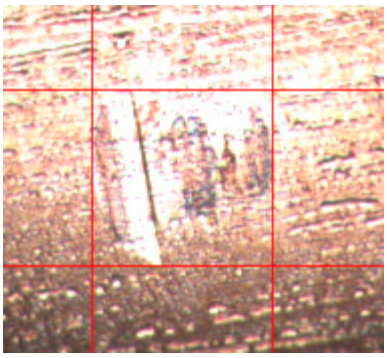
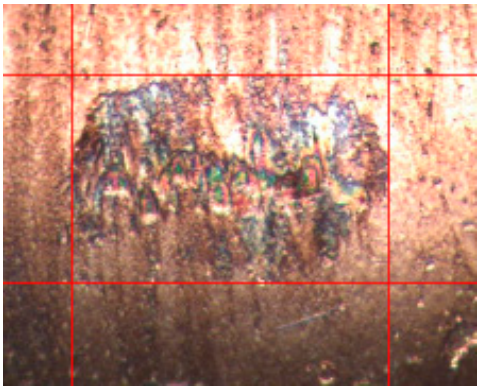
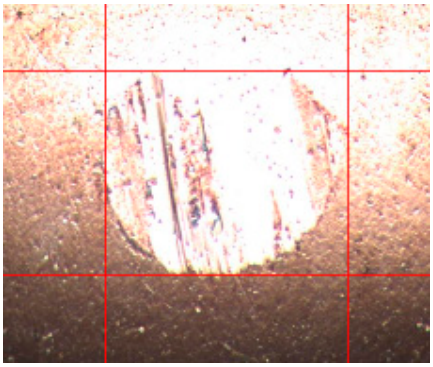
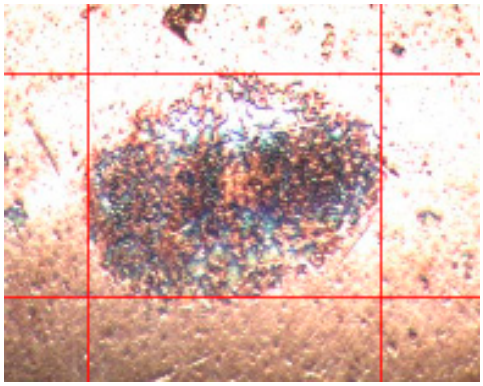
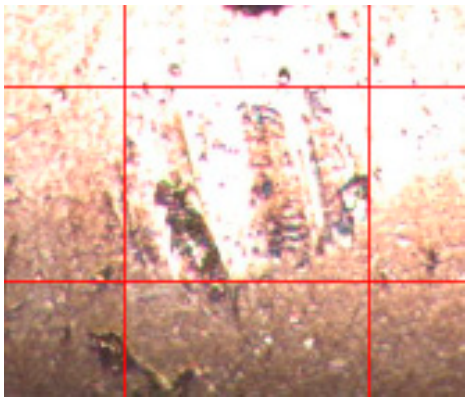
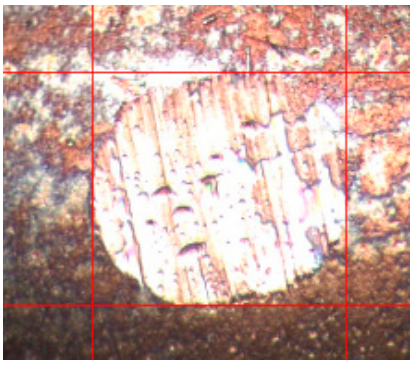
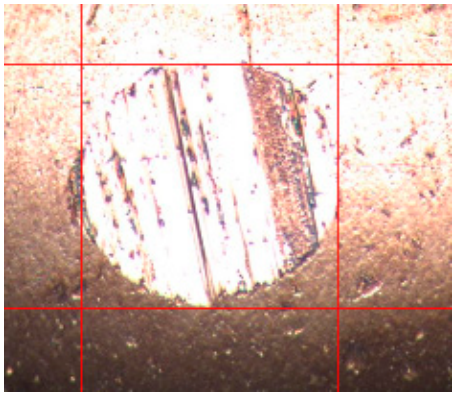
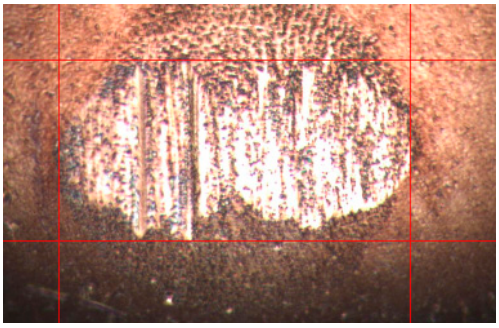
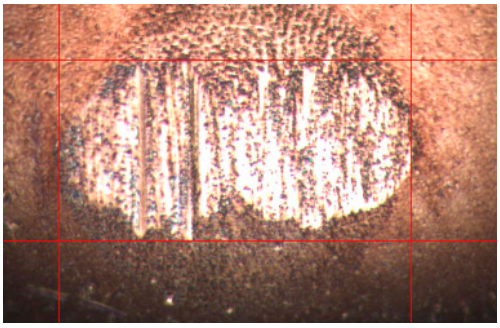
DO Concentration *C* (% m/m)	LO Diluted with DO	
	FLO	**ULO**
1		
2		
5		
10		

Table 4. *Cont.*

DO Concentration *C* (% m/m)	LO Diluted with DO	
	FLO	ULO
15		
20		
100		

The more oval shape of the wear scar recorded on the samples when testing FLO mixtures is noticeable. On the other hand, the wear scar during the testing of ULO samples was more uniform in both directions (similar to a circle). The reason can be attributed to the improved lubricity of used oils compared to fresh oils. This is explained by the presence of oil aging products, such as resins and organic acids, in their composition, which increases the adhesion of oil to the friction surface of the sample.

The location of the depressions in the wear scar also differed for wear scars on samples mating with mixtures of DO with fresh and ULO. In the first case, the wear was point-like (micro-cutting, plastic deformation, and scratching). On the other hand, for samples cooperating with mixtures of DO and ULO, we observed parallel grooves running through the entire length of the wear scar, indicating the dominant influence of plastic deformation. The reason for this is the contamination with solid particles suspended in the oil, which are the result of engine component wear.

The depth of the wear scar may accompany a slight increase as the concentration of DO in the mixture increases, but these variations are not consistent and could be due to random factors such as the local chemical composition of the lubricant, impurities dispersed in the oil, different viscosity, volatility of the tested mixtures, and so on. Due to the complexity of the wear process being analyzed, further long-term research is required to determine the detailed geometric relationships. This is beyond the scope of this experiment.

4. Conclusions

The conducted tests confirmed the research hypothesis that the changes in lubricity, coefficient of friction, and percentage relative decrease in oil film thickness are similar for LO/DO mixtures prepared with fresh and ULO. The presented models and methods can be used in computational tribology as an element of the research process. The linear approximation of μ and r trends is just a hypothesis that we made with a certain margin of error we have estimated. In the future, other, more complex approximation models (e.g., polynomial) might be made but with a higher value of the coefficient of determination.

Dilution of LO with DO has an effect on lubricity, which was improved for the cases in question in the concentration range of DO in 0–2% m/m mixtures in comparison to the undiluted LO. On the other hand, at higher concentrations of DO in the mixtures ($C > 2\%$ m/m), lubricity of the mixture will deteriorate (the size of the wear scar increases up to a maximum value corresponding to pure DO).

The lubricity of mixtures containing ULO exhibits an upward trend with a steeper slope in comparison to the mixtures based on the FLOs, which is attributed to the presence of oil aging products such as resins, organic acids, and relatively small amounts of asphaltenes in the mixture. As the DO content increases, the viscosity of lubricating LO/DO mixtures decreases simultaneously, leading to a deterioration in lubrication conditions. This results in an increase in the coefficient of friction and a decrease in oil film thickness. The regression model for the friction coefficient and oil film thickness did not show significant differences for the tested concentrations of DO in LO whether the mixtures were prepared using FLO or ULO.

A qualitative visual assessment of the wear scar on the bead's surface confirmed an increase in the intensity of wear when conducting tests in a mixture with a higher concentration of diesel oil in the LO. At the same time, micro-milling marks were observed across the entire surface of the wear scar. In tests involving mixtures of DO with ULO, the occurrence of furrowing was observed. This may be attributed to the presence of metallic impurities in the LO, which are products of wear on engine components.

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Abbreviations

ASTM	American Society for Testing and Materials
AVP	average absolute oil vapor pressure during the HFFR test
BOCLE	ball-on-cylinder lubricity evaluator
C	exact (expected) mass concentration of DO in the lubricating oil
CIMAC	The International Council on Combustion Engines e.V. (Fr. Conseil International des Machines à Combustion)
C_w	concentration of solid impurities in the lubricating oil
DIN	German Institute for Standardization (Ger. Deutsches Institut für Normung e.V.)
DO	diesel oil
EP	extreme pressure lubricating oil additives
f(*C*)	function with dependent parameter *C*
FAME	fatty acid methyl esters
F	frictional force
FLO	fresh lubricating oil
h_1	air humidity in the laboratory room at the beginning of the HFFR test
h_2	air humidity in the laboratory room at the end of the HFFR test
HFFR	high-frequency reciprocating rig
ISO	International Organization for Standardization
LO	lubricating oil
M_w	wear of engine components
N	normal contact force
r	relative oil film resistance drop
ΔR	absolute oil film resistance drop
R_1	oil film resistance at the beginning of the HFFR test
R_2	oil film resistance at the end of the HFFR test
R^2	coefficient of determination
RMSE	root-mean-square error
SAE	Society of Automotive Engineers
SAE 30	viscosity grade of lubricating oils according to the SAE J300-2021 standard
SLBOCLE	scuffing load ball-on-cylinder lubricity evaluator
t_1	air temperature in the laboratory room at the beginning of the HFFR test
t_2	air temperature in the laboratory room at the end of the HFFR test
u_B	type-B standard uncertainty
ULO	used lubricating oil
$WD_{1.4}$	normalized HFFR wear scar diameter
WSD	mean wear scar diameter
x	average size of the wear scar in the direction perpendicular to the axis of oscillation of the HFFR tribometer
y	average size of the wear scar parallel to the axis of oscillation of the HFFR tribometer
μ	friction coefficient

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