

Article

Study of the Relationship between the Level of Lubricating Oil Contamination with Distillation Fuel and the Risk of Explosion in the Crankcase of a Marine Trunk Type Engine

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Abstract: Fuel contamination of engine lubricating oil has been previously determined to arise from two independent phenomena: the effect on oil flash point, and the effect of changing lubrication conditions on tribological pairs. This paper combines these effects and holistically analyzes the consequences of fuel in the lubricating oil of a trunk piston engine on the risk of crankcase explosion. The author hypothesized that diesel fuel as an oil contaminant increases the risk of an explosion in the crankcase of an engine due to the independent interaction of two factors: (1) changes in the oil's combustible properties, and (2) deterioration of the lubrication conditions of the engine's tribological nodes, such as main bearings, piston pins, or crank bearings. An experiment was performed to evaluate the rheological, ignition, and lubrication properties of two oils (SAE 30 and SAE 40) commonly used for the recirculation lubrication of marine trunk piston engines for different levels of diesel contamination. The hypothesis was partially confirmed, and the results show that contamination of the lubricating oil with diesel fuel in an amount of no more than 10% does not significantly affect the risk of explosion in the crankcase. However, diesel concentrations above 10% call for corrective action because the viscosity index, lubricity, coefficient of friction and oil film resistance change significantly. Deterioration of the tribological conditions of the engine bearings, as seen in the change in viscosity, viscosity index, and lubricity of the oil, causes an increase in bearing temperature and the possibility of hot spots leading to crankcase explosion.

Keywords: trunk type engine; crankcase explosion; lubricating oil properties; oil dilution with distillation fuel; lubricity; flash point temperature



Citation: Chybowski, L. Study of the Relationship between the Level of Lubricating Oil Contamination with Distillation Fuel and the Risk of Explosion in the Crankcase of a Marine Trunk Type Engine. *Energies* **2023**, *16*, 683. <https://doi.org/10.3390/en16020683>

Academic Editors: Haifeng Liu and Zongyu Yue

Received: 25 November 2022

Revised: 27 December 2022

Accepted: 4 January 2023

Published: 6 January 2023



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1. Introduction

1.1. Genesis of Undertaking the Research Topic

There have been many research papers report analyses on the mechanism of detonation in vapor cloud explosions [1–3]. Crankcase explosions still occur across many marine internal combustion engine types (two- and four-stroke; slow, medium, and fast speed; single and dual fuel) [4–6]. Such explosions damage the engine and its immediate surroundings [7,8], and often cause serious injury and death to crew members [4,6,9].

By virtue of their design, trunk piston engines are prone to hot gas and fuel blow-throughs from the combustion chamber into the crankcase when piston rings, pistons, and cylinder liners malfunction or are damaged [10]. The pistons and sealing rings separate the crankcase from the combustion chamber [11,12]. Hot gas blow-through into the crankcase can cause increased oil evaporation or ignition [13–15].

An explosion can also be caused by diesel oil entering the crankcase through a cracked piston bottom (crown). The risk is exacerbated by the possibility of fuel entering the crankcase, e.g., from a malfunctioning injection apparatus [16–18]. Explosion in the crankcase of trunk piston engines is also associated with increased temperatures outside the engine [19], i.e., due to a nearby fire or maintenance work performed in violation

of health and safety regulations (e.g., welding or grinding) [4]. Figures 1 and 2 summarize the most important locations responsible for crankcase explosions for in-line cylinder and V-shaped cylinder arrangement engines, respectively [11].

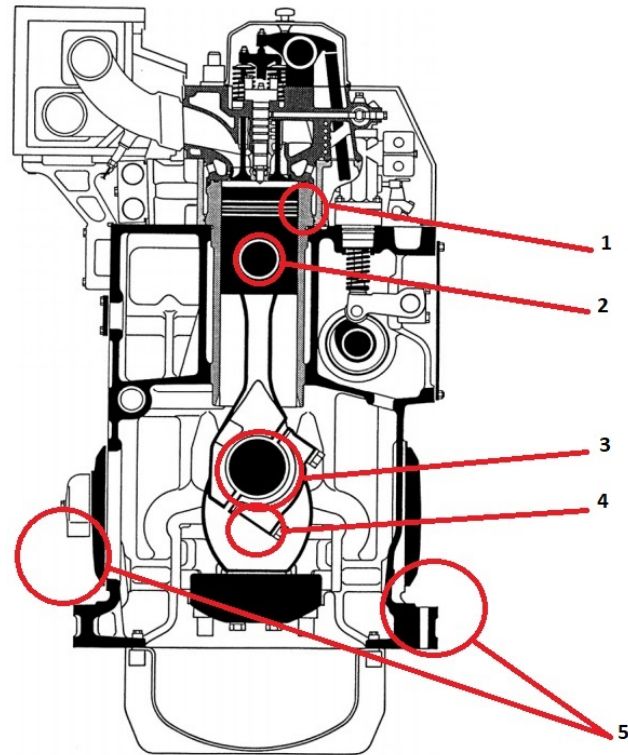


Figure 1. Components of an inline trunk type engine and its surroundings that can cause an explosion in the crankcase [11]: 1—cylinder liner, piston, piston rings; 2—gudgeon pin bearing; 3—crank pin bearing; 4—main bearing; 5—engine environment.

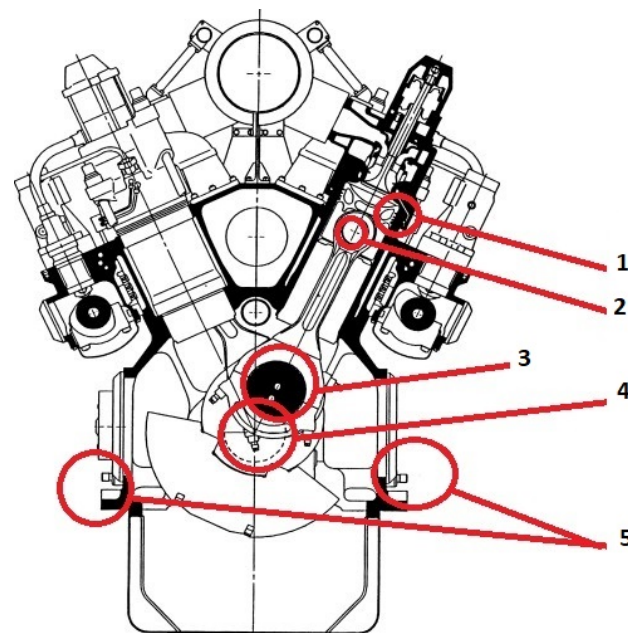


Figure 2. Components of a V-shape trunk type engine and its surroundings that can cause an explosion in the crankcase [11]: 1—cylinder liner, piston, piston rings; 2—gudgeon pin bearing; 3—crank pin bearing; 4—main bearing; 5—engine environment.

Regulations require that marine engines be equipped with appropriate instrumentation to monitor crankcase conditions (e.g., oil mist detectors and/or crank-piston cartridge bearing thermometers) and/or gas sensors and explosion valves [20–23]. The conditions for the formation of crankcase explosion (CCE) have been discussed in detail in a number of publications [24–26].

Fuel has a lower flash point than lubricating oil (minimum 60 °C), and its presence could theoretically contribute to a crankcase explosion that would not have occurred otherwise. Other authors have pointed out that fuel in oil is among the factors increasing the risk of crankcase explosion [27], or indicating that volatility or flash point (FP) of lubricating oil differentiates the category of liquid-fuels two-phase explosions [28]. For safety, the circulation oil is subjected to periodic laboratory measurement of its viscosity and flash point [11]. In practice, a 2–5% fuel dilution is considered excessive and calls for immediate maintenance [29]. The causes of lubricating oil contamination with fuel and recommended corrective actions are shown in Appendix A Table A1 [30].

The present article is a critical response to the publication “Guideline on the relevance of lubrication flash point in connection with crankcase explosions” published by CIMAC (the International Council on Combustion Engines) Working Group 8 “Marine Lubricants” [31]. Among its conclusions is the statement: “Flash point testing of lubricating oils as an accurate or early indicator of the potential risk of a crankcase explosion has not been proven and so it is no longer recommended for this purpose”. Since CIMAC is a generally recognized organization with a high opinion-forming influence, the author of this article undertook to verify the publication’s statements. The purpose of this investigation was to settle the dispute among experts regarding the effect of fuel contamination of engine-circulating oil on the risk of crankcase explosion.

The CIMAC publication [31] presents the following information in a concise way:

- main conditions required for crankcase explosion;
- methods of crankcase explosion risk detection;
- methods of crankcase explosion prevention and minimizing the effects;
- list of rules, standards, and regulations;
- description of secondary explosion phenomena;
- analysis of lubricant flash point as a reliable indicator for the risk of crankcase explosion.

The CIMAC publication’s conclusions [31] were drawn based on investigations conducted by its authors, but no source documents were identified. It states that “fuel contamination of lubricating oil has not been detected or reported in any of the reported cases of crankcase explosions occurring in recent years”. This observation is debatable. That the authors did not record such a situation in their reports does not invalidate the possibility. Often, the detailed and exact causes of explosions are not fully known or are not always disseminated to the public.

The publication [31] further states: “the latest research results also demonstrate that fuel-contaminated oil does not increase the risk of a crankcase explosion” and “as such flash point measurement of a lubricating oil is not a reliable or an early indicator for detecting the risk of a crankcase explosion, neither is it deemed to be a suitable test whose results can be depended on for this purpose”. These conclusions were presented in a declarative manner without citing sources. Such statements are debatable because contamination of the circulating lubricating oil with fuel can change its ignition temperature and ignition index [31–33]. Contamination also can change the oil’s rheological properties, thus contributing to a deterioration of lubrication conditions for engine bearings, their accelerated wear, and subsequent seizure (formation of hot spots).

1.2. Dilution of Lubricating Oil with Fuel and Explosion Hazard

Experience shows that dilution of lubricating oil with fuel is detrimental to the engine, and its effects include deterioration of engine efficiency, shortening of oil life, and reduction in engine reliability and safety [29,30,34]. Diesel fuel has a much lower viscosity than oil; therefore, distillate fuel contamination reduces oil viscosity [35,36]. This viscosity

reduction reduces both the oil's lubricating effectiveness and the strength of the oil film, which increases the wear on the cylinder liner and bearings [30,34,37]. Progressive dilution of oil with fuel can lead to significant wear and tear and ultimately to engine failure.

The literature describes other problems that result from lower oil viscosity (or degraded oil in general), including reducing the effectiveness of oil additives, increasing oil volatility, and increasing the rate of oil oxidation [28,30,38,39]. Deterioration of lubricating oil properties in turn forces more frequent oil changes and increases engine-operating costs [40,41].

The main cause of fuel leakage from the combustion chambers into the crankcase is blow-through, which is related to the deterioration of piston rings, pistons, and cylinder liners [34]. Fuel that penetrates the cylinder liner into the crankcase intensifies wear of the piston–ring–liner tribological node, which can lead to piston seizure. The temperature increase resulting from this process can be sufficient to initiate an explosion (hot spot) [37]. Seizure between two components, e.g., piston and cylinder liner, is the result of insufficient lubrication (oil contamination, lack of oil, inadequate oil lubricity) or exceeding permissible loads (deformation of cooperating components, excessive pressure force) [42–44].

The subject of the effect of oil ignition temperature on the formation of crankcase explosions was taken up as early as the middle of the last century, by Ferguson, in a publication summarizing his paper at the Oil and Gas Power Conference (held in Dallas, TX, USA in 1951) [45]. The study was prompted by a preliminary analysis of 104 crankcase explosions in various engine types occurring in the 10 years preceding publication. Ferguson summarized prior studies of the mechanism of explosion formation and investigated the inflammation properties of various oils employed for diesel engine lubrication. Ferguson stated that “no significant differences were found in the minimum ignition temperature of a wide variety of lubricating oils, even where diluted with up to 20 per cent diesel fuel”. The ignition temperature was determined using a test bench, the crankcase explosion apparatus (CEA), which simulated oil mist conditions in the crankcase. These temperatures were significantly higher than the autoignition temperature determined according to ASTM guidelines and the flash point temperature. The flash point ranged from 1400–1600 °F (760–871 °C), depending on the measurement conditions. Ferguson compared the CEA results obtained with autoignition temperature and flash point temperature and found the latter to be significantly lower. Figure 3 shows the autoignition temperatures as a function of flash point temperature for oil diluted with diesel fuel. It shows that the Celsius autoignition temperature determined under laboratory conditions is about half that of the CEA ignition temperature. Ferguson explained this fact through the influence of ignitor size, inflammable mixture inlet temperature, and air flow during the test. According to his observations, the ignition temperature in the CEA decreased with:

- decreasing air velocity;
- increasing the temperature of the flammable mixture;
- increasing the size of the ignitor.

Ferguson argued that by intensifying these factors, the ignition temperature in CEA would tend toward the value established under laboratory conditions. It is not clear how the above statement provided him with the basis for his conclusion that “normal fuel dilution will have no significant effect on crankcase explosions” [31]. Nevertheless, he also pointed out that a detailed analysis of the effect of lubricating oil dilution with fuel and details of the mechanism of explosion formation in the crankcase required further research. The large difference between the resulting CEA and ASTM autoignition temperatures depends largely on the specifics of how the test was conducted, including a realistic atomization of the oil (Ferguson used large droplets).

The inadequacy of Ferguson's physical model can be demonstrated by analyzing crankcase oil flammability results presented in Freestone et al. [46], which were published five years later. They showed the occurrence of two areas of flammability in the range of 270–350 °C and above 400 °C. The authors of the paper [46] write: “It is significant that with all surfaces ignition was possible at a temperature as low as 270 deg. C (518 deg. F)

and in one instance at 265 deg. C (509 deg. F). Therefore, to ensure complete safety, a detecting system should give warning before a temperature of 265 deg. C (509 deg. F) is reached by an overheated part.”

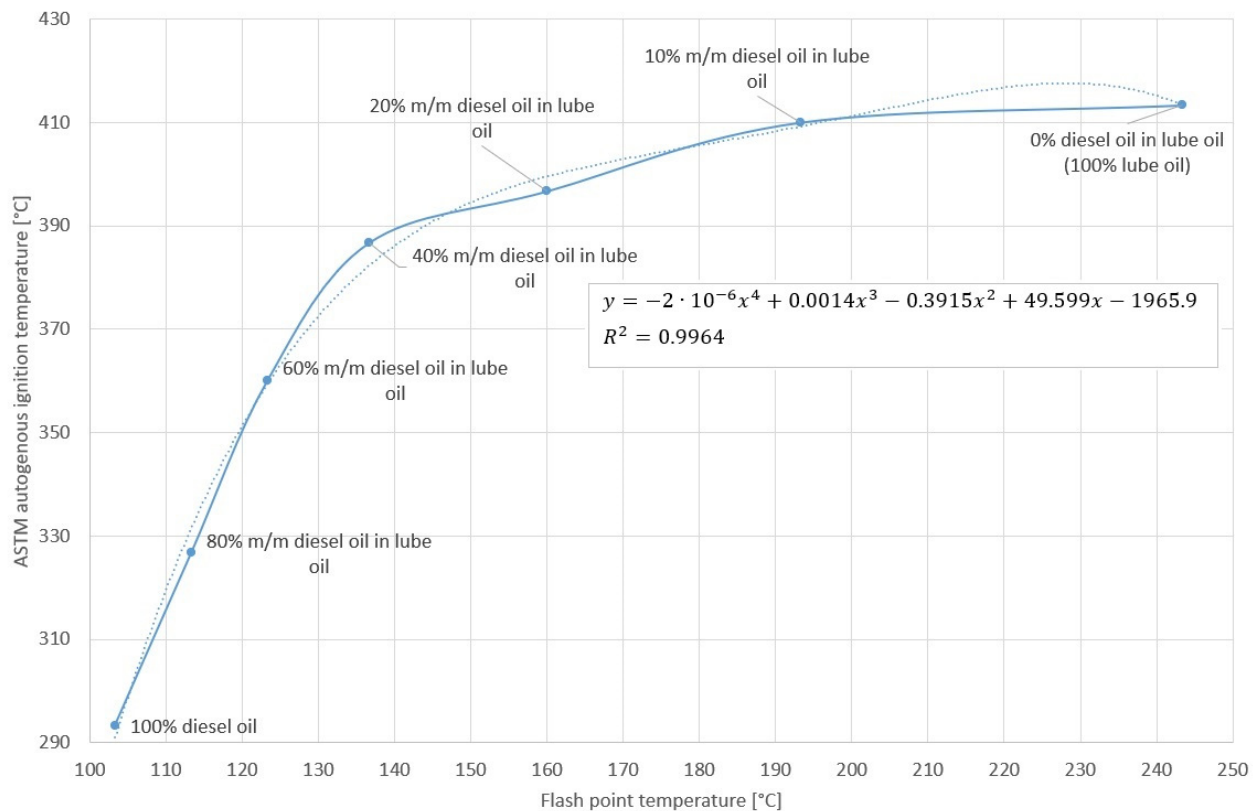


Figure 3. Dependence of autoignition temperature on flash point temperature for engine lubricating oils diluted with diesel fuel in the Ferguson experiment (own work prepared on the basis of [45]); blue dotted line is the trend line described by the function $y = f(x)$.

Further insights into the possible causes and consequences of crankcase explosions are pointed out in guides for marine engine operators, such as “Diesel Engine Maintenance Training Manual” issued by the German Bureau of Ships, which states that one of the root causes of crankcase explosions may be “overheating or dilution of lube oil” [47].

In the light of modern knowledge, crankcase explosions are the result of a multi-stage process, which consists of the following steps [11]:

- evaporation of oil in contact with a hot spot inside the crankcase;
- condensation of oil vapors in contact with cooler areas in the crankcase, resulting in a white oil mist with a droplet diameter of 5–10 μm ;
- gradual increase in the concentration of oil mist, which increases until the lower explosive limit is reached (47 mg of oil per 1 L of air, though some studies say this value 50 mg/L [11,28,48]), which corresponds to a weight concentration of oil mist in the air equal to 13%;
- ignition of the flammable mixture, which can occur at temperatures of 270–330 °C and above 400 °C (according to other sources, 280–400 °C [49], and even 200–400 °C [50]).

Ferguson used much lower fuel/air ratios of 1.3–5.8%, and the process itself was simplified relative to the sequence of events indicated above. In addition, he noted that ignition did not occur in an atmosphere of milky haze, indicating significant differences between the conditions of his experiment and actual crankcase explosions.

Further evidence can be found by studying the occurrence of secondary explosions, which are the result of air from outside entering the crankcase after the primary explosion. The vacuum created after the primary explosion causes a fresh load of air to be sucked

in from outside, triggering a secondary explosion, which is usually more serious in its consequences than the primary. Figure 4 shows the failure of the high-speed crankshaft of the main engine No. 2, which was followed by an explosion that injured a mechanic officer who was at the engine. This observation confirms the fact that explosions can occur in the crankcase when oil mist contacts components at a much lower temperature than found using CEA.

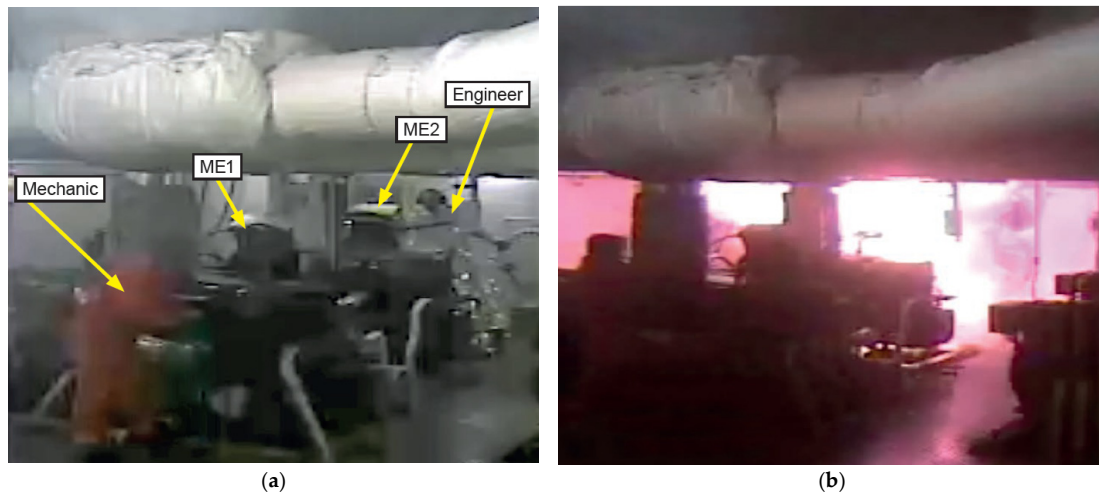


Figure 4. CCTV footage showing the explosion of a high-speed trunk piston engine: (a) just before the accident; (b) at the time of the accident (adapted from [51]).

According to an analysis of the actuality of the topic of explosions in crankcases of marine main propulsion engines presented in the publication [4], as many as 61% (60 out of 98 explosions analyzed) of the exploded crankcases were observed in trunk piston engines out of all engines. The aforementioned analysis did not capture auxiliary engines (virtually all of them are now trunk piston engines), and many explosions of the main sinuses may not have been reported. On the other hand, according to Rattenbury, in the years 1990–2001, the causes of crankcase explosions in four-stroke engines were damage to main or crank bearings (39%), damage to pistons (47%), and other reasons (14%) [52]. Examples of crankcase explosion-related damage to unshielded engines are shown in Figure 5.

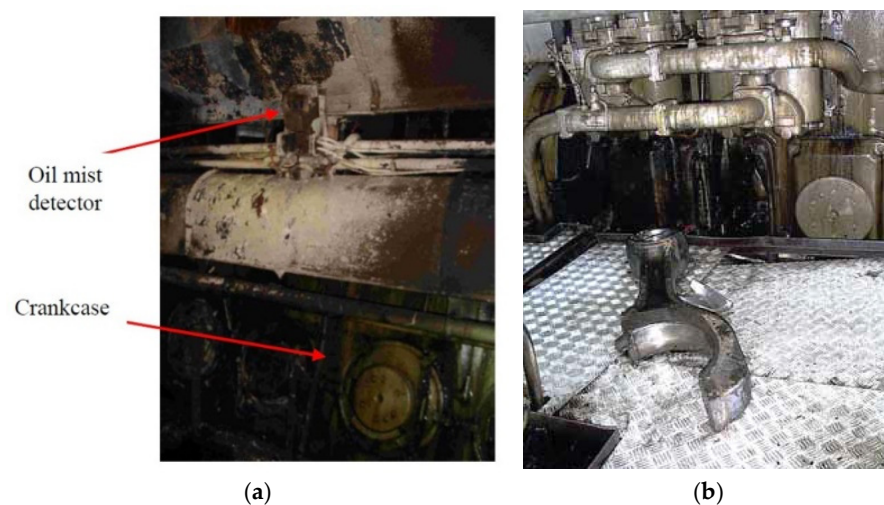


Figure 5. Damage of trunk piston engine after explosion in crankcases of trunk piston engines: (a) burned oil mist detector after failure of the engine lubrication system [53]; (b) conrod as found after explosion caused by failure of piston guide part of Wärtsilä Vasa 32 engine [54].

Each of these cases could potentially be linked to fuel dilution of lubrication oil. Thus, a quick diagnosis of oil contamination with fuel makes it possible to avoid damage, particularly in the cylinder/ring area, thereby preventing serious and costly engine failures, and avoiding crankcase explosion [55]. The above fact is pointed out by ship mechanics' handbooks as one measure to prevent crankcase explosions: "routine test on used L.O. for viscosity, flash point and contamination" [49].

1.3. Methods for Detecting Lubricating Oil Contamination with Fuel

In addition to evaluating lubricating oil contamination with fuel using analysis of oil properties such as viscosity and flash point, advanced diagnostic methods can be used. A summary of the main research methods and their advantages and disadvantages is presented in Appendix A Table A2.

There is a number of methods for analysis of fuel dilution in lubricants, e.g., gas chromatography (GC) based on ASTM methods D3524, D3525, and D7593 [56], flame ionization detector (FID), Fourier-transform infrared (FTIR), spectroscopy, and Spectro Q6000 fuel dilution meter (FDM) using surface acoustic wave (SAW) sensor [14,56].

In the present study, the flash point and viscosity measurements of the lubricating oil were used. These tests are the simplest and cheapest. Thus, they are most commonly used in operational practice for marine engine lubricating oils.

2. Materials and Methods

The research procedure related to the implementation of the study in question consisted of a series of stages according to the scheme shown in Figure 6.

Based on the background provided in the introduction, and stemming from the recommendations presented in the CIMAC publication [31], a hypothesis was established:

Diesel Fuel (DO) contamination of oil increases the risk of crankcase explosion for a trunk piston engine due to independent influence of two factors:

- (1) change in the flammable properties of the oil;
- (2) deterioration of lubrication conditions of the engine's tribological nodes.

To test the hypothesis, a detailed literature search was conducted and a set of parameters were selected that may provide information about the change in ignition and lubricity properties of the lubricating oil. Then, detailed tests were carried out on lubricating oil samples (SAE 30 and SAE 40 grades) diluted with diesel oil at selected present mass concentrations (0, 1, 2, 5, 10, 20, 50 and 100%). Oils and oil blends of the SAE 30 and SAE 40 classes were used in the experiment because these oils are used in the circulating lubrication systems of marine trunk combustion engines of almost all engine manufacturers. The oils were tested to determine their properties:

- rheological properties (kinematic viscosity ν , density ρ , temperature coefficient of density change ε , dynamic viscosity η , and viscosity index VI were determined);
- ignition properties (flash point FP temperature, derived cetane number DCN , calculated cetane index CCI , calculated carbon aromaticity index $CCAI$, and calculated ignition index CII were determined);
- lubricant properties (the average wear scar diameter WSD during the tribometer test, the coefficient of friction μ under test conditions, and the parameter describing the thickness of the oil film under test conditions $FILM$ were determined).

The characteristics of the lubricating oils and diesel fuel used in the experiment, along with the various measurements methods, are described in the following subsections.

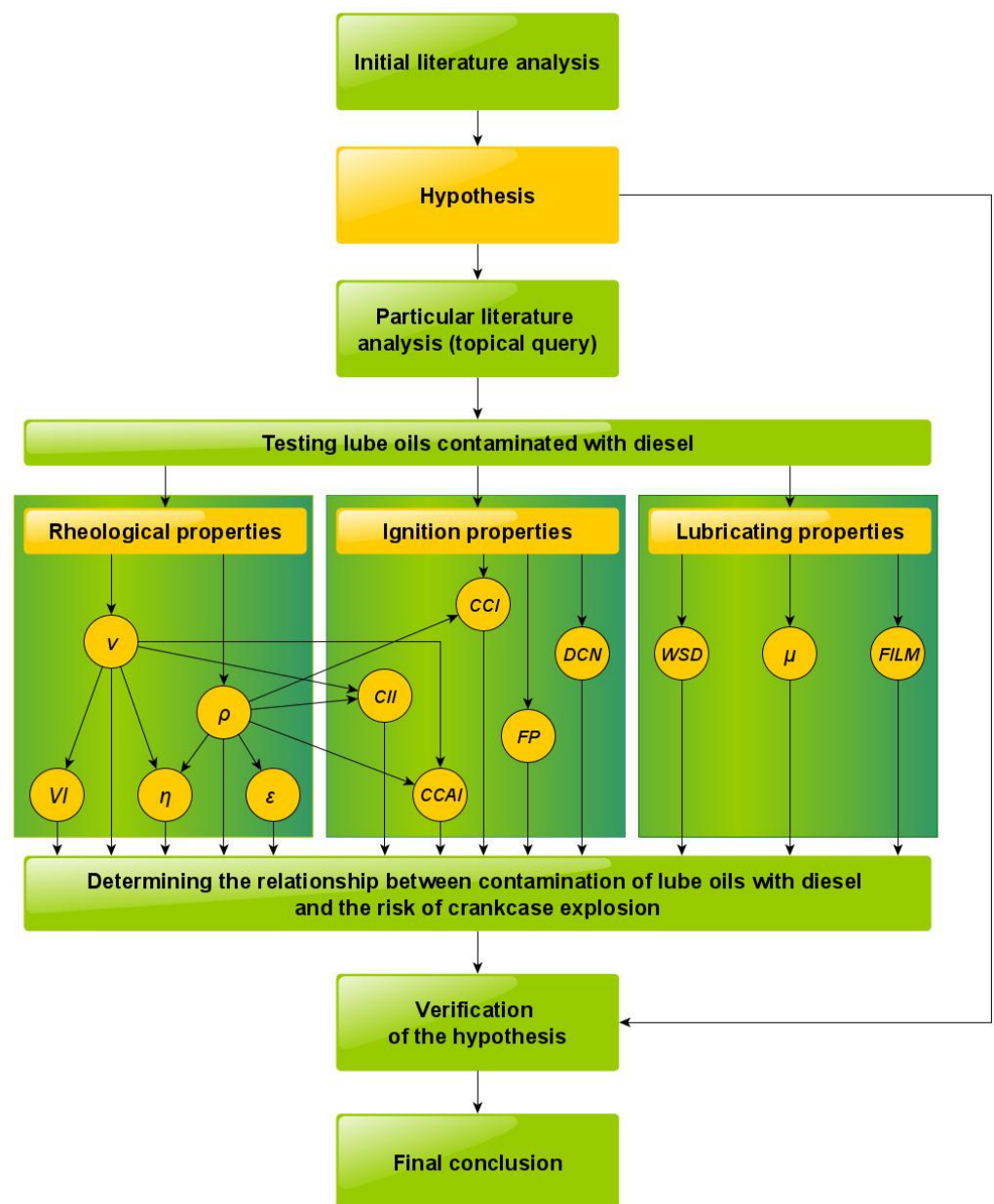


Figure 6. Research methodology adopted (description in text).

2.1. Tested Diesel and Lubricating Oils

The dataset in [57] outlines the key requirements of ISO 8217:2017 [58] distillation diesel for marine engines. The dataset shows the requirements for engine lubricating oils according to the viscosity classification of oils as described in SAE J300–2021 [59]. The experiment used diesel fuel that met the requirements of fuels belonging to the DMX category, as well as some of the most commonly used industrial marine engine lubricating oils of the SAE 30 and SAE 40 viscosity classes. Orlen Efecta Diesel Bio (designation CN27102011D) was used in the study [60], whose nominal parameters are shown in Appendix A Table A3 and in the dataset [57]. Meanwhile, the lubricating oils used in the study were Agip Cladium 120 SAE 30 CD and Agip Cladium 120 SAE 40 CD [61–63], the characteristics of which are shown in Appendix A Table A4 and in the dataset [57].

Agip Cladium SAE 30 CD and Agip Cladium SAE 40 CD oils are AGIP-ENI's high quality API CD (Series III) grade engine oils for the lubrication of naturally aspirated and highly charged marine, traction and industrial compression–ignition engines. The additive

package allows engines to run on inferior fuels (marine and higher sulphur fuels) while maintaining high engine performance [61,62].

2.2. Density, Viscosity and Viscosity Index of Lubricating Oil

Changing density and viscosity affects both the anti-seize and ignition properties of lubricating oil. These features will be discussed later in the article.

Density ρ is the ratio of the mass m of a particular substance to the volume V occupied by that substance under vacuum conditions:

$$\rho = \frac{m}{V}. \quad (1)$$

Under operating conditions, oil/fuel is lighter than the same oil/fuel due to the air displacement acting on it under atmospheric conditions. Such a difference is assumed to be 0.0011 tons/m³ for fuels with a density of 0.800–1.010 tons/m³.

The reference temperature for conventional lubricating oils and liquid fuels is 15 °C. The relationship between the density under operating conditions ρ_t and the density under reference conditions ρ_{15} (the information about the value of this density comes from the laboratory analysis performed) is described by the formula:

$$\rho_t \approx \rho_{15} - \varepsilon \cdot (t - 15), \quad (2)$$

where t is the measured temperature of the substance under operating conditions, and ε is the coefficient of change of density of a substance when it is heated by 1 °C (1 K).

Viscosity is a property of liquids and plastic solids that characterizes their internal friction resulting from the movement of fluid layers relative to each other during flow.

Dynamic viscosity η expresses the ratio of shear stress τ_F to shear rate $\dot{\gamma}$:

$$\eta = \frac{\tau_F}{\dot{\gamma}}. \quad (3)$$

Kinematic viscosity ν is defined as the ratio of dynamic viscosity η to fluid density ρ :

$$\nu = \frac{\eta}{\rho}. \quad (4)$$

Viscosity index is a unitless measure of a fluid's change in viscosity relative to temperature change. The viscosity index can be calculated using the following formula:

$$VI = \begin{cases} \frac{L-U}{L-H} \cdot 100, & \text{if } VI \leq 100 \\ 100 + \frac{e^{\left(\frac{\log H - \log U}{\log Y}\right)} - 1}{0.00715}, & \text{if } VI > 100 \end{cases}, \quad (5)$$

where U is the oil's kinematic viscosity at 40 °C, Y is the oil's kinematic viscosity at 100 °C, and L and H are the viscosities at 40 °C for two hypothetical oils of viscosity indices equal to 0 and 100, respectively, with the same viscosity at 100 °C as the oil whose viscosity index is determined. These L and H values are provided in tables in ASTM D2270 standard.

In this experiment, in order to generally evaluate the properties of lubricating oils contaminated with diesel fuel, density and viscosity tests of lubricating oils with different diesel content (0%, 1%, 2%, 5%, 10%, 20%, 50% and 100%) were conducted at selected temperatures (15, 20, 30, 40, 50, 60, 70, 80, 90, 100 °C).

The density of individual samples in this experiment was determined using a DMA 4500 density analyzer (Anton Paar GmbH, Graz, Austria) with an oscillating U-tube (Figure 7) performing measurements in accordance with PN-EN ISO 12185:2002. The accuracy of the measurement temperature setting is 0.02 °C, while the accuracy of density measurement is $5 \cdot 10^{-5}$ g/cm³.



Figure 7. The Anton Paar DMA 4500 used in the study (photo. M. Szmukała).

The kinematic viscosity of the individual samples in this experiment was determined using a Cannon-Fenske Opaque glass capillary viscometer (Paradise Scientific Company Ltd., Dhaka, Bangladesh) and a TV 2000 viscometric bath (Labovisco bv, Zoetermeer, the Netherlands); see Figure 8.

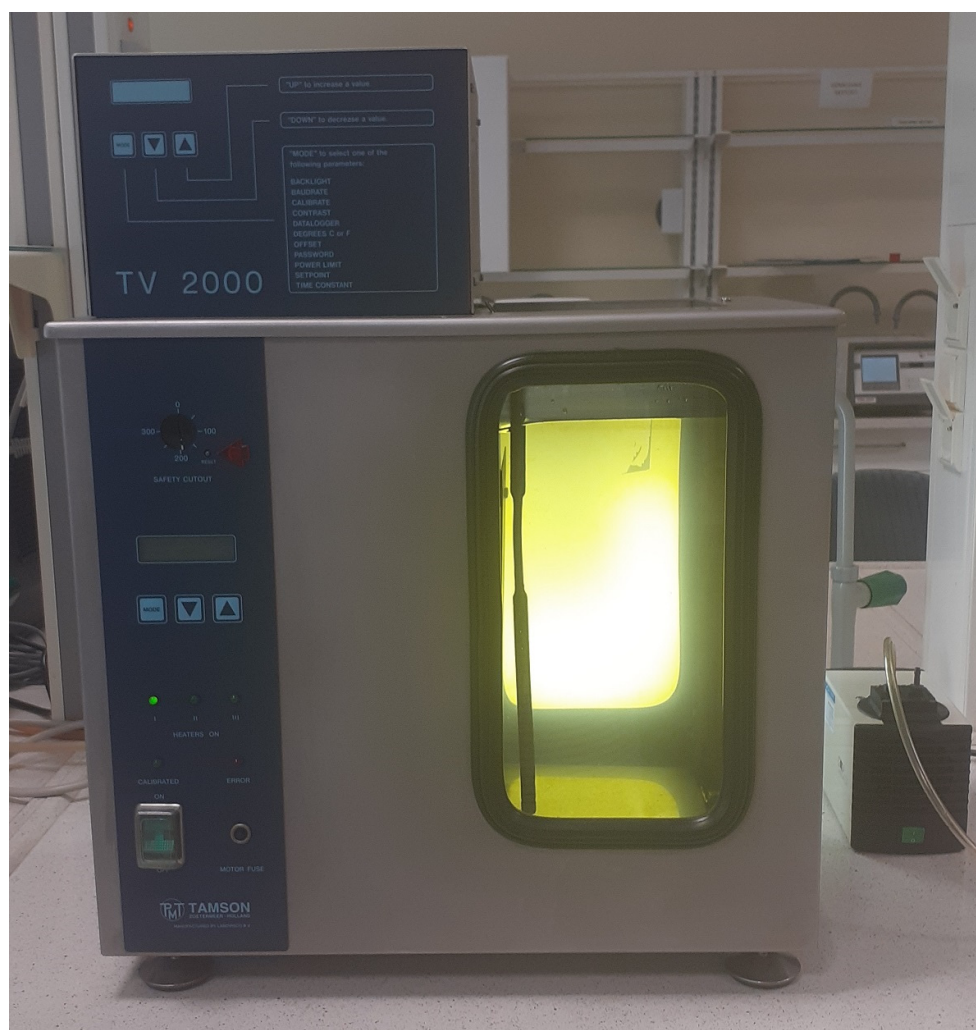


Figure 8. TV 2000 viscometric bath used in the study (Photo. M. Szmukała).

The viscosity measurement kit allows measurements to be taken in accordance with PN-EN ISO 3104:2004. The accuracy of the measurement temperature setting is 0.01 °C, while the accuracy of the viscosity measurement is 0.1 mm²/s (data verified based on the calibration reports of the device).

2.3. Anti-Seizure Properties of Lubricating Oil

Lubricity is the ability of oil to form a boundary layer through chemical and physical adsorption on solids. The function of the boundary layer is to reduce friction resistance and protect the cooperating surfaces of the tribological pair from excessive wear and galling. Lubricity characterizes the behavior of a lubricant during boundary friction; therefore, it is an ensemble characteristic, since the lubricating properties do not depend only on the characteristics of the oil, but also on the cooperating components (properties of structural materials, contact geometry and the type of movement performed) and their load [64]. The lubricating and anti-wear properties of oils and lubricants are determined using tribometers, selected kinds of which are characterized in Appendix A Table A5.

In this experiment, in order to evaluate the lubricating and anti-wear properties of lubricating oils contaminated with diesel, lubricating oils with different diesel contents (0%, 1%, 2%, 5%, 10%, 20%, 50% and 100%) were tested for lubricity. Measurements were made with a high frequency reciprocating rig (HFFR) tribometer model HFFR V1.0.3 (PCS Instruments, London, UK) performing measurements in accordance with ASTM D6079 and PN-EN ISO 12156-1—Figure 9. The construction of the device is shown in [65].



Figure 9. The PCS HFFR V1.0.3 instrument used in the study (photo. M. Szmukała).

A sample of the test liquid is placed in the test reservoir at 60 °C, according to ISO [65], a temperature determined by the bath. A fixed steel ball is held in a vertically mounted chuck and forced with mass against a horizontally installed stationary steel plate 4 with an applied load. The test ball oscillates at a constant speed with a constant pitch, while the interface with the plate is fully immersed in the fluid. Oscillation is provided by an electromagnetic vibrator along with a counterweight providing a fixed motion of the ball determined using appropriate elements. The sample load is monitored with an inverter. Test conditions such as metallurgical properties of the plate and ball, fluid temperature, load, oscillation frequency, and stroke length and external conditions are specified in the norm [65]. The diameter of wear scar *WSD*-generated on the test ball is taken as a measure of anti-wear properties and fluid lubricity. Wear assessment is carried out either visually or with a digital camera. In addition, the device used provides information on the averaged value of the friction coefficient μ and the percentage reduction in oil film resistance (*FILM* parameter).

The *FILM* parameter provides a rough assessment of oil film thickness and quality by measuring the electrical contact potential (ECP), which is a measure of contact resistance

(oil film resistance). The contact resistance circuit applies a potential of 15 mV to the sample contact resistor and a series stabilizing resistor. The stabilizing resistance set by the control software, together with the contact resistor, forms a potential divider circuit. The default value of the stabilizing resistor is 10 Ω . After the test, the HFFR apparatus provides the value of the percentage reduction in the oil film resistance value. Large values of the *FILM* parameter indicate separation of the cooperating metal surfaces, while values close to or equal to zero indicate the existence of metallic contact (oil film breakage) between the mating surfaces.

2.4. Ignition Properties of Lubricating Oil

The essential indicators for determining the ignition characteristics of liquid fuels are flash point, autoignition temperature, and autoignition (ignition) delay. The flashpoint of a material is the lowest liquid temperature at which, under certain standardized conditions, a liquid gives off vapors in a quantity capable of forming an ignitable vapor/air mixture (standard EN IEC 60079-10-1). The autoignition temperature or kindling point of a substance is the lowest temperature at which it spontaneously ignites in a normal atmosphere without an external source of ignition, such as a flame or spark. The flash point in this experiment was determined in a closed crucible using the Pensky–Martens method in accordance with EN ISO 2719. To carry out the test, the flashpoint Pensky–Martens semi-automatic apparatus was used (Walter Herzog GmbH, Lauda-Königshofen, Germany); see Figure 10.

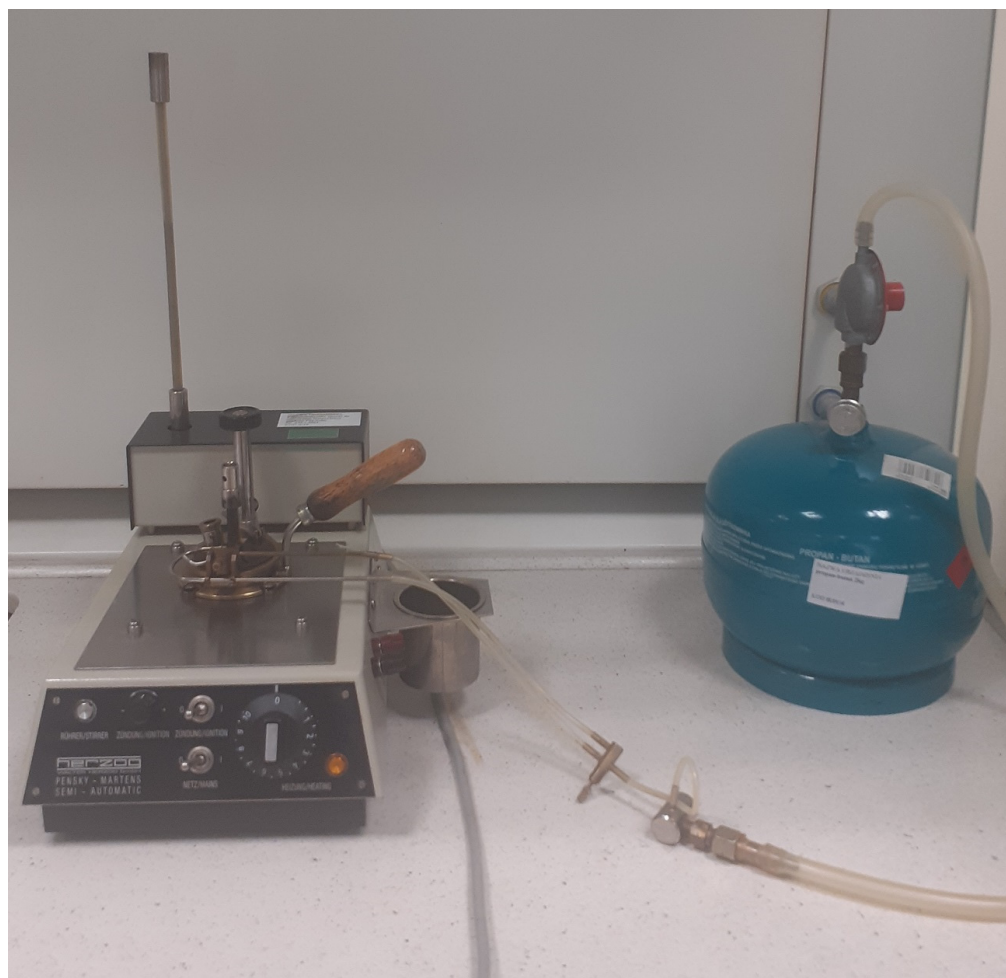


Figure 10. Flashpoint Pensky–Martens semi-automatic apparatus from Walter Herzog GmbH used in the study (photo. M. Szmukała).

The autoignition delay is defined as the time between the atomization of a flammable substance and the start of the combustion process after autoignition has occurred. This indicator is usually used for evaluating the diesel engine fuels. There are several methods for measuring the autoignition properties of fuel [66–68]. Table A6 in Appendix A shows a comparison of several selected methods for measuring the autoignition properties of fuel. An indicator of the combustion speed of diesel fuel and compression needed for ignition is the cetane number (CN; alias cetane rating). For marine fuels, CN values above 45 correspond to very good ignition properties, 40–45 from good to very good, 35–40 from good to acceptable, 28–35 from bad to acceptable, 25–28 from very bad to bad, while below 25 very bad or unfit for use.

Cetane numbers are difficult to measure accurately, as the method requires a special diesel engine called a cooperative fuel research (CFR) engine. The test is conducted in accordance with the guidelines of ASTM D613 (ISO 5165). In order to facilitate the measurements, substitute methods were introduced:

- constant volume combustion chamber instrument (CVCC) analyzers such as the ignition quality tester (IQT) according to ASTM D6890, cetane ignition delay (CID) according to ASTM D7668, or fuel ignition tester (FIT) according to ASTM D7170 for measuring the derived cetane number (DCN);
- laboratory methods for determining flammability indices, cetane indices (CI and CCI), and others based on the physical and chemical properties of a substance, e.g., “four variable equations” (ASTM D4737) based on density, 10% 50% and 90% recovery temperatures or “two variable methods” (ASTM D976), which use just density and the 50% recovery temperature.

Apart from the indicators determined experimentally, calculated indicators are used in operational practice. This applies to situations where the measurement of autoignition delay is hampered by technical capabilities. This situation includes residual fuels such as heavy fuel oils. Among such indices are the calculated carbon aromaticity index (CCAI) and the calculated ignition index (CII).

CCAI is Shell’s calculation of the autoignition capability of residual fuels (heavy fuel oils, HFO). It is calculated based on the measured viscosity ν (mm²/s) for a given fuel determined at t (°C) and the density at 15 °C ρ_{15} (kg/m³). For residual fuels, CCAI falling within the range of 790–830 corresponds to excellent to good combustion quality, 830–850 corresponds to good to average combustion quality, 850–870 corresponds to average combustion quality, and 870–950 corresponds to poor or very poor combustion quality. CCAI can be determined from one of the equivalent formulas:

$$CCAI = \rho_{15} - 140.7 \cdot \log[\log(\nu + 0.85)] - 80.6 - 210 \cdot \ln\left(\frac{t + 273}{323}\right), \quad (6)$$

$$CCAI = \rho_{15} - 140.7 \cdot \log[\log(\nu + 0.85)] - 80.6 - 483.5 \cdot \log\left(\frac{t + 273}{323}\right). \quad (7)$$

CII is BP’s calculation of the autoignition capacity of residual fuels (HFO). It is calculated based on the measured viscosity ν (mm²/s) for a given fuel determined at t (°C) and the density at 15 °C ρ_{15} (kg/m³). The values obtained from the calculation of CII for residual fuels are interpreted analogously as CN for distillate fuels. CII is determined from the formula:

$$CII = (270.795 + 0.1038 \cdot t) - 0.254565 \cdot \rho_{15} + 23.708 \cdot \log[\log(\nu + 0.7)]. \quad (8)$$

In this experiment, to evaluate the ignition properties of lubricating oils contaminated with diesel fuel, flash point temperature and cetane indices of lubricating oils with different diesel content (0%, 1%, 2%, 5%, 10%, 20%, 50% and 100%) were tested. Determination of the derived cetane number (DCN) was not possible for lubricating oil–diesel blends; thus, only the diesel DCN value was determined. This was done using the Herzog cetane ID

510 instrument (PAC L.P., Houston, TX, USA). The inability to measure DON for mixtures of fuel and lubricating oil is due to the specifics of the measuring device. Calculation of the cetane index was possible only for mixtures with diesel fuel content in lubricating oil equal to or greater than 50% m/m. This limitation was due to the complex composition of lubricating oils, which are not a pure mixture of hydrocarbons (they contain a number of additives). Since the rheological properties of lubricating oils are similar to residual fuels, the values of CCAI and CII indices were determined for the measured values of density and kinematic viscosity of mixtures of the lubricating oils tested with diesel fuel. The calculated values of CII and CCAI were determined for all concentrations planned in the experiment.

3. Results and Discussion

3.1. Rheological Properties

Figures 11 and 12 show the measured density values of the tested lubricating oils of the SAE 30 and SAE 40 grades, respectively, with different degrees of contamination with diesel fuel: 0, 1, 2, 5, 10, 20, and 50% m/m; compared with pure diesel (i.e., 100%).

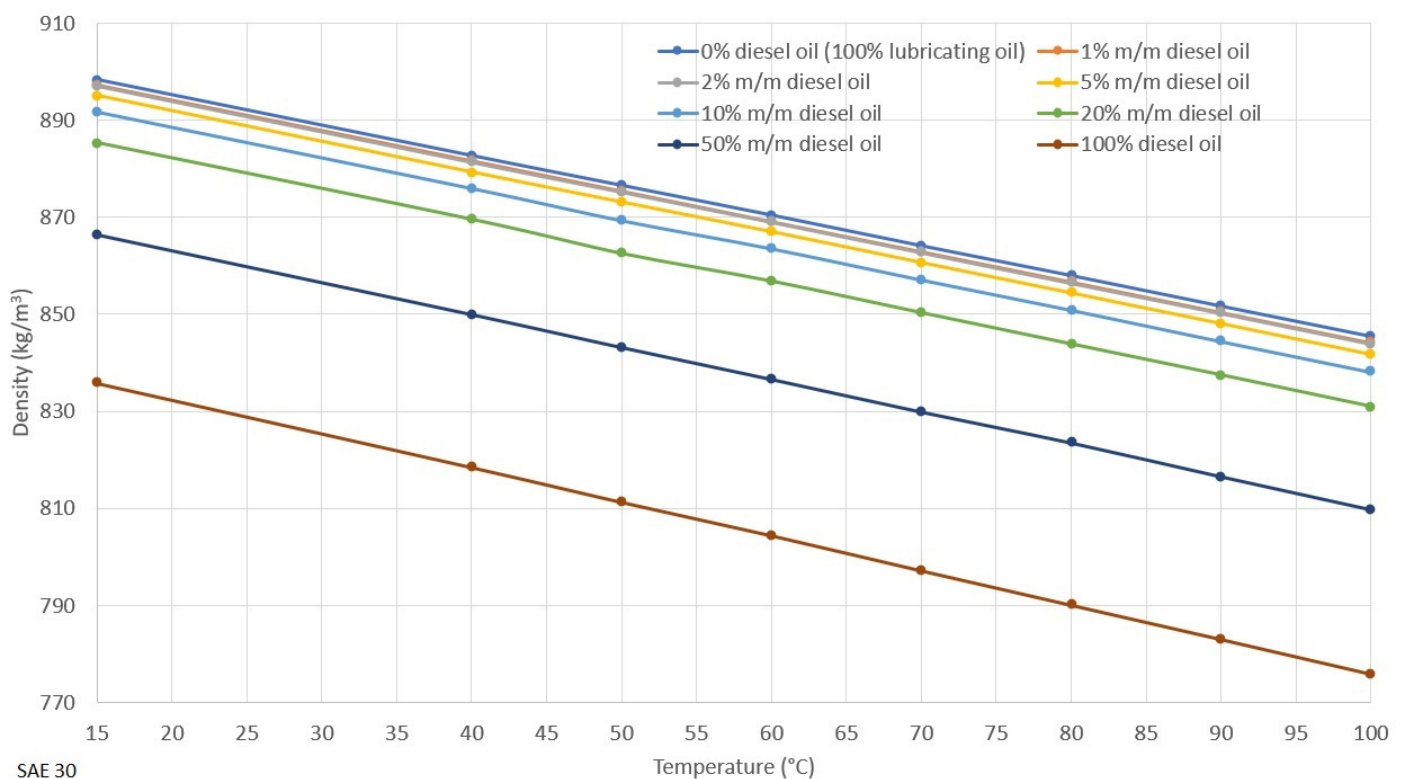


Figure 11. Measured values of SAE 30 class oil density in the temperature range of 15–100 °C at different levels of lubricating oil dilution with diesel fuel.

The density values at a given temperature are similar for oils of both classes. Increased concentration of diesel in the lubricating oil results in a significant reduction in density. From these data, the temperature coefficients of change of substance density, ϵ , were calculated using Equation (2). The coefficient values were determined for a temperature of 100 °C. Figure 13 shows a summary of the values for different levels of dilution.

The ϵ values for SAE 30 oil are higher than those for SAE 40 oil. Moreover, the value of the ϵ coefficient increases with an increase in the content of diesel fuel in the lubricating oil. This trend is due to the higher value of this index for diesel fuel than for lubricating oil. For the oils tested, the difference between diesel and lubricating oil ϵ values for SAE 30 oil was 0.084, while for SAE 40 oil, it was 0.089.

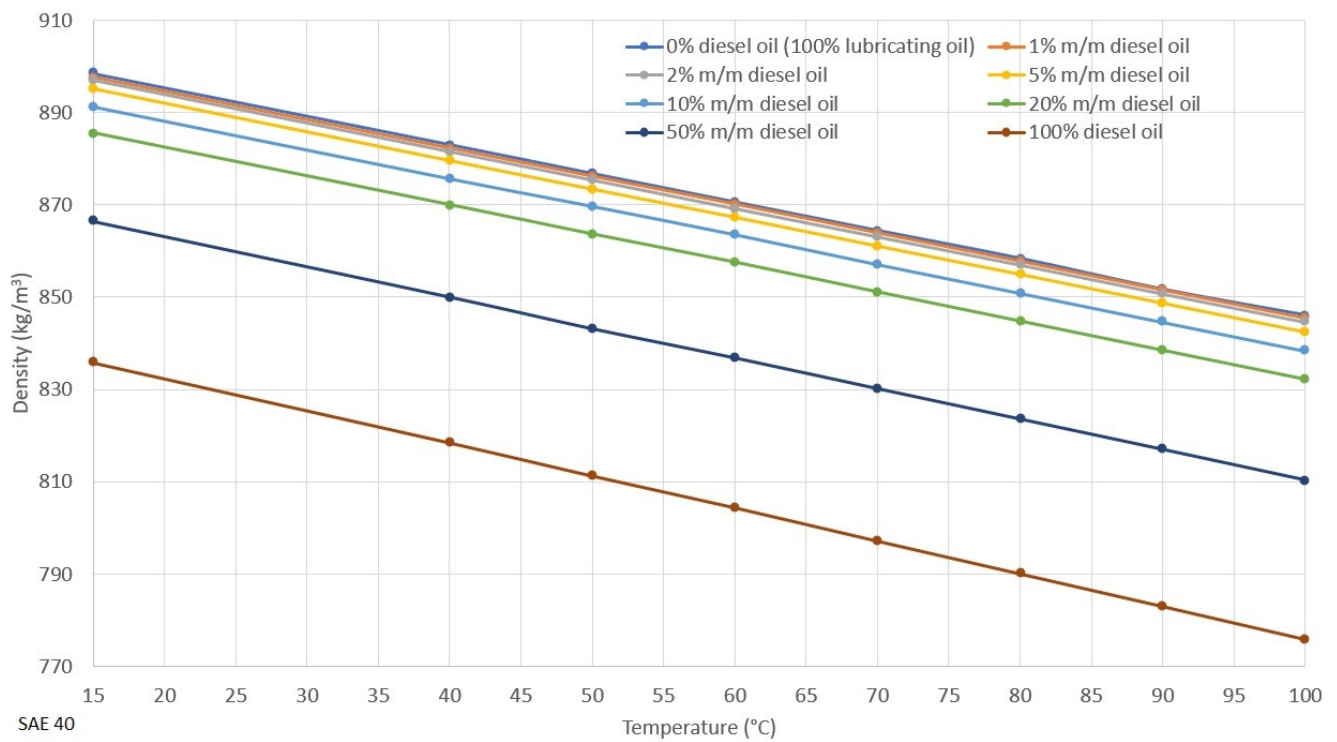


Figure 12. Measured values of SAE 40 class oil density in the temperature range of 15–100 °C at different levels of lubricating oil dilution with diesel fuel.

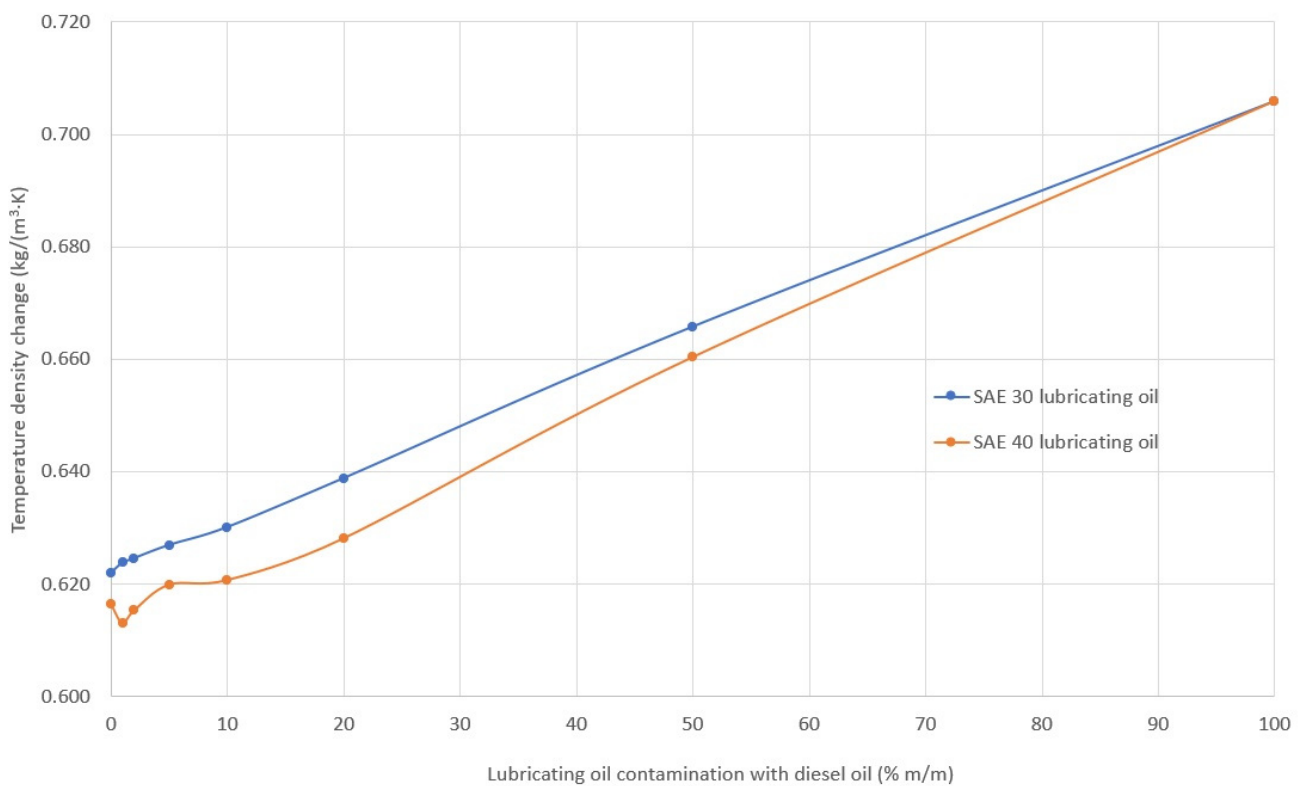


Figure 13. Calculated values of the coefficient of temperature change in density of the lubricating oils tested at different levels of lubricating oil dilution with diesel fuel.

The measured kinematic viscosity values of lubricating oil–diesel blends for different concentrations in the temperature range of 40–100 °C for SAE 30 and SAE 40 grade oils

are shown in Figures 14 and 15, respectively. Their viscosity decreases with increasing temperature. Increasing the diesel content in the lubricating oil mixture results in a decrease in kinematic viscosity at a given temperature.

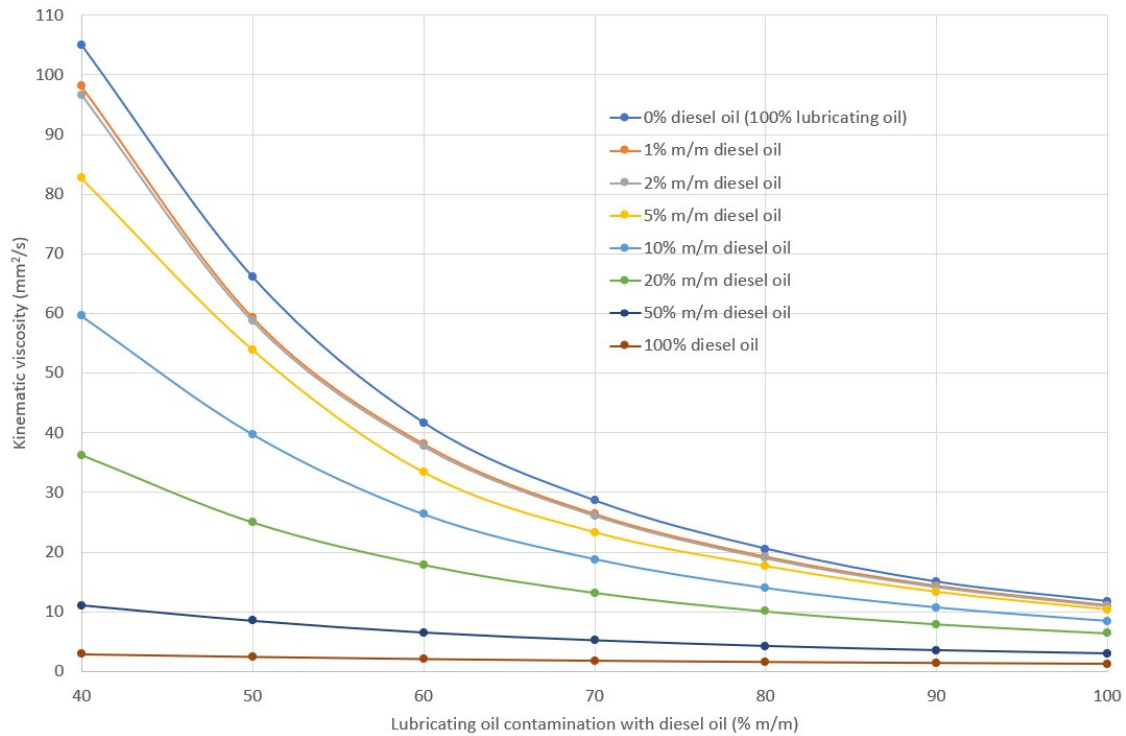


Figure 14. Measured kinematic viscosity values of SAE 30 grade oil in the temperature range of 40–100 °C at different levels of lubricating oil dilution with diesel fuel.

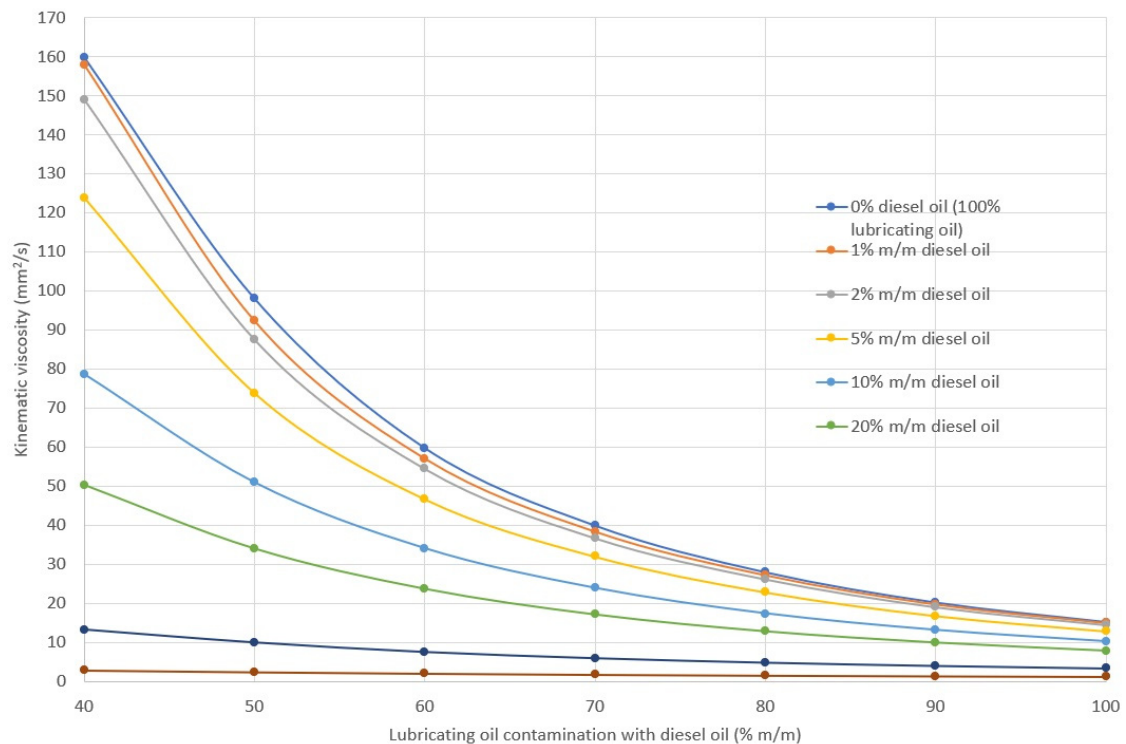


Figure 15. Measured kinematic viscosity values of SAE 40 grade oil in the temperature range of 40–100 °C at different levels of lubricating oil dilution with diesel fuel.

Viscosity of oils belonging to each SAE class must fall within an allowed range at 100 °C. Experimental results show that contamination of the lubricating oil with diesel fuel in an amount within the range of 5–10% m/m results in the oil not meeting SAE viscosity requirements.

Based on the measured values of kinematic viscosity and density of the blends, dynamic viscosity values were calculated for the various lubricating oil–diesel blends. The results of calculations for lubricating oils of SAE 30 and SAE 40 grades are shown in Figures 16 and 17, respectively.

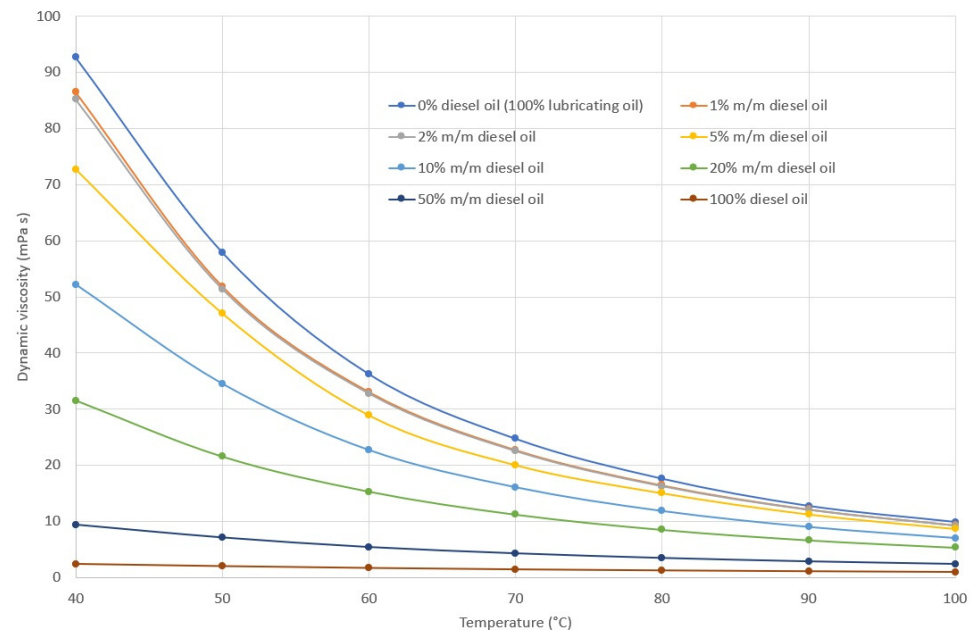


Figure 16. Measured values of dynamic viscosity of SAE 30 class oil in the temperature range of 40–100 °C at different levels of lubricating oil dilution with diesel fuel.

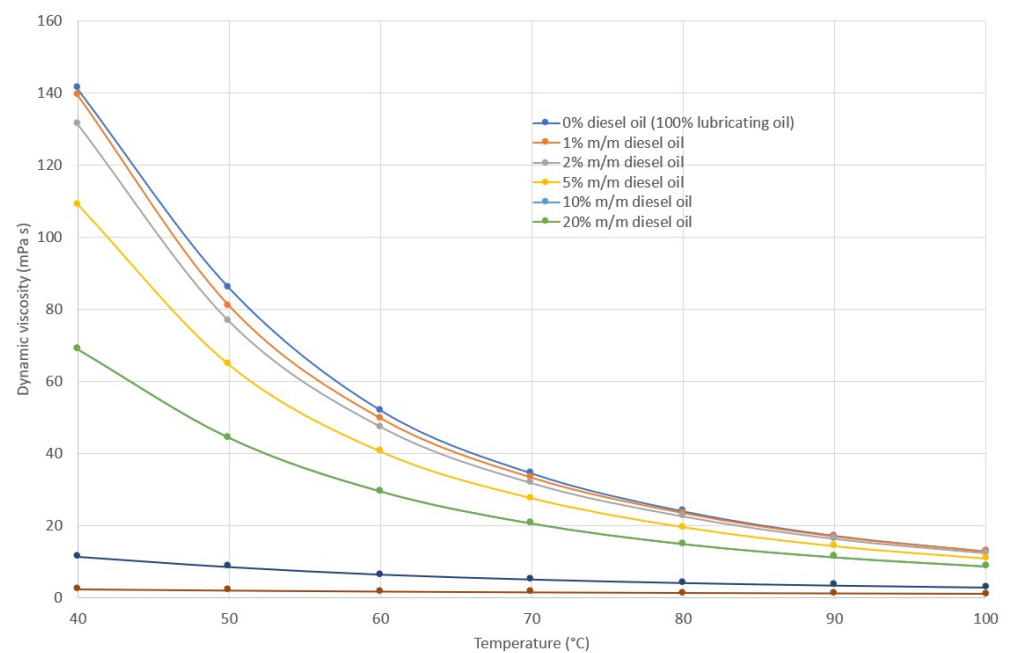


Figure 17. Measured values of dynamic viscosity of SAE 40 class oil in the temperature range of 40–100 °C at different levels of lubricating oil dilution with diesel fuel.

Since both density and viscosity decrease with increasing oil temperature, the dynamic viscosity value resulting from their product will also decrease with increasing temperature. At the same time, the value of dynamic viscosity at a given temperature and the temperature drop in dynamic viscosity in a given temperature range decrease when the diesel content of the lubricating oils tested increases.

Based on the viscosity of the tested oils at 40 °C and 100 °C, viscosity index *VI* values were calculated. Calculators available on the websites of Olezol [69] and Anton Paar [70] were used for the calculations. The change in *VI* values for different lubricating oil contaminants is shown in Figure 18.

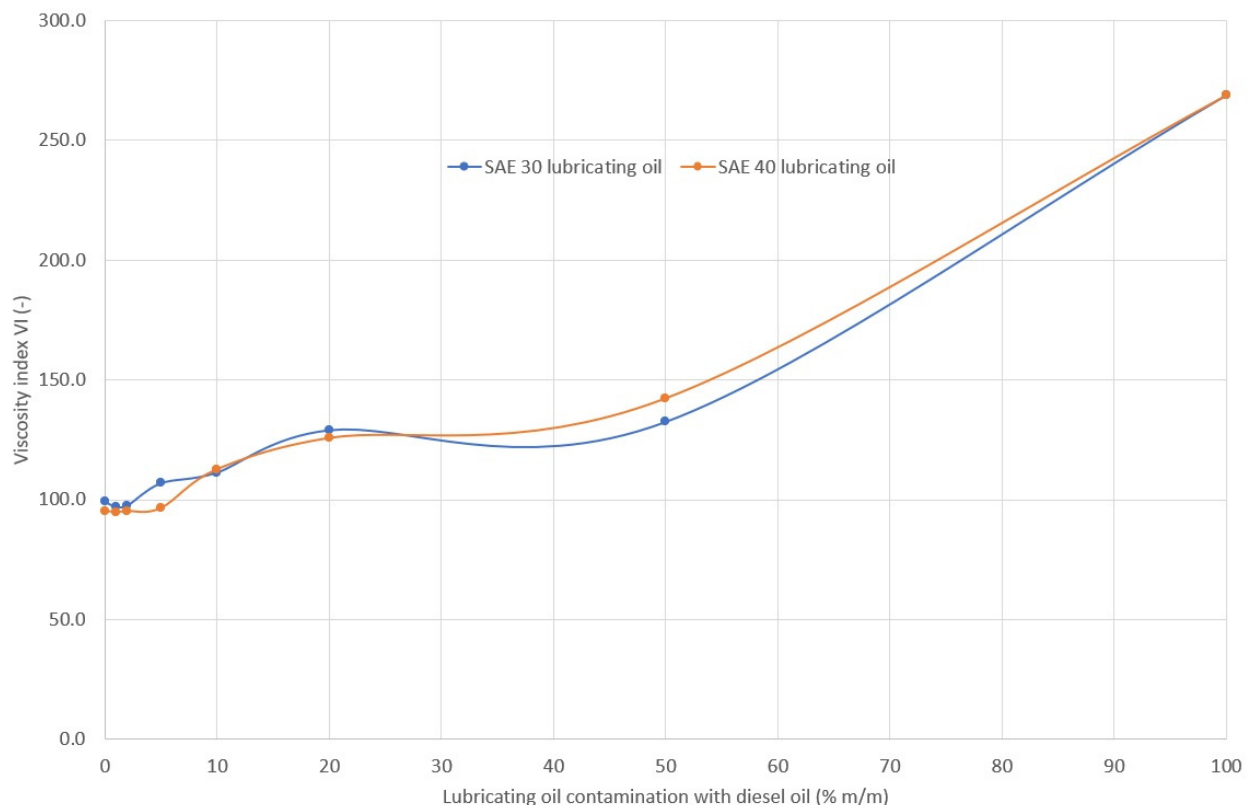


Figure 18. Calculated viscosity index values of the tested lubricating oils at different levels of lubricating oil dilution with diesel fuel.

Changes in *VI* for SAE 30 and SAE 40 oil are similar. *VI* in the diesel concentration range of 0–10% m/m remains at a similar level in the range of 100–110, gradually increasing the value of the increment as the diesel oil content in the mixture increases. This trend shows that with increasing diesel content in the lubricating oil mixture, the viscosity of the mixture shows less and less variation with temperature (the higher the *VI* value, the smaller the decrease in viscosity at a given temperature increment).

3.2. Anti-Seizure Properties of Oil

Figure 19 shows the results of oil lubricity measurements. Here, lubricity is defined as the wear scar diameter *WSD* (the average of the major and minor axis of the wear scar) measured on the test ball as a result of the HFFR apparatus test for different diesel contents in the lubricating oils tested. Microscopic images of the wear marks for each of the tests performed are summarized in Appendix B.

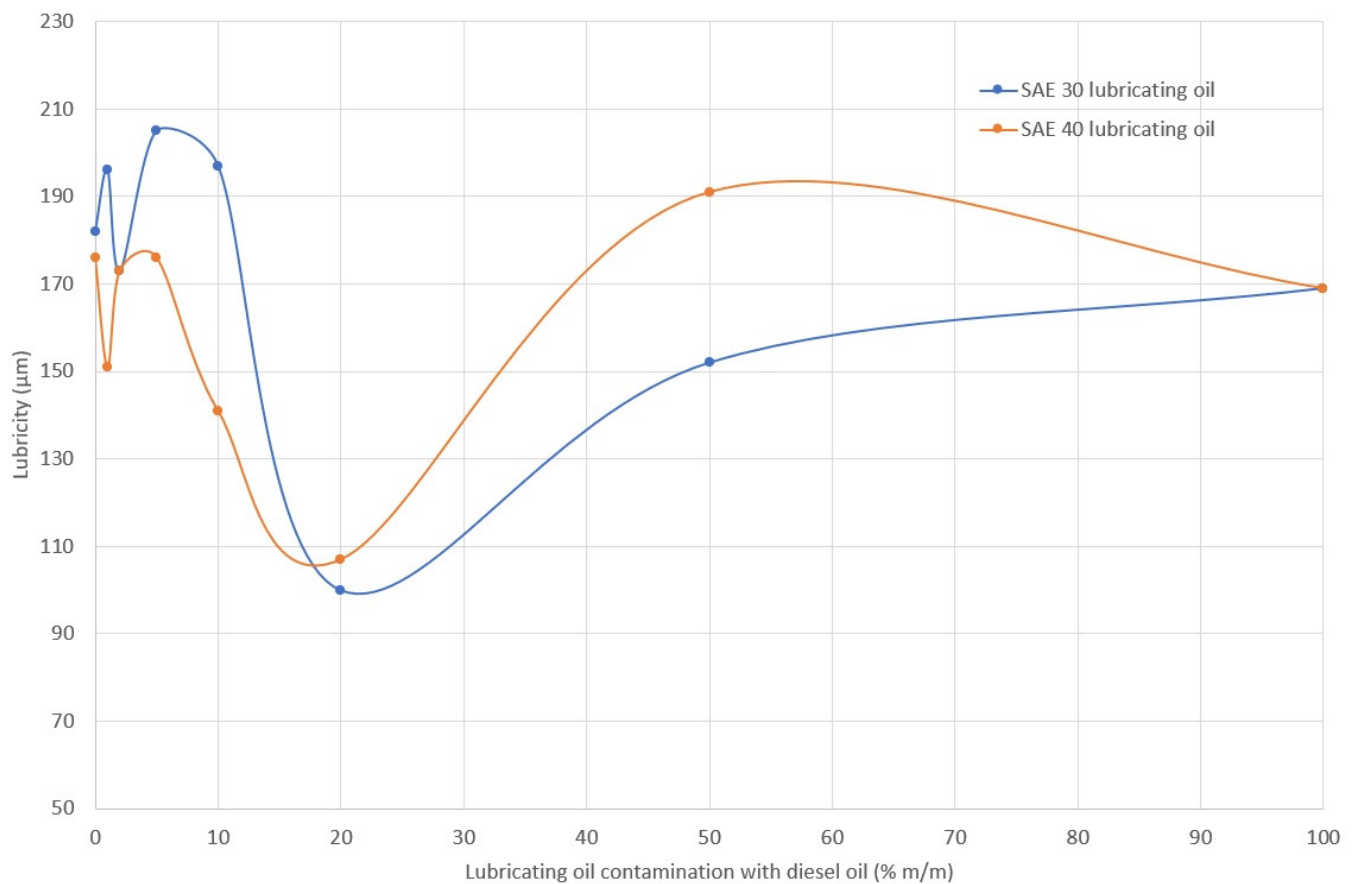


Figure 19. Lubricity of tested lubricating oils at different levels of lubricating oil dilution with diesel fuel.

Lubricity values measured for pure oils are in the range of 180–190 μm . The results show slight fluctuations in the lubricity values in the low diesel concentration range (contamination of the lubricating oil with diesel up to approx. 10% m/m diesel in the lubricating oil). For this range, the maximum lubricity variations for the two oils tested are between 141 μm (SAE 40, 10% m/m diesel oil) and 205 μm (SAE 30, 5% m/m diesel oil). At a diesel concentration of ~20% m/m, the greatest decrease in lubricity values is observed (~100–107 μm), followed by an increase in lubricity. From about 50% m/m diesel content to a value of 100% (pure diesel oil), the lubricity value varies in the range of $\sim\pm 20$ μm relative to the lubricity value for pure diesel oil of 170 μm .

The HFFR used in the experiment also provides information on oil film continuity (defined as the percentage loss of oil film resistance during the test, so that 100% corresponds to full oil film separation of mating components), along with averaged friction coefficient values. These are only auxiliary indicators that can supplement the analysis based on measured oil lubricity. Figures 20 and 21 show the measurements for these two indicators.

The conducted tests show that in the range of lubricating oil contamination with diesel fuel in the concentration range of 0–10% m/m, the resistance of the oil film does not change. Thus, the mating elements in the HFFR apparatus are separated by a layer of lubricant, and there is no metallic contact between elements.

The averaged friction coefficient of mating elements in the HFFR apparatus changed little for diesel fuel concentration 0–10%. An increase in the friction coefficient was observed above 10% m/m, followed by a decrease in its value above 50% m/m.

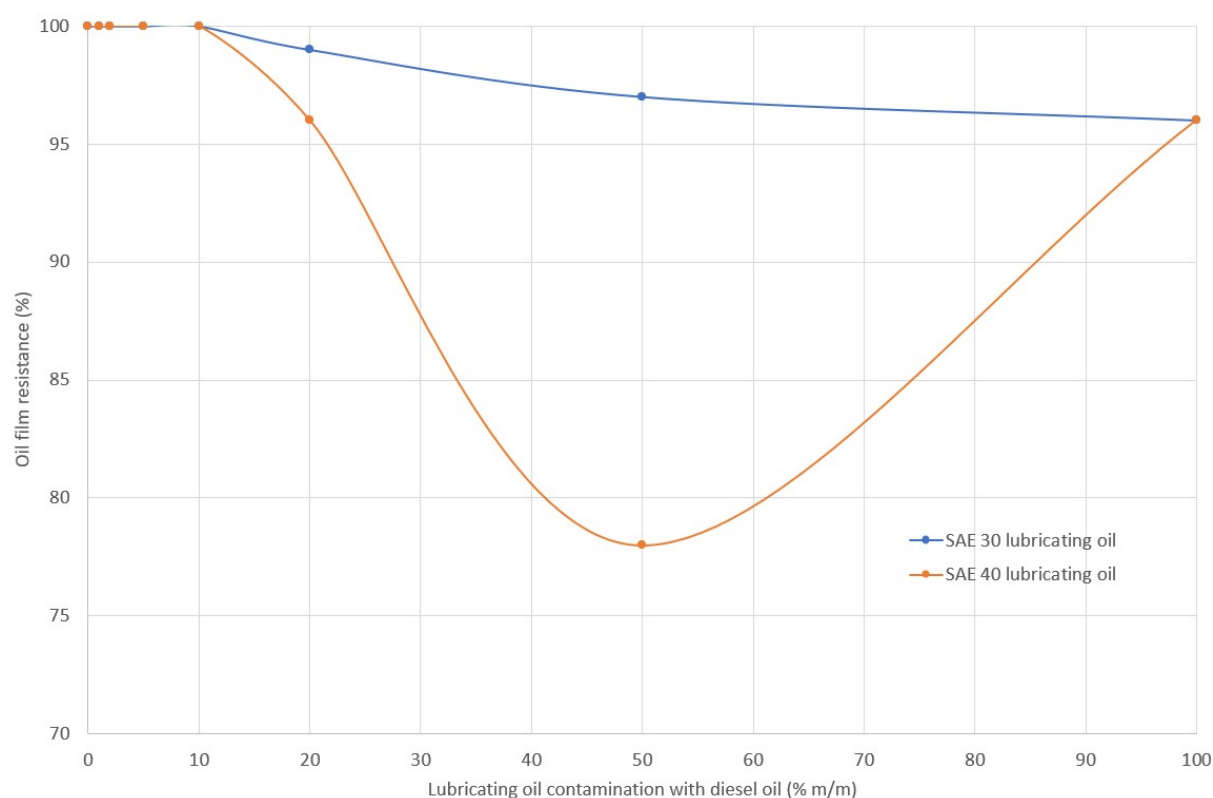


Figure 20. Percentage loss of oil film resistance of the lubricating oils tested at different levels of lubricating oil dilution with diesel fuel.

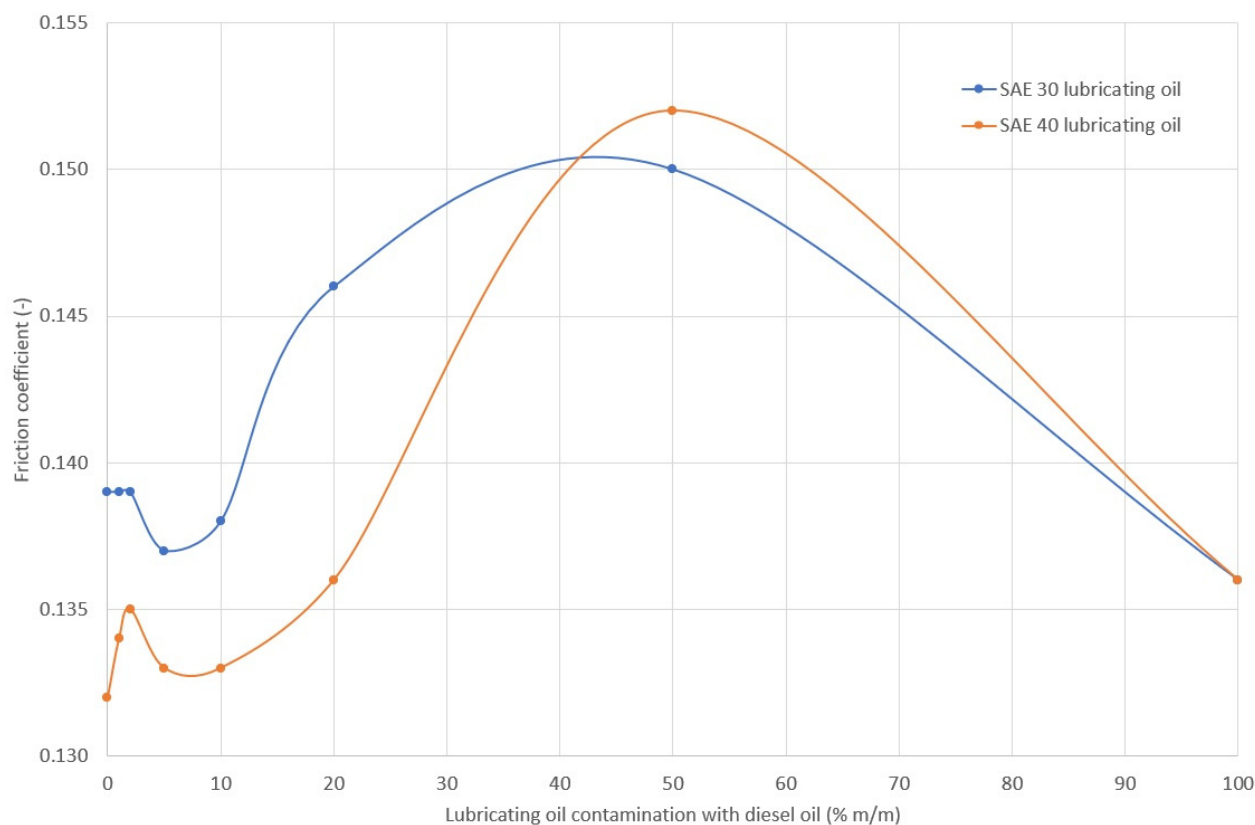


Figure 21. Averaged coefficient of friction of mating elements in the HFFR apparatus separated by a layer from the tested lubricating oils at different levels of lubricating oil dilution with diesel fuel.

The observed changes in lubricity, coefficient of friction, and percentage loss of oil film resistance with diesel testify to the complexity of the wear process and the difficulty of objectively determining the lubricating properties of oils. The lubricity information obtained can be used as a coarse indicator showing the effect of lubricating oil contamination. Simultaneous consideration of the aforementioned indices along with the viscosity values of the tested oils shows that their lubricating (anti-wear) properties deteriorate with increasing fuel contamination. A detailed determination of the relationship between these properties and the lubricity value obtained by the HFFR method requires further detailed research.

3.3. Ignition Properties of Oil

Flash point temperature is the primary indicator describing the ignition properties of oils and fuels. Figure 22 shows the results of measuring the flash point of the tested mixtures of oil with DO. As expected, the ignition temperature of the mixture decreases with an increase in the diesel content of the lubricating oil.

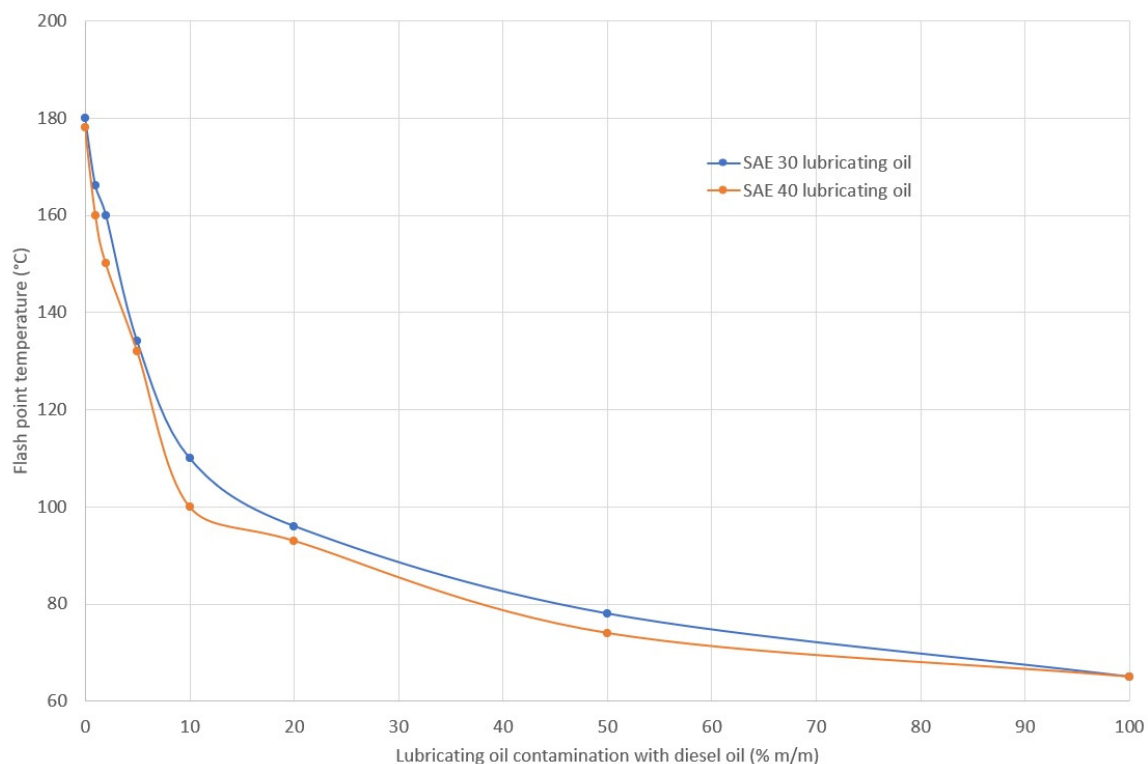


Figure 22. Flash point temperature determined in a closed crucible for the lubricating oils tested at different levels of lubricating oil dilution with diesel fuel.

Measured ignition temperatures were significantly lower than those obtained by Ferguson. This difference is due to both the different composition of the oil (lubricating oil and diesel oil) as well as different conditions under which the experiments were conducted. In the Ferguson experiment, the ignition temperature of the diesel oil was 103 °C, while in the present experiment, the pure diesel fuel tested had an ignition temperature of only 65 °C. The observations show that the literature results are not authoritative for modern distillate fuels and lubricating oils. Importantly, a significant reduction in the ignition temperature of the oil as a result of its contamination with diesel was confirmed.

Note that for a 5% m/m contamination of the engine's circulating oil with diesel fuel, which can occur in operating practice, the flash point decreased by as much as 46 °C compared to that of pure lubricating oil. Such a large decrease indicates a significant

relationship between fuel contamination and the ignition properties of the oil, and thus the risk of ignition in the crankcase.

The autoignition delay described by the cetane number and other indicators indicated in Section 2 characterizes an oil in terms of its ability to ignite (the shorter the ignition delay, the better the autoignition properties). In the case in question of the analysis of the autoignition capability of lubricating oils, the lower the cetane number, the better the oil is. Figure 23 shows results of the self-ignition capability tests.

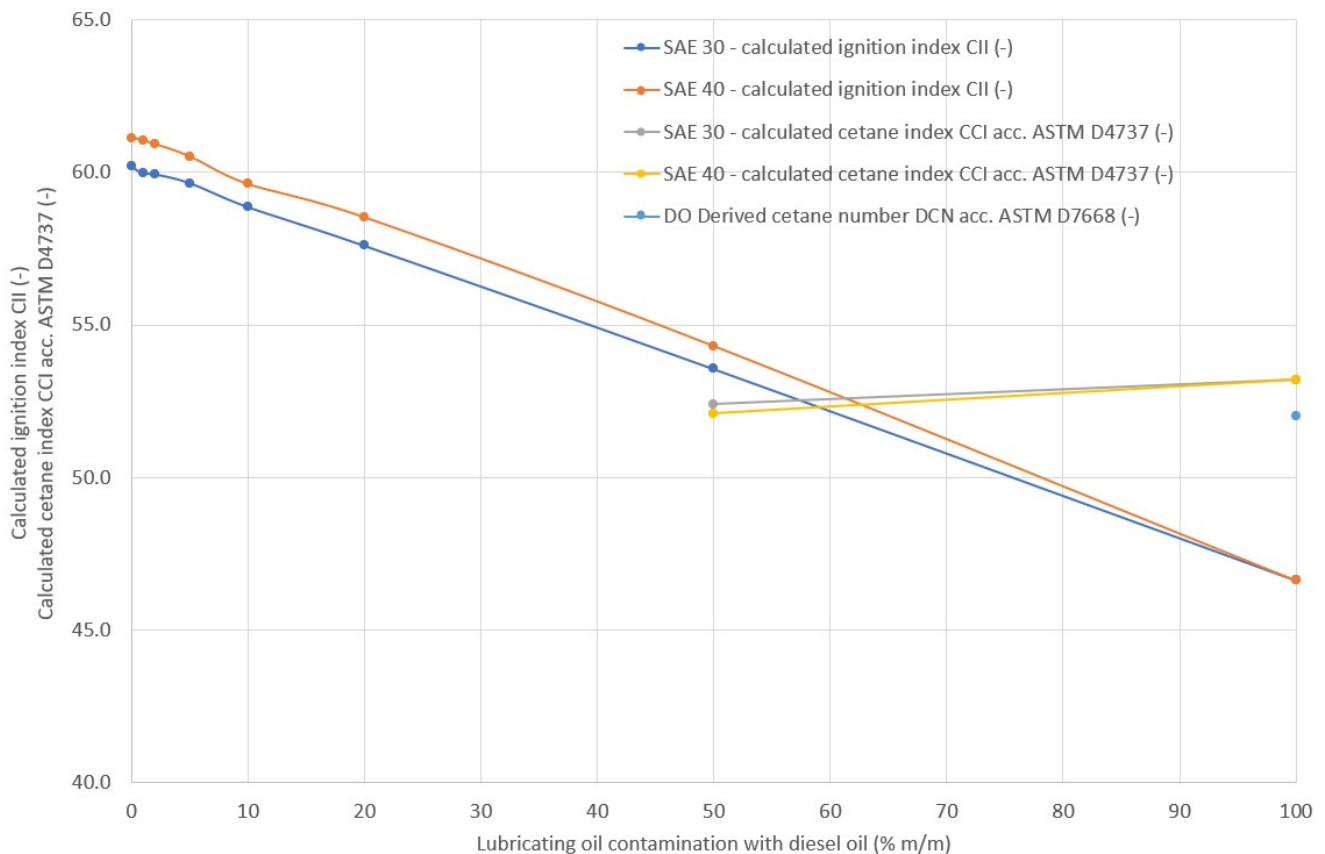


Figure 23. Ignition and cetane indices of tested lubricating oils at different levels of lubricating oil dilution with diesel fuel.

Figure 24 shows ignition indices analogous to the cetane number: derived cetane number, *DCN*, calculated cetane index, *CCI*, and calculated ignition index, *CII*. The *DCN* value was found to be 52 for pure diesel fuel. The *CCI* values were determined due to technical feasibility (difficulty in distilling the fractions) for the 50% m/m concentration of diesel fuel in the lubricating oils tested and for pure diesel fuel. In the concentration range of 50–100% m/m, the *CCI* value ranges from 52.1 to 53.2 for the tested oils. In contrast, the calculated average *CII* values for the entire concentration range are between 60.2 and 46.6 for SAE 30 oil and between 61.1 and 46.6 for SAE 40 oil. With an increase in the diesel content of the mixture in both cases, the *CCI* value decreases, which may indicate a slight increase in the ignition delay and a deterioration in the mixture's self-ignition capability. Nevertheless, these values are high throughout the measurement range (>45), which, by analogy with fuels, can be interpreted as a very low autoignition delay, and therefore very good ignition properties.

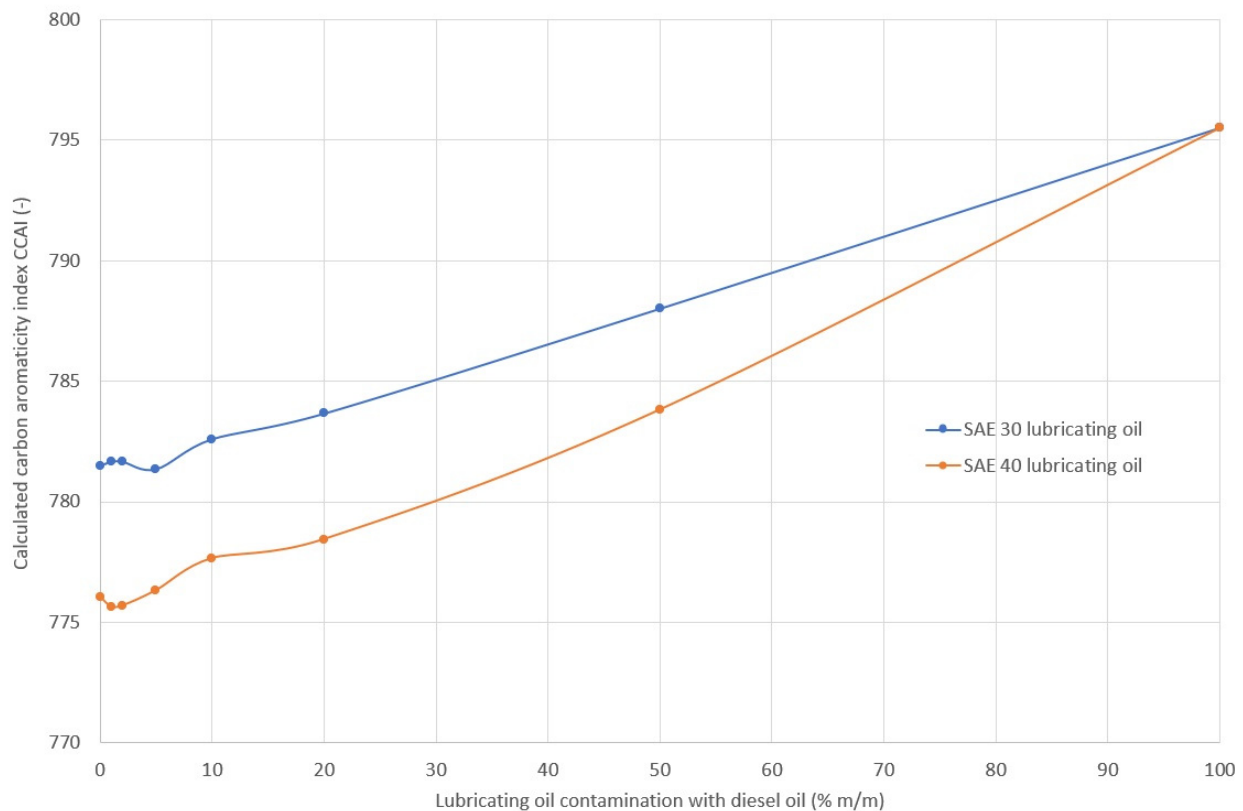


Figure 24. Calculated carbon aromaticity index of the tested lubricating oils at different levels of lubricating oil dilution with diesel fuel.

Analogous to *CII*, the value of the calculated carbon aromaticity index *CCAI* was determined for the tested mixtures. *CCAI* values increase with increasing diesel fuel contamination. *CCAI* values vary between 781.4 and 795.5 for SAE 30 oil blends and between 775.6 and 795.5 for SAE 40 oil blends. Relating these values to the standards provided for residual fuels, lubricating oil contamination with diesel fuel has no significant effect on the autoignition delay, which corresponds to very good autoignition properties.

4. Final Conclusions

There is no doubt that measuring the ignition temperature of the oil makes it possible to quickly diagnose a situation where fuel contamination has occurred in the oil. Because laboratory tests of lubricating oil are carried out periodically at fixed intervals between tests, they will not be a valuable measure in the situation of sudden and rapidly developing damage to piston rings, pistons, cylinder liners, and injectors. However, it cannot be ruled out that in situations of long-developing engine deterioration, testing the oil for potential fuel contamination may be a key element in increasing the safety of engine operation [71]. For the same reason, the flash point test has been adopted by all major used oil laboratories as a service standard to vessel operators.

It should be emphasized that the authors of the CIMAC publication [31] do not rule out the possibility of using an indicator such as flash point to diagnose whether or not oil contamination with fuel (residual or distillate) has occurred. The publication states that “For engines which alternate between heavy fuel and distillate fuel usage, flash point measurements can be used to monitor the origin of possible fuel contamination (the contamination of heavy fuel and distillate fuel can compensate the resulting changes in viscosity)”.

The main observations from the author’s own experiment are as follows:

1. A decrease in the lubricating oil flash point is an indicator of oil contamination with fuel.

2. A change in viscosity does not necessarily indicate contamination (among other contaminations), since, depending on the type of fuel, oil viscosity can:

- not change (engines powered by different fuels);
- decrease (engines powered by distillation fuel);
- increase (engines fueled by residual fuel).

A change in viscosity itself is not necessarily caused by contamination of the oil with fuel, but could be due to contamination with other oil (such as cylinder oil), contamination of the oil with water, bacteria, fungi, and protozoa; oxidation of the oil, etc. [72–74].

3. Changing the oil composition can change its viscosity, which alters the distribution of the number and size of droplets in the oil mist. Occurrence of this mist, once set limits are exceeded, promotes the initiation of explosions.
4. A reduction in the ignition temperature of a mixture may be indirectly associated with a reduction in the autoignition temperature (although not necessarily) [14,75]. If this situation occurs, the risk of explosion increases in view of the higher volatility of diesel fuel than lubricating oil. Contamination of lubricating oil with distillation fuel does not significantly affect the autoignition delay, which, for clean and contaminated oil, corresponds to conditions that can be classified as very good autoignition properties [76].
5. Deterioration of the tribological conditions of the bearings, as seen in the change in viscosity, viscosity index, and lubricity of the oil, causes an increase in bearing temperature and the possibility of hot spots. Viscosity index, lubricity, coefficient of friction and reduction in oil film resistance change significantly when the concentration of diesel fuel in the lubricating oil exceeds 10%. The observation is in line with some previous works [36]. At such concentrations, increased friction in tribological pairs lubricated with lubricating oil contaminated with diesel fuel can intensify the wear of mating components, increase their temperature, and ultimately intensify the formation of white oil mist in the crankcase.

Summing up, there are two extreme approaches in the literature to the subject of diesel lubricating oil contamination and the effects of this contamination on engine operation. The first, which was the inspiration for the article, is the approach presented by Ferguson and in the paper published by CIMAC. This approach states that the effects of diesel contamination in lubricating oil are negligible even at high diesel concentrations in the lubricating oil. The second approach points to an increased risk of engine seizure and cites 2–5% diesel content in lubricating oil as alarming levels. However, neither approach is well-argued, and a holistic approach to the subject has not been presented. In this article, results show that when the diesel oil content in the lubricating oil exceeds 10%, oil–film rupture occurs, and this can result in increased wear of tribological couples, such as bearings in the crank–piston system. At the same time, given the decrease in viscosity and thus the deterioration of lubrication conditions, and the decrease in evaporation and ignition temperatures, one can conclude that the synergistic interaction of these factors increases the risk of explosion in the engine crankcase. Further conclusions could be provided as a result of an oil mist morphology analysis, which is planned to be the next step in the future research.

Funding: This research was funded by the Ministry of Science and Higher Education (MEiN) of Poland, grant number 1/S/KPBMiM/22. The APC was funded by MDPI.

Data Availability Statement: All data are available in the dataset: Chybowski, L. Lube oil—diesel oil mixes-dataset; 2022, Ver. 3, DOI: 10.17632/scbx3h2bmf.3. Dataset is available at <https://data.mendeley.com/datasets/scbx3h2bmf/3> (accessed on 8 November 2022) [57].

Acknowledgments: Laboratory tests were performed on behalf of the author at the Center for Testing Fuels, Working Fluids, and Environmental Protection (CBPCRiOs) of the Maritime University of Szczecin. The author would like to thank Magdalena Szmukała and Barbara Żurańska for the technical support.

Conflicts of Interest: The author declares no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

ASTM	American Society for Testing and Materials
CCE	crankcase explosion
CEA	crankcase explosion apparatus
CFR	Cooperative Fuel Research
CID	cetane ignition delay
CIMAC	International Council on Combustion Engines
CCAI	calculated carbon aromaticity index
CCI	calculated cetane index
CI	cetane index
CII	calculated ignition index
CN	cetane number
CVCC	constant volume combustion chamber
DCN	derived cetane number
DO	diesel oil
ECP	electrical contact potential
FDM	fuel dilution meter
FID	flame ionization detector
FILM	measure of oil film resistance
FIT	fuel ignition tester
FP	flash point temperature
FTIF	Fourier-transform infrared
GC	gas chromatography
HFO	heavy fuel oil
HFRR	high frequency reciprocating rig
IEC	International Electrotechnical Commission
IQT	ignition quality tester
ISO	International Organization for Standardization
SAE	Society of Automotive Engineers
SAE 30, SAE 40	viscosity grades of lubricating oils according to SAE J300-2021 standard
SAW	surface acoustic wave
VI	viscosity index
WSD	wear scar diameter
Symbols	
m	mass of the substance
t	measured temperature of the substance under operating conditions
V	volume of the substance
$\dot{\gamma}$	shear rate
ε	the coefficient of change of density of a substance when it is heated by 1 °C
η	dynamic viscosity of the substance
λ	thermal conductivity coefficient
μ	coefficient of friction
ν	kinematic viscosity of the substance
ρ	density of the substance
ρ_{15}	density of the substance at 15 °C
ρ_t	density of the substance at temperature t
τ	time
τ_F	shear stresses

Appendix A.

Table A1. Fuel inflow caused by mechanical effect (based on [30]).

Action	Effect	What to Do
Continued operation with stops and start.	The fuel does not burn off completely.	Reduce the mileage change interval to the strictest change interval indicated by the manufacturer.
Starting in the cold.	The fuel does not burn off well because the combustion temperature is low.	Wait for the engine to increase in temperature before accelerating.
Problems in the injection system.	The droplets of fuel being injected into the chamber are big, leading to poor combustion.	Incomplete combustion is occurring; inspect the injectors.
Poor combustion.	The fuel is not burning off completely.	Incomplete combustion is occurring. Check that the combustion chamber and the injection system are working properly.
Worn-out engine parts: valve guides, injectors, and wear.	Conditions change in the combustion chamber, meaning it is no longer optimized.	Inspect the engine and injectors.
Excessive acceleration.	Excess inflow of fuel.	Incomplete combustion is occurring; adjust control system.
Mixture of rich fuels.	Excess fuel.	Incomplete combustion is occurring; inspect the injection system.
Faulty injectors.	Can produce excessive inflow of fuel or inadequate fuel injection.	It does not burn fuel as well, resulting in deposits. Inspection of the injection system.

Table A2. Advantages and disadvantages of the main methods of detecting fuel in lubricating oil (prepared on the basis of [56]).

Method	Advantages	Disadvantages
Gas Chromatography	Widely accepted industry standard Highly precise Suited for high volume labs Can detect biodiesel and ethanol	Can only be carried out in a lab Mandates costly equipment and gases Takes much time to produce best results Requires an expensive equipment and gases
Viscosity Analysis	The availability of portable instruments and lab instruments Accepted routine test for testing lubricant condition Optimum screening test for probable fuel dilution Ability to detect ethanol and biodiesel	Inability to definitively indicate fuel dilution issue Mandates a careful technician
Flash Point Testing	A pass/fail result is enough in the case of most applications Ability to detect ethanol Very little sample required (1–2 mL)	Inability to detect biodiesel Mandates a careful technician Knowledge of the oil/fuel type mandatory for quantitative measurement Risks posed by heating fuel-laden samples
FTIR Spectroscopy	Low cost per sample after initial equipment purchase; test can be carried out quickly	Mandates the use of costly equipment; calibrations are mostly specific to a narrow sample type
Surface Acoustic Wave Sensing	Easy to use Portable Requires only 0.5 mL of sample Less expensive than gas chromatographs Can complete the test quickly Easily adaptable to different oil/fuel types	Inability to measure biodiesel Mandates calibration with a reference fluid

Table A3. Properties of Orlen Efecta Diesel Bio as declared by the manufacturer [60].

Specification	Parameter
Cetane index	≤ 51
Initial boiling point	75–180 °C
Boiling temperature range	95% vol. distills to 360 °C
Flash point (determined in a closed crucible)	>56 °C
Autoignition temperature (according to DIN51794:2003-05)	approx. 240 °C
Kinematic viscosity (according to EN ISO 3104)	1.5–4.5 mm ² /s (2.549 mm ² /s) at 40 °C approx. 2.151 mm ² /s at 50 °C
Density	820–845 kg/m ³ at 15 °C
Relative vapor density	approx. 6 (air = 1)
Cloud point	−7 °C
Cold filter plugging point	−8 °C

Table A4. Manufacturer-declared physicochemical properties of Agip Cladium 120 CD lubricating oils used in tests [61–63].

Specification	Parameter	
Oil	Agip Cladium 120 SAE 30 CD	Agip Cladium 120 SAE 40 CD
Kinematic viscosity (according to EN ISO 3104)	108 mm ² /s at 40 °C 12.0 mm ² /s at 100 °C	160 mm ² /s at 40 °C 15.7 mm ² /s at 100 °C
Viscosity index	100	100
Total base number	12 mg KOH/g	12 mg KOH/g
Flash point (marked in closed crucible)	225	235 °C
Pour point	−18 °C	−15 °C
Density	895 kg/m ³ at 15 °C	900 kg/m ³ at 15 °C

Table A5. Basic characteristics of several machines to study the lubricating properties (compiled from [65,77]).

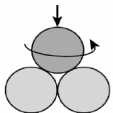
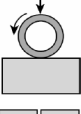
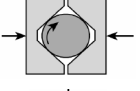

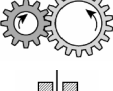

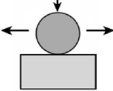
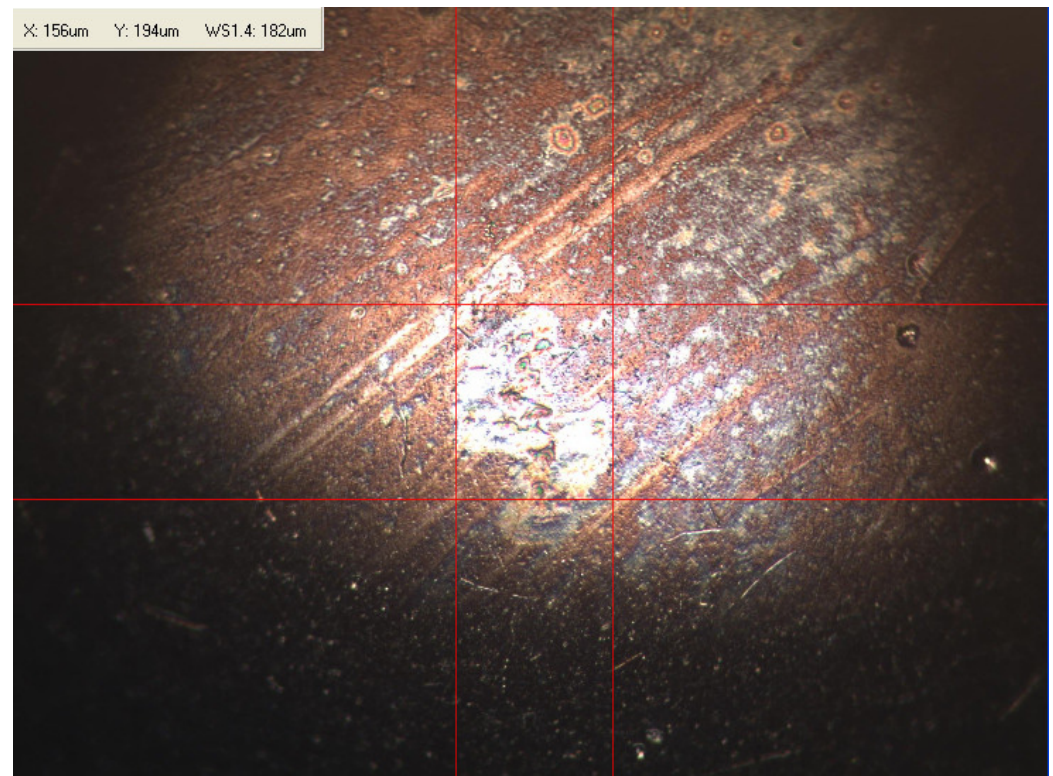
Tribometer	Friction Association	Type of Contact	Application of Tests
Four-ball machine		Punctual	Testing the anti-wear properties of lubricating oils, plastic lubricants and other operating fluids.
Timken		Linear	Testing the anti-wear properties of plastic lubricants.
Falex		Linear	Testing the properties of the solid lubrication film, anti-wear properties of lubricating oils and the properties of plastic lubricants.
Almen-Eieland		Surface	Testing the anti-wear properties and maximum load of lubricating oils and plastic lubricants.
FZG		Linear	Testing the anti-wear properties of lubricating oils and plastic lubricants, especially gear oils.
Vickers		Punctual	Testing the anti-wear properties of thermo-oxidizing fluids hydraulic fluids, turbine oils, gear oils.
HFRR		Punctual	Testing the anti-wear properties of diesel oils, heating oils and lubricating oils.

Table A6. ASTM cetane rating Standards and Applicable Ranges (prepared on the basis of [66–68]).

ASTM Standard	CN Applicable Range	Range (mix.—min.)	Instrument
D6890 (DCN)	33–64 64–100	31.0 36.0	IQT (CVCC)
D613 (CN)	40–56	16.0	CFR engine
D7170 (DCN)	39.5–55.2	15.7	FIT (CVCC)
D7668 (DCN)	39.4–66.8 [66] 35.0–60.0 [67] 15.0–100.0 [68]	27.4 [66] 25.0 [67] 85.0 [68]	CID 510 (CVCC)
D976 (CI)	30–60	30.0	Correlation
D4737 (CCI)	32.5–56.5	24.0	Correlation

Appendix B. Photographs of Traces of Wear on a Moving Component after an HFRR Lubricity Test

**Figure A1.** SAE 30–100%; DO—0%.

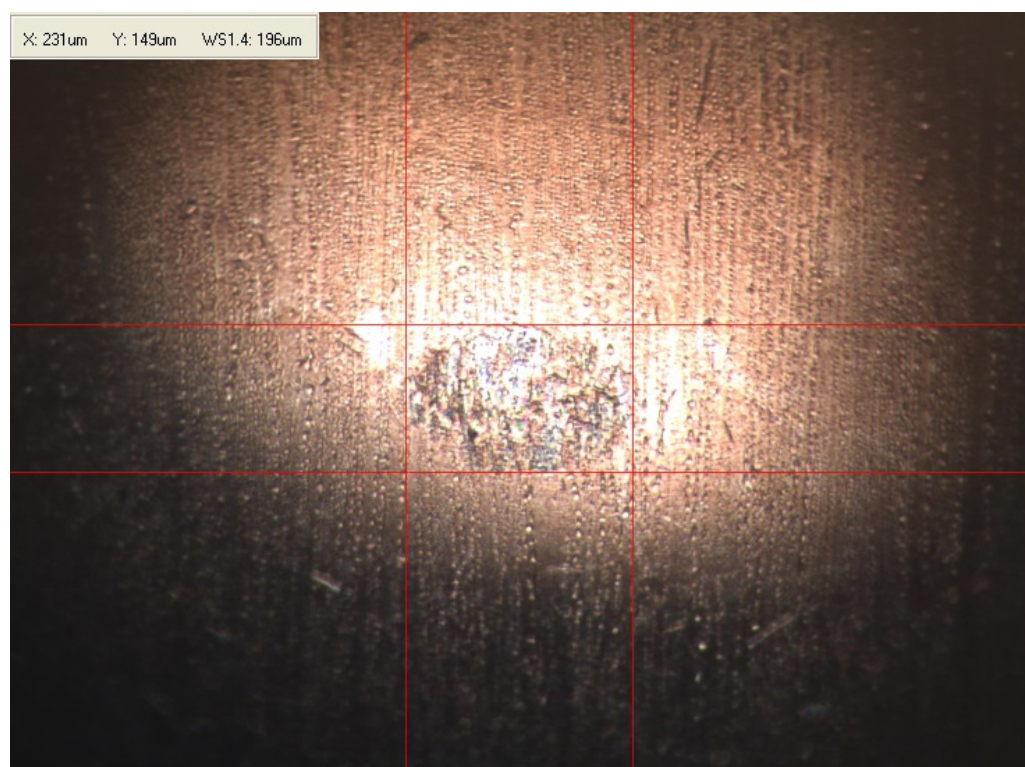


Figure A2. SAE 30—99% m/m; DO—1% m/m.

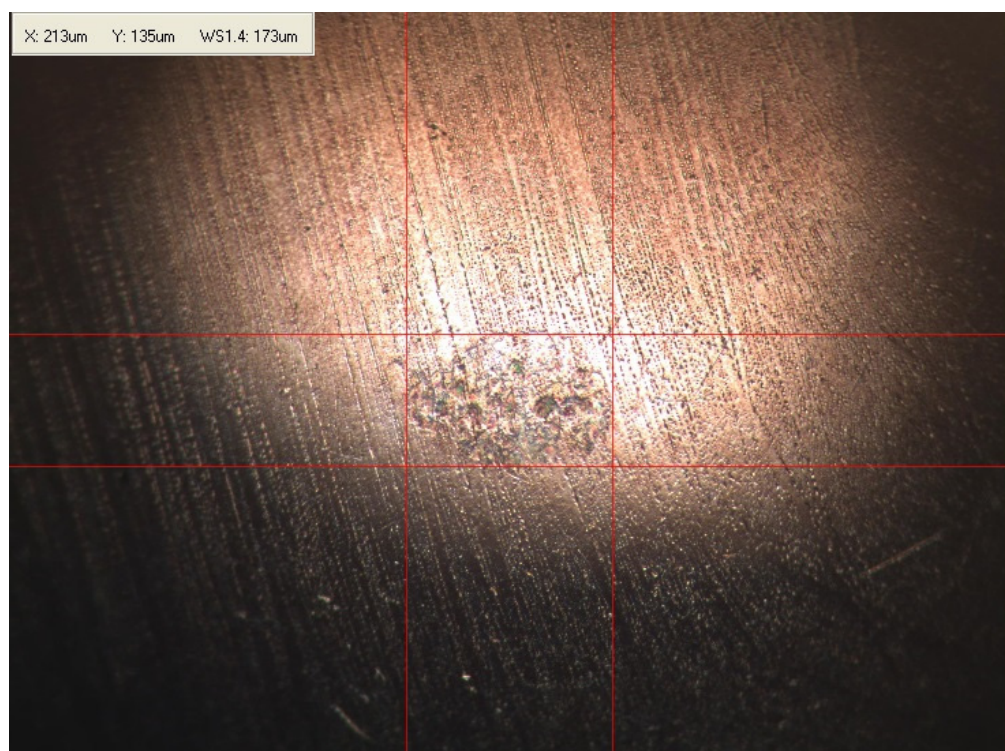


Figure A3. SAE 30—98% m/m; DO—2% m/m.

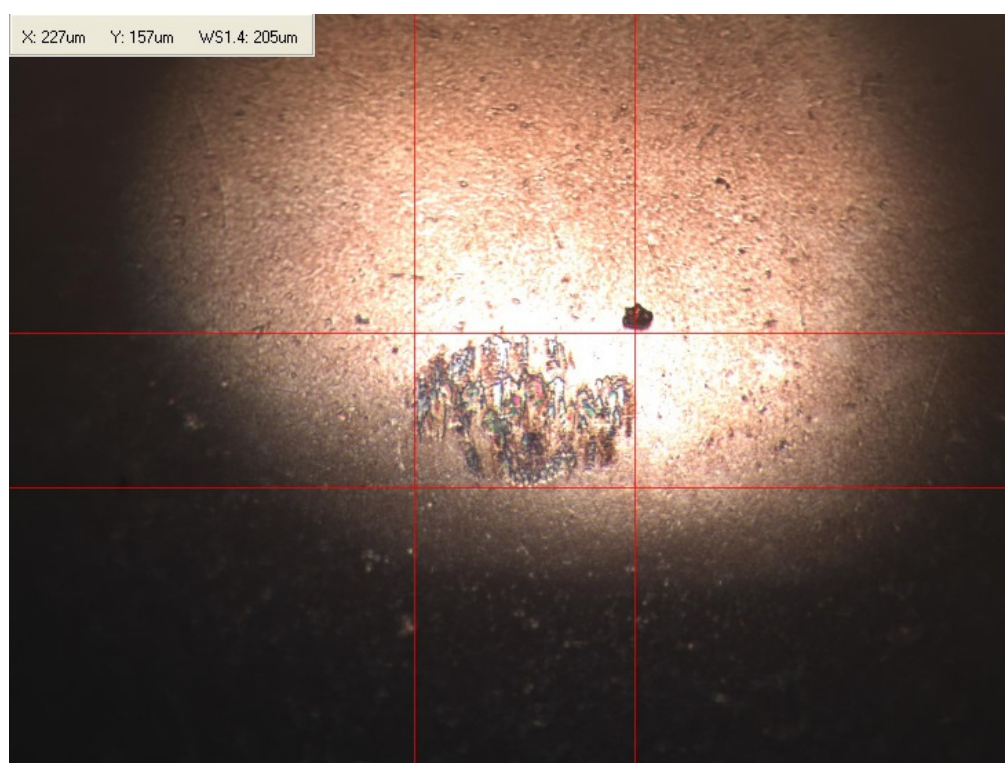


Figure A4. SAE 30—95% m/m; DO—5% m/m.

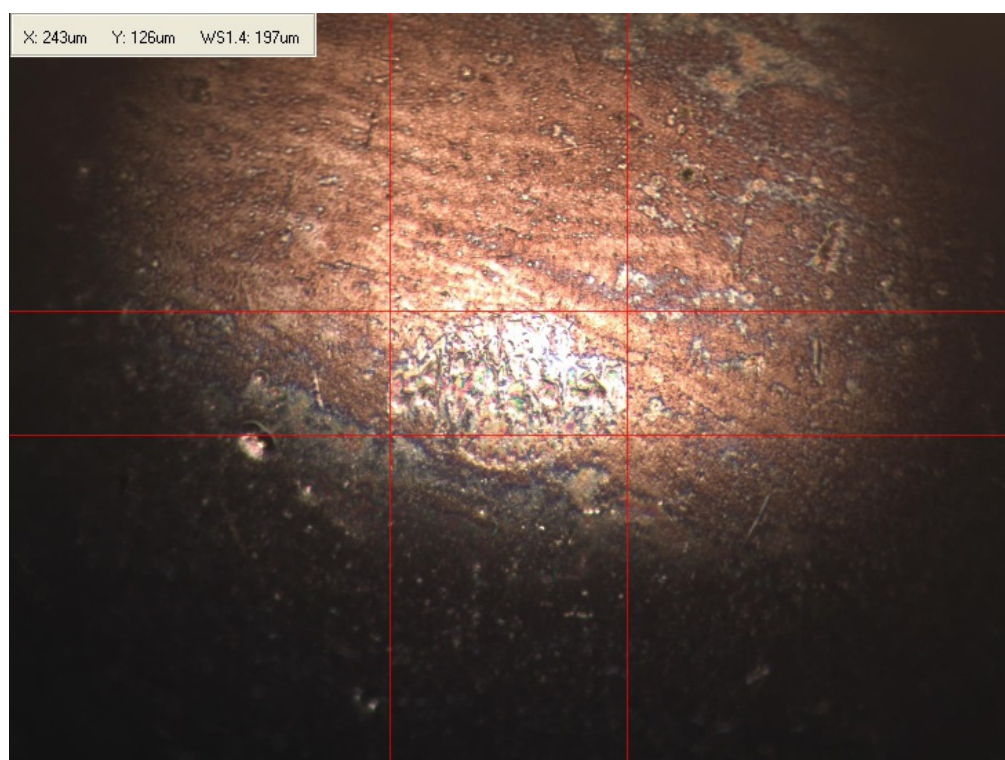


Figure A5. SAE 30—90% m/m; DO—10% m/m.



Figure A6. SAE 30—80% m/m; DO—20% m/m.

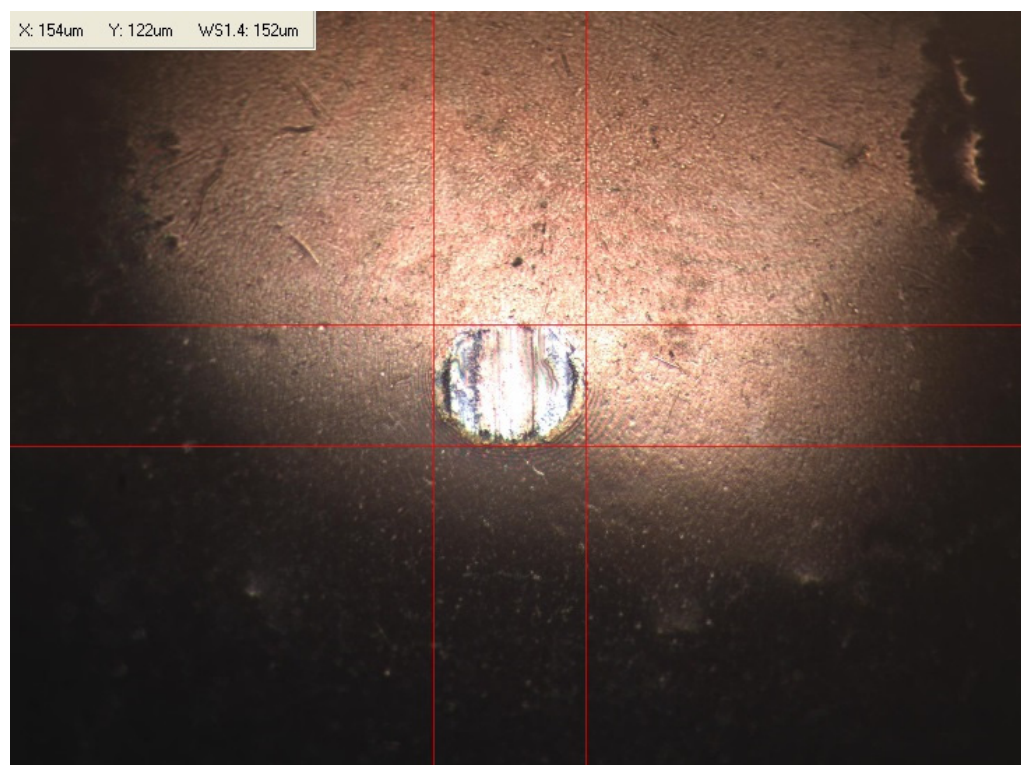


Figure A7. SAE 30—50% m/m; DO—50% m/m.

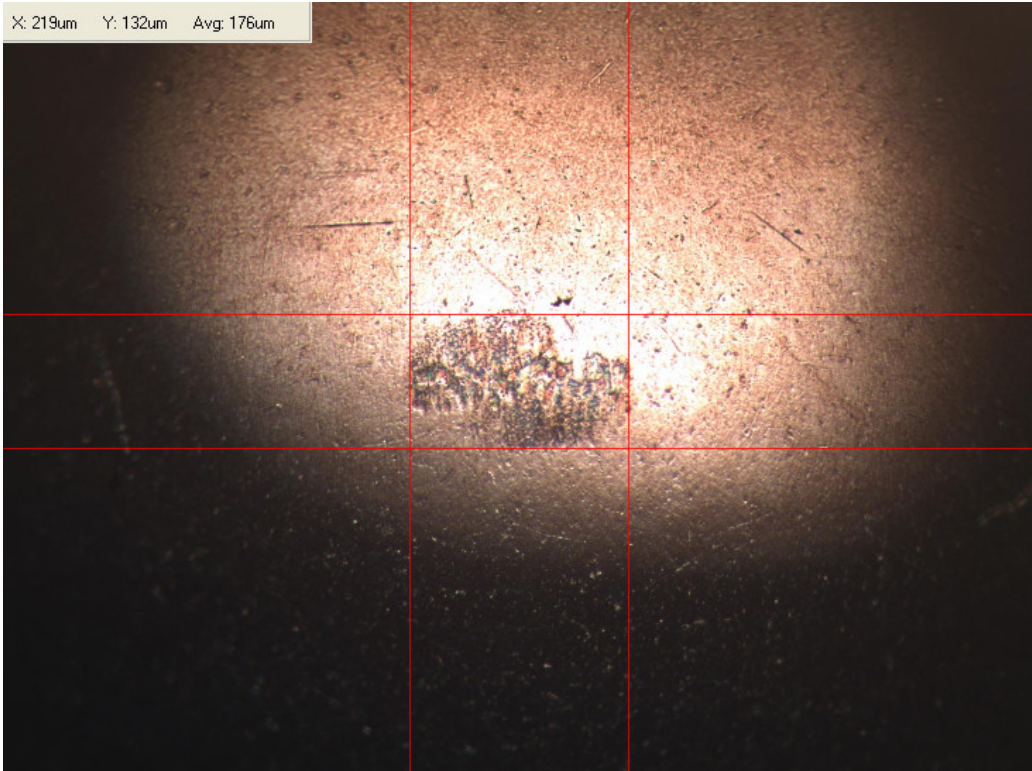


Figure A8. SAE 40—100%; DO—0%.

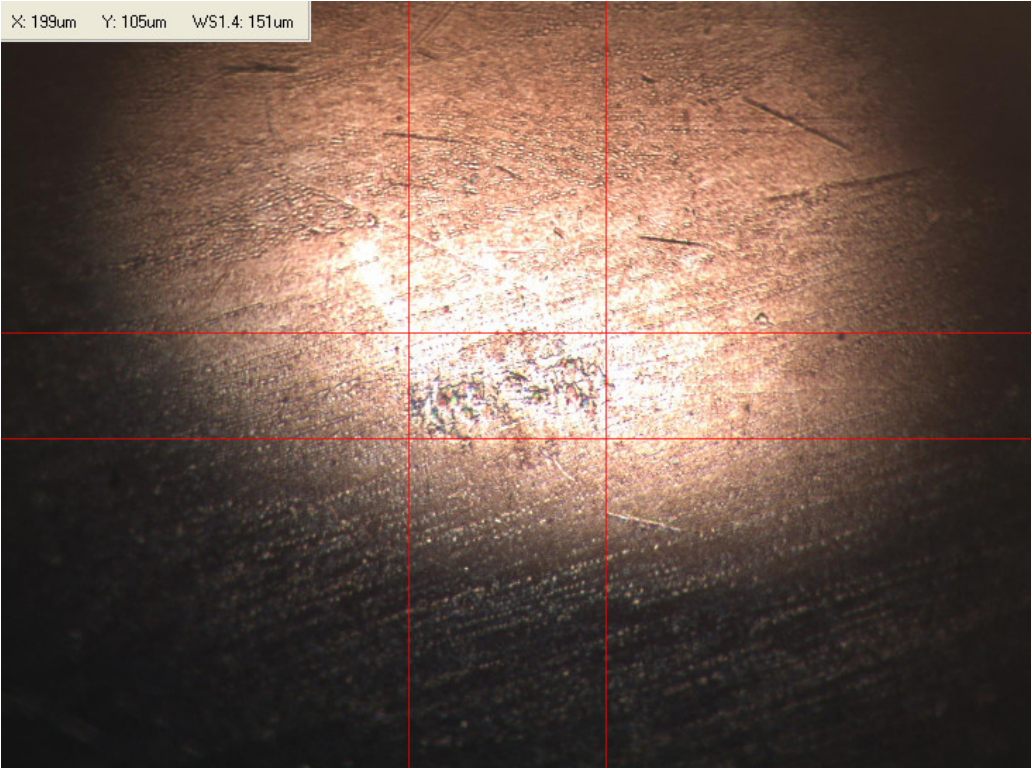


Figure A9. SAE 40—99% m/m; DO—1% m/m.

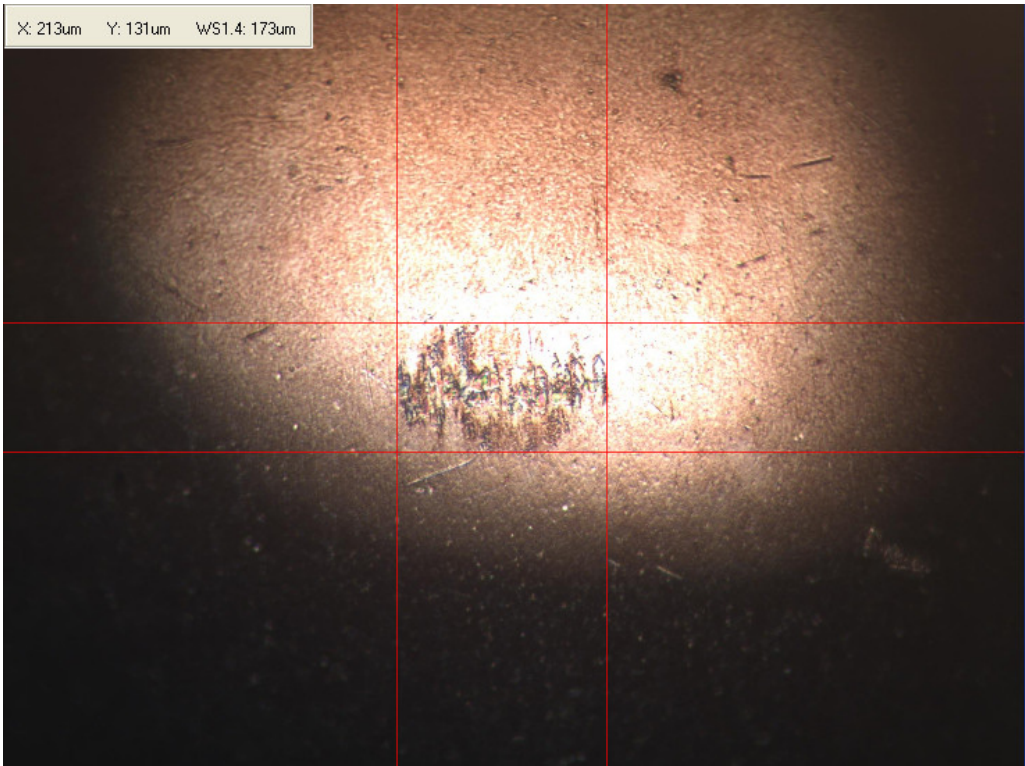


Figure A10. SAE 40—98% m/m; DO—2% m/m.

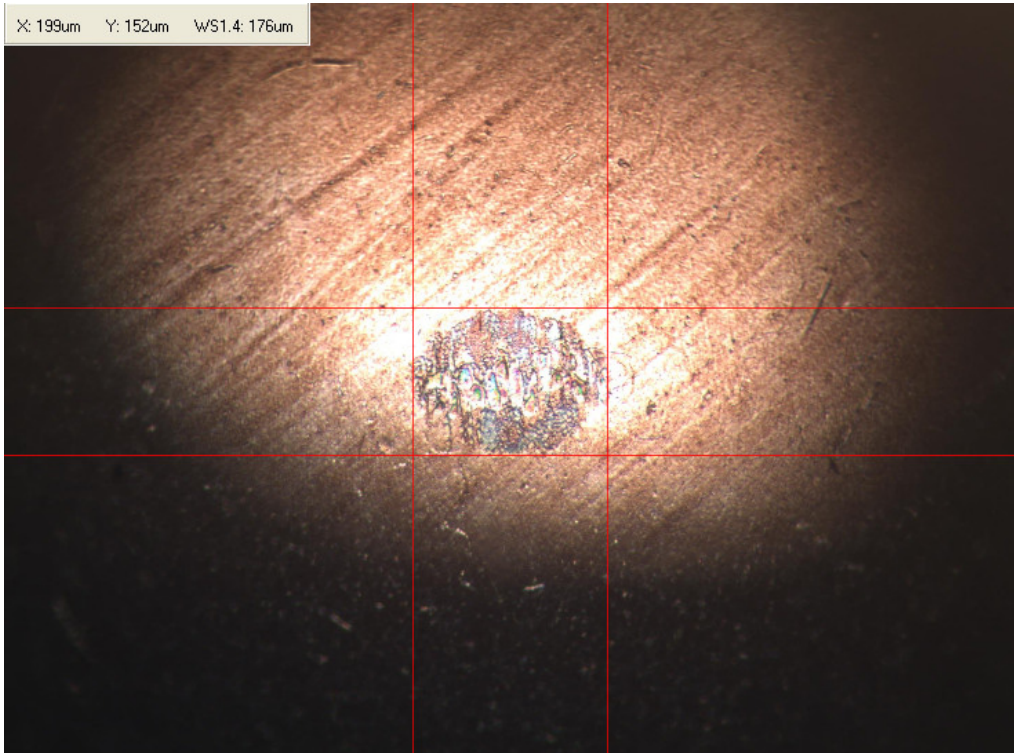


Figure A11. SAE 40—95% m/m; DO—5% m/m.

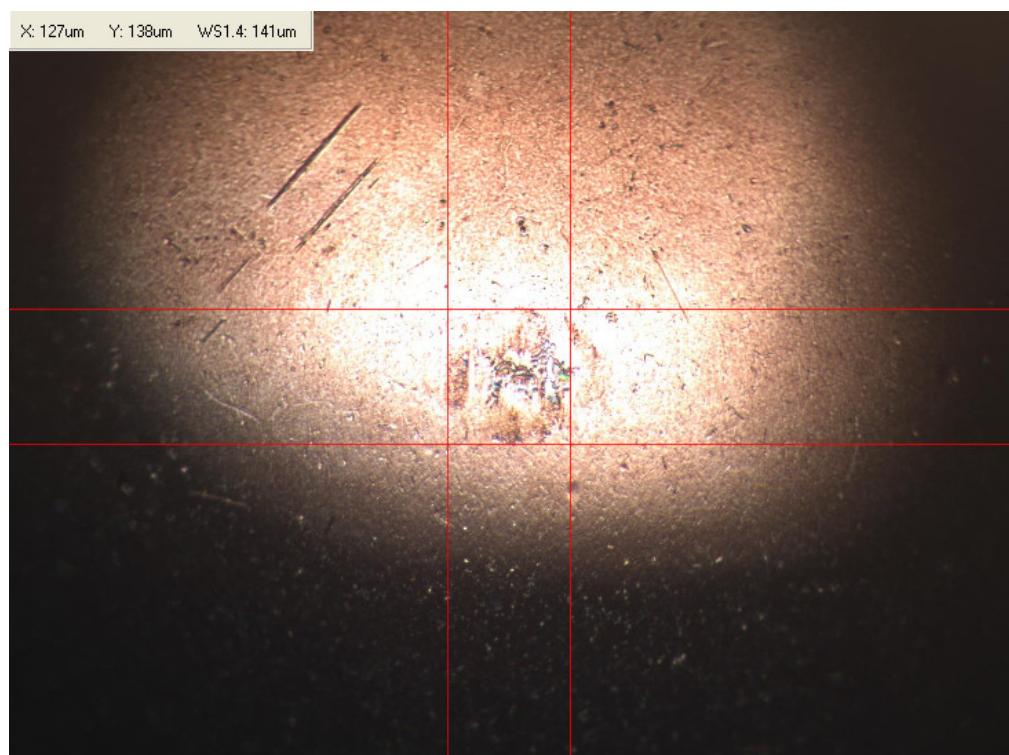


Figure A12. SAE 40—90% m/m; DO—10% m/m.

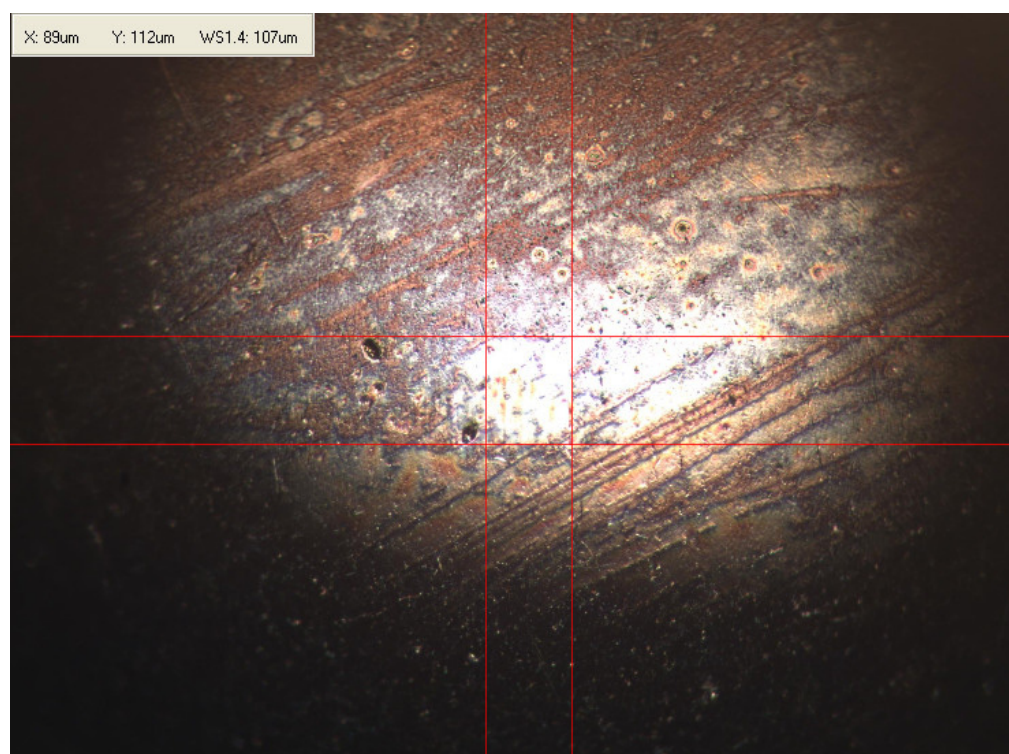


Figure A13. SAE 40—80% m/m; DO—20% m/m.

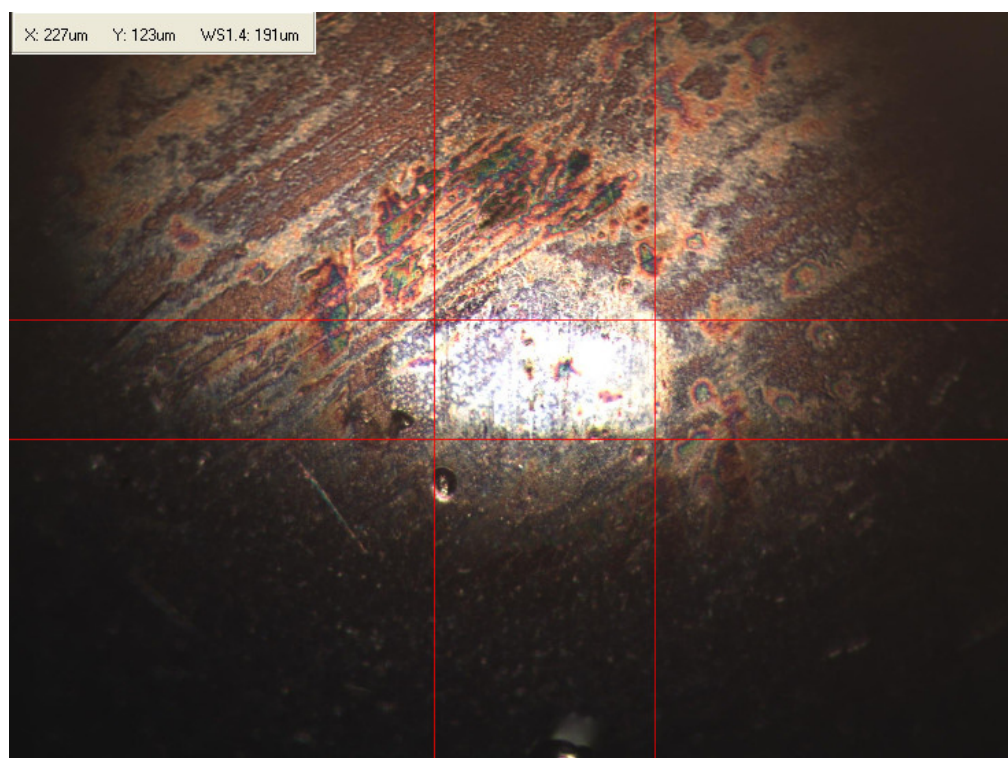


Figure A14. SAE 40—50% m/m; DO—50% m/m.

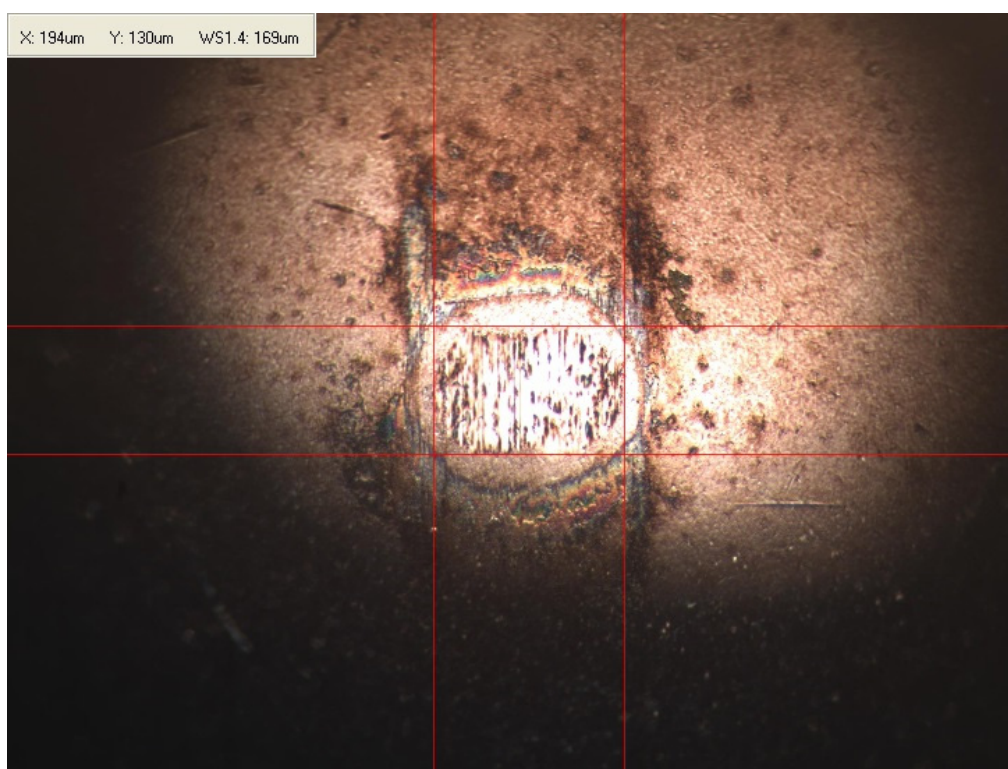


Figure A15. SAE 30/SAE 40—0%; DO—100%.

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