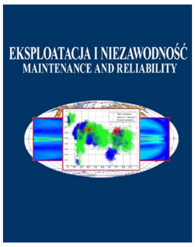

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Design of a tribotechnical diagnostics model for determining the technical condition of an internal combustion engine during its life cycle

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Highlights

- The methods used in tribotechnical diagnostics to determine the technical condition of engine oils are described.
- A model of tribotechnical diagnostics used to determine the technical condition of an internal combustion engine during its life cycle has been designed.
- In the tribotechnical laboratory, measurements were performed using each of the described methods and limit values were determined for assessing the technical condition of the Honda GCV 165 internal combustion engine.
- The results are supported by the individual measurements shown in the figures.

Abstract

The paper proposes a model of tribotechnical diagnostics, which allows us to determine the technical condition of an internal combustion engine within its life cycle and then take measures, including its decommissioning due to excessive wear of major components. The paper also focuses on tribodiagnostic methods that are suitable for assessing the technical condition of internal combustion engines used in various means of transport (automobiles, railway locomotives powered by internal combustion engines, aircraft powered by reciprocating internal combustion engines, special and garden equipment). An internal combustion engine from agricultural equipment was selected for the experiment and monitored throughout its life cycle. The paper describes in detail the appropriate methods used for the proposed tribotechnical diagnostics model, including the results from the measurements by these methods. The said methods were then evaluated and mutually compared. The following advanced instrumental analytical methods were used to evaluate the collected engine oil samples: atomic emission spectrometry (AES), ferrography, automatic laser counter and LNF particle classifier, FTIR infrared spectrometry. The result of the work (paper) is the design of a tribotechnical diagnostics model for determining the technical condition of an internal combustion engine during its life cycle and the determination of limit values for assessing the technical condition of a Honda GCV 165 internal combustion engine. The results are based on individual measurements.

Keywords

tribotechnical diagnostic, Fourier transform infrared spectrometry, kinematic viscosity, atomic emission spectrometry, ferrography.

1. Introduction

Tribotechnics is a field that uses knowledge from research on friction, wear and lubrication to reduce friction coefficients or to optimise the friction course and reduce wear of the mutually moving bodies. Tribotechnical diagnostic methods use the lubrication medium in complex mechanical closed systems as a source of multidimensional, complex information about the processes, changes and wear modes occurring in the systems. Tribotechnical diagnostics solves two major problem areas:

- condition detection, shelf life extension and lubricating oil degradation prediction;
- detection of the mode, location and trend of wear of a mechanical system (internal combustion engine, transmission, hydraulic system, etc.) by evaluating the presence of foreign substances in the lubricant, both quantitatively and qualitatively [4, 5].

Wear detection in oil-lubricated mechanical systems is based on the knowledge that oil exhibits a certain percentage of impurities after a particular period of operation. These are mainly metallic abrasion (wear particles) which are dispersed in the oil and which, when quantified by some suitable method (e.g. atomic emission spectrometry, spectral analysis, polarography, ferrography, etc.), allow indirect monitoring of the mechanical changes in the system in which the oil is used. Certain conclusions are drawn from the amount of metallic abrasion, the intensity of growth, shape, size and material composition, etc. From these parameters, the severity of the failure and the urgency of remedial action can be inferred. An important diagnostic factor is the possibility of locating the site of increased abrasion. According to the type of metallic abrasion, if we know the material of the parts of the system lubricated and rinsed with oil, it is possible to determine the friction pair in which the degradation wear increases sharply [4].

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Engine oil is important for maintaining optimum engine performance [13], reducing fuel consumption and emissions [15]. Engine oil is subjected to significant oxidation, high temperature, pressure and penetration of unwanted contaminants from the external environment during its operation in the engine. These factors affect the quality of the engine oil and consequently lead to a reduction in the presence of additives. In addition to the actual chemical ageing of the oil, the degradation of engine oil is also caused by residues of incompletely burnt fuel, condensed water, or coolant that penetrates the lubricating medium [19]. In addition, small dust impurities from the surrounding environment, which are sucked in during driving and lead to clogging of the air filter, affect oil degradation [22]. Diesel engine oils are heavily contaminated with soot. Green et al. [7] report that soot generated in the engine can cause hard sludge, high lubricant viscosity, or oil gelation. According to Soejima [21], soot particles tend to aggregate and this is the main cause of engine oil gelation at high temperatures. Oil and engine manufacturers consider viscosity to be a key factor in lubrication quality. In literature [19, 20] it is stated that in the case of large volume diesel engines the range of viscosity change is 20% compared to the viscosity of new oil which is still acceptable to ensure lubrication. The quantity that allows evaluating the change in lubricant viscosity as a function of temperature change is the viscosity index. The higher is the value of the viscosity index, the less the viscosity changes with temperature. Therefore, large changes in viscosity can occur during engine oil usage. This issue is described in detail in [18, 25].

Oil oxidation is accompanied by darkening of the oil, an increase in its acidity and viscosity, odour and the formation of insoluble oxidation products [15]. The increase in viscosity can also be caused by coolant penetrating the oil due to operational damage to the engine seals. An increase in engine oil viscosity also occurs when the base oil has a high evaporation rate so that the more volatile fractions decrease during operation. This is reflected in increased oil consumption and an unfavourable composition of exhaust emissions. Conversely, a decrease in the viscosity of the operating oil is due to dilution of the oil by the fuel, or also due to oil splitting under thermal stress [15, 19].

Differential FTIR spectroscopy is nowadays commonly used for monitoring thermal and oxidative degradation of engine oil, reducing additive content and penetration of impurities into the oil charge. With the development of information technology and the extension of spectrometer software to include multivariate mathematical and statistical software, predictive models [16] have recently begun to be developed from which several quality parameters of crude oils, lubricating oils, and fuels can be obtained from a single spectrum that may be both chemical and physical in nature. The most common multivariate methods for evaluating entire spectral regions include Principal Components Analysis (PCA) [9], Partial Least Square (PLS) [8], Interval-PLS (iPLS) and Principal Components Regression (PCR) [26].

In order to define the optimal oil change interval, it is important to analyze the lubricant quickly and accurately. An effective oil analysis program is often based on off-line engine oil analysis, performed in laboratories where selected engine oil properties are analyzed. Viscosity, viscosity index (VI), total base number (TBN), and total acid number (TAN) [10] can be included among the important basic observed parameters of engine oils, which are directly related to the quality of engine oil and thus to determining the optimal change time.

Instrumental methods such as Fourier transform infrared spectrometry (FTIR) are used to assess the quality parameters of the used engine oil [3, 1]. Atomic emission and absorption spectrometry is a technique for the detection and quantification of metallic particles in used engine oil that result from wear, contamination and additive packaging [12]. Analytical ferrography, a technique that separates solid metal particles from engine oil using magnetic induction, is also used [14]. Another instrumental method that is often used is the laser particle counter and classifier, which is used to count and classify particles in the lubricating medium according to their size and number [11]. In the publication [6], the analysis and design of the engine oil change interval in buses is carried out on the basis of a combination of basic and instrumental methods of tribotechnical diagnostics.

In recent years, scientists have been trying to predict the classification of oils using artificial neural networks, according to Rodrigues et al. [17]. Authors Valis et al. [24] in their publication, they performed an analysis of petroleum contaminants, which was performed using applications of the fuzzy inference system (FIS) and neural networks. Another area of development is the connection of tribodiagnostics with on-board diagnostics, which would affect the engine oil change periods and the related service life of internal combustion engines. Wei at al. deals with this issue [27].

2. Programme for monitoring the engine oil condition of internal combustion engines

To ensure high accuracy and objectivity, the programme monitoring internal combustion engine condition should include the following two categories of analysis:

a) analysis of the properties of the newly used engine oil (properties of the new lubricant),
b) analysis of engine oil contamination (properties of the lubricant used).

ad a) Analysis of the properties of the newly applied engine oil – the primary function of this analysis is to determine the basic properties of the engine oil for a given type of internal combustion engine. High demands are placed on engine oils depending on the type of internal combustion engine. Therefore, it is necessary to specify a suitable engine oil before the engine oil is recommended for use in a given internal combustion engine. This engine oil must ensure a trouble-free operation of the internal combustion engine even with the required oil change interval during service maintenance, or perform oil quality monitoring either off-line or on-line, which is a current trend that is becoming more and more common. Failure to select the appropriate engine oil for the internal combustion engine at the time of design and subsequent in-plant testing could result in damage to the machine's internal combustion engine, causing severe damage and long-term machine outage, which is unacceptable to end users. In addition, it could increase the cost of claims for the manufacturer. Therefore, in order to determine the appropriate initial engine oil, the user operating a fleet of vehicles should analyse and verify the operating parameters of the manufacturer's recommended engine oils. Unless some of the properties of the new engine oil are accurately known, effective monitoring of the oils used is difficult. When testing used oils, it is also important to always use the same laboratory instruments and procedures as when determining the properties of new engine oil.

ad b) Analysis of the properties of contaminated engine oil is related to the operation of the internal combustion engine, where it is common for unwanted contaminants to enter the lubrication media. In an internal combustion engine, wear between metallic materials occurs during operation, and coolant from the cooling system may also enter the lubricating medium. Also, fuel can enter through leaks in the combustion chamber, and last but not least, particulate matter can enter the engine through the air filter. The lubricant serves only as a carrier or source of the information being retrieved. As friction increases, the number of larger particles, size, shape and concentration of particles increases. These allow us to monitor the internal condition of the friction surfaces and indicate the type of wear that is occurring. These can be major causes of failure of the lubricant's fundamental properties [23]. Many users do not realize that even when using new and high-quality lubricants, particles and other contaminants can enter the combustion engine and cause engine failure. Therefore, when engine oil contamination is regularly monitored and controlled, important preventive maintenance goals are achieved that can lead to proactive and predictive maintenance, which extends the life of the engine oil and reduces the maintenance costs of an internal combustion engine machine.

3. Tribodiagnostic method used to determine the quality of engine oils

As part of the experiment, we carried out the following engine oil measurement tests using the following instruments:

1. Basic tests:
   - determination of kinematic viscosity and viscosity index – Spectro Visc Q^{300},
2. Operational tests:
   - Fuel Sniffer – Fuel Sniffer Spectro FDM Q^{600},
3. Advanced instrumental analytical methods:
   - atomic emission spectrometry (AES) with rotating disc electrode – Spectroil Q^{100},
   - ferrography – ferrograph Spectro T^2FM,
   - Fourier transform infrared spectrometry (FTIR) – Spectro FTIR Alpha Oil Analyzer Q^{410},
   - automatic laser particle counter and classifier – Laser-Net Fines-C – Spectro LNF C.

3.1. Determination of kinematic viscosity and viscosity index

Viscosity is a characteristic property of lubricating oils and expresses the degree of their internal friction. Viscosity is one of the most important properties that affect the flow properties of substances. It determines, for engine oils, the lubrication regime, the formation and bearing capacity of the lubricating film, the amount of resistance of moving parts, the sealing capacity and the pumpability. Engine oil viscosity is subject to pressure and temperature changes during operation of the engine and it is therefore desirable that the engine oil viscosity changes as little as possible under these variable operating conditions.

The essence of the kinematic viscosity test is the determination of the flow time of a constant volume of liquid through the capillary of a calibrated viscometer at a certain hydrostatic height of the liquid and at a strictly controlled temperature. The kinematic viscosity is determined from the product of the measured flow time t and the constant K of the viscometer used (the constant expresses the geometrical characteristics of the instrument).

$$\nu = Kt \tag{1}$$

Kinematic viscosity is usually measured at 40°C and 100°C. From these values the viscosity index VI can be calculated

$$VI = \frac{L-U}{L-H}100\ , \tag{2}$$

where L – oil viscosity with $VI = 0$ (oil from Mexican crude oil) at 100°F (37,78°C), whose viscosity at 210°F (98,89°C) remains the same as that of the oil tested at the same temperature, U – viscosity of the tested oil at 100°F (37,78°C), H – is the viscosity of the oil with $VI = 100$ (oil from Pennsylvania crude oil) at 100°F, whose viscosity at 210°F is the same as the viscosity of the test oil at the same temperature [2].

The temperature dependence of oil viscosity is of particular importance for engine oils because these oils operate over a very wide temperature range. A viscosity index has been introduced to characterise the temperature dependence of engine oil viscosity. The temperature-viscosity dependence of the tested oil is compared to an oil with low temperature-viscosity change ($VI = 100$ with oil with high temperature-viscosity change $VI = 0$), as shown in Figure 1.

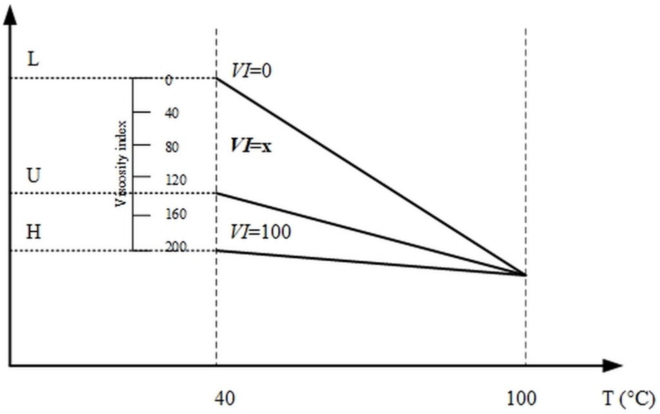

Fig. 1. Principle of determining the viscosity index

3.2. Determination of the presence of fuel in engine oil by Fuel Sniffer

The Fuel Sniffer measures the concentration of fuel vapour present in the atmosphere above the oil. The Fuel Sniffer assumes that the fuel vapour in the bottle above the oil is directly proportional to the fuel present in the oil. The Spectro FDM Q^{600} Fuel Sniffer, applied in the measurements, uses a built-in surface acoustic wave (SAW) sensor to perform these measurements. The SAW sensor consists of a piezoelectric substrate into which electrodes are lithographically integrated. The detection mechanism is reversible absorption of vapours in the polymer. Once the device is excited by an external voltage of radio frequency, synchronous Rayleigh waves are generated on the surface of the device. A minimum of 100 ml of an oil sample is required to measure contamination and the entire measurement takes about 60 seconds. The measurement result is presented as a percentage of fuel contamination in the oil.

3.3. Atomic emission spectrometry with rotating disk electrode

Atomic emission spectrometry (AES) is used to determine the content of wear metals (such as iron, aluminium, copper, chromium and lead), contaminants and additives in oil samples. The method is suitable for the determination of individual elements in gear oil, engine oil, hydraulic fluid, biological samples and for environmental monitoring, industrial applications, analysis of geological samples, etc. Atomic emission spectrometry is a suitable method for single-element analysis of samples with a large variation in composition, where the number of metals to be determined in the sample is small but the selection of metals varies. For the measurements, we used atomic emission spectrometry with a Spectroil Q^{100} rotating disk electrode.

The standard configuration of the Q^{100} spectrometer includes 22 elements. In general, these elements can be divided into abrasive metals – 15 elements, i.e. aluminium, cadmium, chromium, copper, iron, lead, magnesium, manganese, molybdenum, nickel, silver, tin, titanium, vanadium, zinc, contaminants – 5 elements, i.e. boron, calcium, potassium, silicon, sodium and additives – 10 elements, i.e. barium, boron, calcium, chromium, copper, magnesium, molybdenum, phosphorus, silicon, zinc.

3.4. Ferrography

Ferrography complements atomic emission spectrometry. This method helps to determine the size, shape and material of particles. The detection of wear in oil-lubricated mechanical systems is based on the observation that the oil reflects their condition and operating conditions after a certain period of operation. To analyse engine oil, we used an instrument called the T^2FM 500 ferrograph (1), see Figure 2 a).

The instrument also provides the possibility of image analysis, which uses a biochromatic microscope (2) connected to a computer

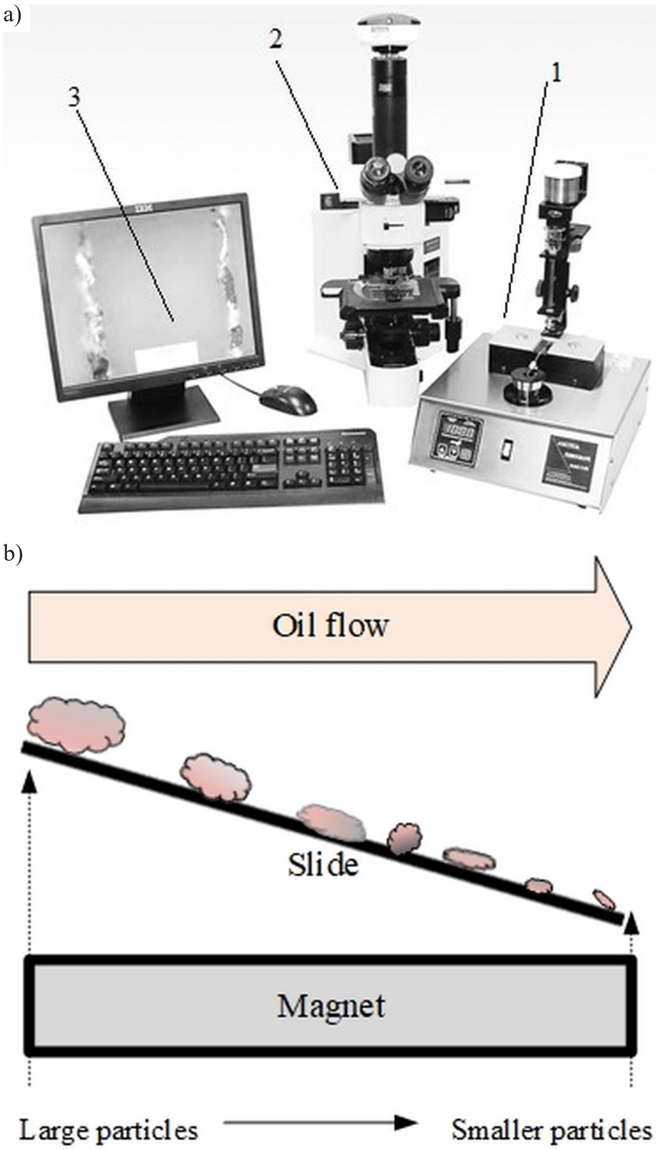

Fig. 2. Measuring instrument ferrograph T^2FM 500 with accessories including the principle of ferrographic analysis

(3) with image capture software to evaluate the particles, thus eliminating subjective evaluation. Analytical ferrography involves microscopic evaluation of individual particles, which provide information about the actual technical condition of the lubrication system and lubricated parts as well as the wear pattern of individual friction pairs. The evaluation of the ferrogram is carried out using a bichromatic microscope (2). The particle image evaluation software is used for the actual evaluation of the particles.

Ferrographic analysis allows the separation of metallic abrasion particles according to their composition, size and other characteristics, which is performed in a strong magnetic field. A sample of the tested lubricant flows over an inclined pad which is placed in a magnetic field. The diluted oil sample flows over an inclined transparent pad, under which a very strong magnet is placed. The principle is shown in Figure 2 b). The inclination of the transparent pad causes a particle size distribution due to the variable magnetic field strength. Larger particles are captured at the beginning (> 15 μm) and smaller particles are captured where the transparent pad is closer to the magnet (1 − 2 μm at the end).

With this method, it is possible to distinguish the shape of the particles, their origin, even if all components are made of the same metal, the place of origin (wear location), morphology, etc. After passing an oil sample, the oil is washed off with a suitable solvent (technical gasoline) and the particles are fixed on a transparent pad with a transparent varnish, thus obtaining a so-called ferrogram. The ferrogram allows the assessment of particle size, the ratio of large particles (10 – 100 μm) to small particles, morphological (shape) characteristics of particles, etc. The evaluation of the ferrogram is performed ferrodensimetrically and ferroscopically.

3.5. Fourier Transform Infrared Spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) is based on the absorption of infrared radiation as it passes through a sample, during which changes in the rotational vibrational energy states of the molecule occur depending on changes in the dipole moment of the molecule. The resulting infrared spectrum is a functional dependence of energy, usually expressed as a percentage of transmittance or units of absorbance on the wavelength of the incident radiation. The advantage is the high speed compared to other methods and the small amount of sample required. Infrared spectrometry is a method designed primarily for the identification and structural characterization of organic compounds and for the determination of inorganic substances (antioxidants, water, soot, oxidation, nitration, sulfation and glycol). The analysis of spectra is based on knowledge of the wavelengths corresponding to specific compounds or characteristic structural groups. Infrared spectrometry is concerned with the analysis of the absorption spectra of molecules absorbing radiation at wavelengths of 0.8 – 1000 μm, i.e. with a wavenumber of 12000 – 10 cm^{-1}. When this radiation is absorbed, the vibrational and rotational states of the molecule increase.

Transmittance T s defined as the ratio of the intensity of the radiation that has passed through the measured sample I to the intensity of the radiation coming from the source I_0.

$$T = \frac{I}{I_0} 100 \ \ [\%] \tag{3}$$

Then the absorbance A s defined as the decadic logarithm of $1/T$.

$$A = -\log \frac{I}{I_0} \tag{4}$$

In the interpretation of infrared spectra, three main characteristics are observed, namely the position and shape of the absorption bands, the number of bands and their intensity. In Fourier transform infrared spectrometry (FTIR), the interferrometrically acquired signal is converted by a mathematical operation - the Fourier transform - into an infrared spectrum [19].

In our tribotechnical laboratory, we use the Spectro FTIR Alpha Oil Analyzer Q^{410} to measure engine oil quality. This device uses the commercial software “Oil Analyzer” which can be used to obtain data on soot, water, glycol, diesel, oxidation, nitration and sulphation products, and the content of antioxidants and anti-wear additives by comparing the spectra of new and worn oil samples.

3.6. Automatic laser counter and particle classifier – LaserNet Fines-C.

This method is unique for its multiple functionalities in the field of tribodiagnostics. The device uses advanced algorithms (fuzzy logic and neural networks) for particle analysis and allows to determine the number of particles and wear fragments and their size distribution, to identify particles according to their mechanism of origin, to sort the analysed particles (to separate impurities, water, air bubbles, etc.), statistically process the results (number of particles per 1 ml, maximum and average particle size, mean values, standard deviation, analysed volume, number of digitally processed images, etc.), report on each wear class (adhesive, abrasive, fatigue), calculate the total number of particles and draw trend lines, i.e. forecast the possible future technical condition, present the results in pictorial, tabular, graphical form (histograms), etc. The instrument registers all particles up to 100 µm in size and also captures air bubbles, which the software excludes from the calculation if they are larger than 20 µm. The measurement is fully automatic and extends the image analysis capabilities by grouping the particles by shape and wear type.

The Spectro LNF C instrument allows us to analyse the shape of particles and determine the number of particles with high accuracy from 4 µm to100 µm. The analysed oil sample flows through the imaging cell where it is illuminated by a pulsed laser diode. The transmitted radiation is detected by the CCD sensor of the camera system. The particles contained in the oil do not transmit light - their outline is therefore captured by the CCD sensor (3500 images per 0.65 ml of processed sample). The images captured by the camera are transferred to a computer where they are analysed at 30 frames per second. The number of objects in each frame is determined by software. The results of the statistical evaluation of the objects are stored and a bitmap image of the objects with a principal dimension greater than 20 µm is created (minimum particle image size is 10 pixels).

4. Experiment results

The experiment used a four-stroke air-cooled single-cylinder engine called Honda GCV 160 E, which is one of the most widely used engines in small agricultural machinery. It is an engine with a displacement of 160 cm^3, overhead camshaft, bore 64 mm and a stroke of 50 mm. The mentioned engine was chosen for the experiment due to its expansion and the general lack of interest in monitoring the course of such small engines. There are many articles that deal with the lifetime monitoring of large-volume internal combustion engines. The subject of the research is the wear of the piston group (piston, piston rings, inner walls of the cylinder), the overhead camshaft and the wear of the plain bearings for the crankshaft bearing.

For lubrication, 0.5 l of engine oil with the designation Divinol Rasenmäheröl Spezial 10W-30 is used, which is intended for year-round use. This engine oil has an API SJ/CF specification. The API SJ designation specifies that this engine oil is designed primarily for spark-ignition engines, taking into account the most stringent emission limits and fuel economy requirements. The API CF designation specifies that this engine oil is intended for indirect injection engines without emission controls. Compared to the API CD engine oil designation which has a lower resistance to piston deposits and bearing corrosion.

Divinol Rasenmäheröl Spezial 10W-30 specification:

- density at 15°C according to DIN EN ISO 12185 – 0,865 g/cm³,
- viscosity at 40°C according to ASTM D7042 – 65 mm²/s,
- viscosity at 100°C according to ASTM D7042 – 10 mm²/s,
- viscosity index according to ASTM D2270 – 145,
- flash point (Cleveland) according to DIN ISO 2592 – >210°C,
- pour point according to ASTM D7346 – 30°C.

The experiment was carried out throughout the entire life cycle of the machine, i.e. from the manufacturing to its decommissioning due to general wear. We will try to demonstrate this in the experiment by individual methods.

4.1. Proposed methodology for engine oil sampling

The design of the tribotechnical diagnostics model includes the main principles of engine oil sampling which significantly affect the measured parameters and subsequent conclusions. Therefore, the following sampling procedure is recommended:

1.take the sample from the most appropriate place (e.g. pour hole, control hole). We do not recommend the engine outlet. First, thoroughly clean the sampling point of the combustion engine, then remove the recommended portion of engine oil into the auxiliary container. It is recommended that a minimum of 100 – 200 ml of engine oil is taken for multi-criteria analysis depending on the methods used.

1. Take the sample about 10 – 15 minutes after the engine has stopped, depending on the type of the combustion engine. The temperature of the medium to be taken should be between 65 and 80°C. Take the required amount of engine oil into a clean and dry plastic sampling container with a cap and seal it hermetically.
2. Fill in the label of the sampler showing the machine identification, the total number of kilometres, the date of sampling and, if applicable, the name of the employee who carried out the sampling.
3. Evaluate the sample as soon as possible after collection, but no later than five days, due to possible chemical changes in the engine oil sample.

For the evaluation of the technical condition (lifetime) of the internal combustion engine, the following tribotechnical diagnostics model has been proposed, see Figure 3. It contains the recommended tribotechnical diagnostics methods and their mutual sequence. Within this model, the limit (critical) values for each measurement method have been determined according to relation (5). To calculate the critical limits, the relation for expressing the percentage differences T according to the given equation is used.

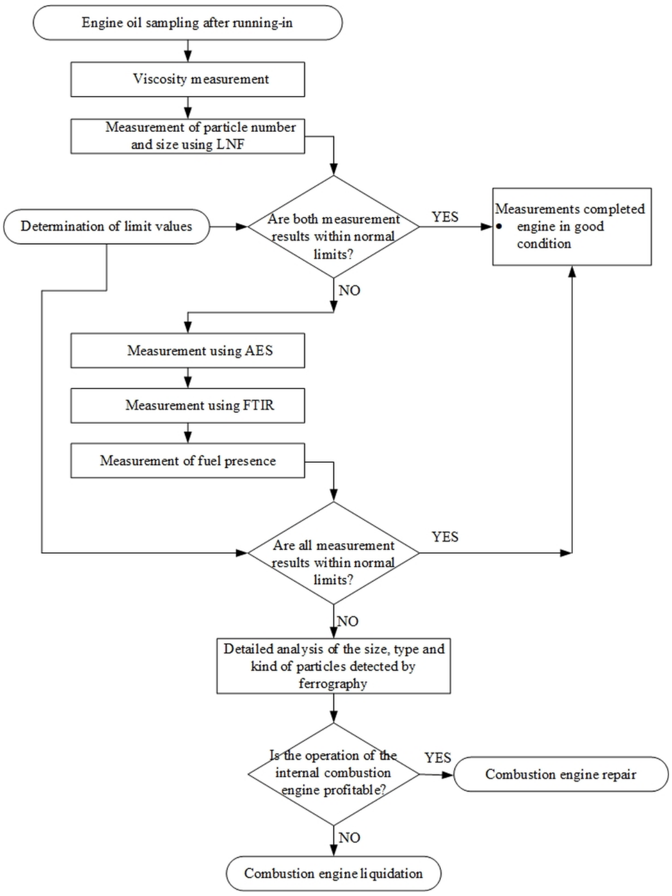

Fig. 3. Design of a tribotechnical diagnostics model for determining the technical condition of an internal combustion engine during its life cycle

$$T = \frac{current - previous}{current} 100 \tag{5}$$

Subsequently, the limit values for engine oil pollution for each measurement method were determined according to the above relation (5), as shown in Table 1. The critical values are those whose result is higher than 20%.

Table 1. Determination of limit values for assessing the technical condition of a Honda GCV 165 internal combustion engine

Measurement method and individual contaminants	Calculated limit value
Viscosity - determination of the viscosity index (–)	≤ 166
Atomic emission spectrometry - abrasive metals (ppm)	
• zinc	≤ 1200
• iron	≤ 80
• aluminium	≤ 37
• silicon	≤ 25
• manganese	≤ 16
• copper	≤ 3
• chromium	≤ 3
Fuel content in oil (%)	≤ 3.3
Determination of particle size and number	
• above 50 μm	< 150 particles/ml
• 25 – 50 μm	< 300 particles/ml
Ferrography	presence of spheroidal artefacts (spheres)
Fourier transform infrared spectroscopy – FTIR	analysis of absorbance bands 900 – 1020 cm^{-1} 1140 – 1270 cm^{-1} 1560 – 165 cm^{-1}

4.2. Measurement results and analysis

From the Figures (4 to 10), it can be seen that the engine life cycle can generally be divided into three stages. The first stage is the run-in period, which extends to approximately 100 hours of operation when the individual components are running in. The second stage is the so-called normal operation stage; it is the longest stage and lasts until about 900 hours of operation. At this stage, individual components gradually wear out. The last stage is the stage of so-called excessive wear when individual parts become excessively worn and there is an increased incidence of failures, which can lead to total engine damage. It is therefore advisable to find a limit value for the lifetime of an internal combustion engine expressed in kilometres or hours of operation, as in the example given (Figures 4 to 10). Based on these measurements, the limit value was set at 900 – 950 operating hours of the internal combustion engine, at which point it is recommended to end the life of the internal combustion engine and consequently the entire machine.

The results of the kinematic viscosity determination with the Spectro Visc Q^{300} are shown in Figure 4. The figure shows the three stages of the internal combustion engine life cycle as already mentioned. In the first stage, there is an increase in the viscosity index from a value of 142 to a value of 162. Subsequently, in the normal operation stage, the values range from 150 to 162. The critical point occurs at 900 hours of operation when there is an increase to 166 and then the viscosity index increases to 179, indicating that thermal and oxidative degradation of the oil is probably occurring. This results in a reduced ability to lubricate the friction surfaces which can ultimately lead to seizure of the internal combustion engine. This is also confirmed by the FTIR method see Figure 9 positions 1 and 2. Depending on the measured values and using equation (5), we have determined the limit values, which are shown in Table 1.

Figure 5 shows the results of measuring the presence of fuel in engine oil with the Fuel Sniffer Spectro FDM Q^{600}. We can see that during operation the fuel present in the engine oil ranges from 2.8 to 3.1%. When the internal combustion engine is running for 900 hours, a slight increase in the presence of fuel starts to occur, which is confirmed in the subsequent measurement when the value increased to 3.4%. From the above curve, we can assume that the internal combustion engine starts to wear excessively during the operation of 900 – 950 hours, mainly between the piston and cylinder liners. Depending on the measured values and using the equation (5) we have determined the limit values, which are shown in Table 1.

Figure 6 presents the results of atomic emission spectrometry measurements with the Spectroil Q^{100}. From the measured values, we selected the following elements for our combustion engine that affect the technical condition of the combustion engine. These elements include iron, aluminium, copper, silicon, chromium, magnesium and zinc. In the mentioned figure, we can see the 3 stages of the life cycle as already described in detail. In this case, the presence of contaminants in the engine oil increases rapidly during the run-in period. Subsequently, in the second stage of operation, the values stabilise at an approximately constant value until 900 hours of operation, when there is a sharp increase in the elements mentioned. Depending on the measured values and using equation (5) we have established limit values, which are shown in Table 1.

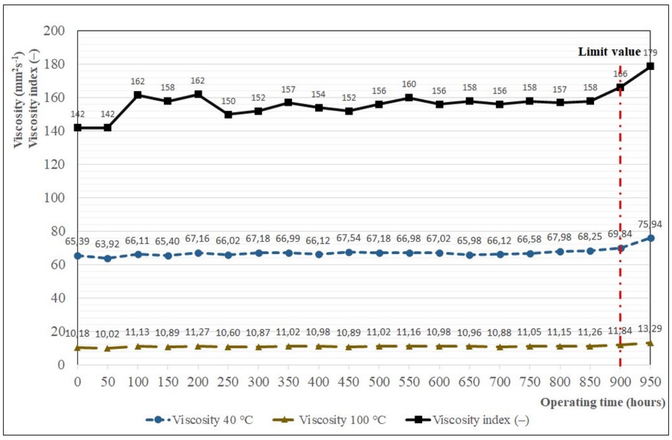

Fig. 4 Dependence of viscosity and viscosity index in engine oil on the operating time of an internal combustion engine

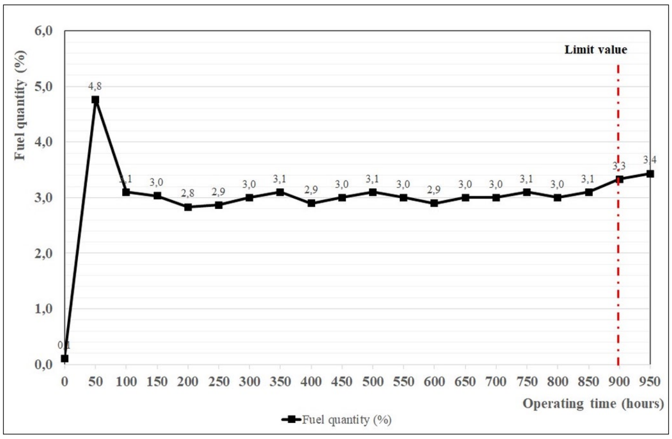

Fig. 5. Dependence of the amount of fuel in the engine oil on the operating time of the internal combustion engine

Figure 7 shows the measurement results of the automatic laser counter and particle classifier using the Spectro LNF Q^{200}. Here too the pattern is similar to that of the previous measurements. It is advisable to focus most attention on the largest particles. In this case, these are particles larger than 50 μm. Figure 7 shows that the trend of the increasing presence of particles of different sizes is approximately the same. Also from the above figure, we can say that the limiting value of the lifetime of an internal combustion engine is 900 hours of operation. In the detailed analysis of the samples,

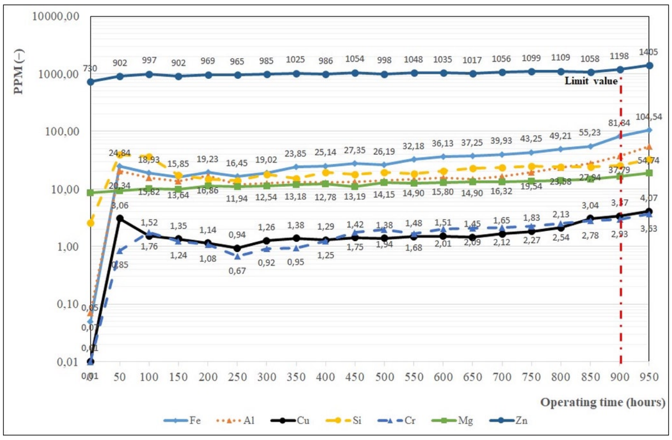

Fig. 6. Dependence of the amount of monitored elements in engine oil on the operating time of the internal combustion engine

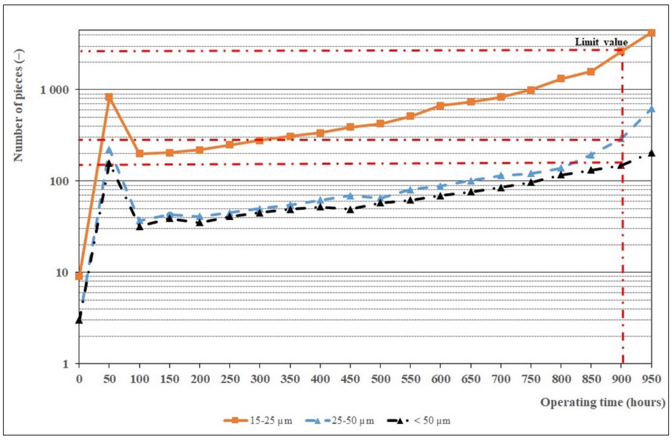

Fig. 7. Dependence of the size and amount of particles in engine oil on the operating time of an internal combustion engine

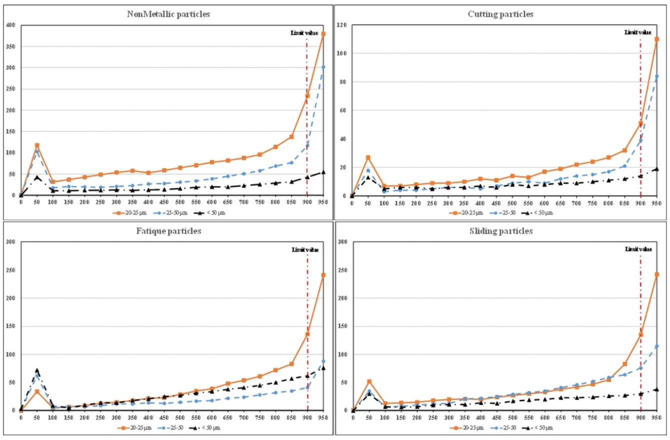

Fig. 8. Dependence of the size and amount of nonmetallic, cutting, fatigue and sliding particles in engine oil on the operating time of an internal combustion engine

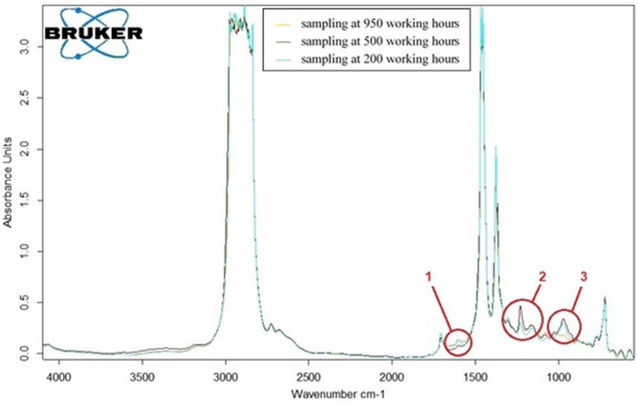

Fig. 9. Dependence of the presence of organic compounds and inorganic substances in engine oil on the operating time of the internal combustion engine

we have identified the presence of various particulate matter such as nonmetallic, cutting, fatigue and sliding particles which are shown in Figure 8. Upon closer examination, we find that the trend of the results of the individual curves is similar to the overall results shown in Figure 7.

Figure 9 shows the analysis of the measurement results using the Spectro FTIR Alpha Oil Analyzer Q^{410} where organic compounds and inorganic substances such as antioxidants, water, soot, oxidation, nitration, sulfation and glycol are analyzed. From the measurement results, we can identify 3 wave spectra where changes occur during the lifetime of an internal combustion engine. This is the wave spectrum marked 1 which is in the band 1560 – 1650 cm^{-1} and identifies the presence of organic nitrates or nitro compounds. The wave spectrum marked 2, which is in the range 1140 – 1270 cm^{-1}, identifies the presence of organic nitrate in the secondary absorption and the possible presence of sulphate detergent and sulphur compound from the fuel. There is also a wave spectrum marked 3, which is in the range of 900 – 1020 cm^{-1}, which most likely identifies changes in the levels of anti-wear additives contained in the engine oil (most commonly TCP – tricresyl phosphate) which in practice indicates depletion of anti-wear additives in the lubricant. This results in a reduced ability of the engine oil to lubricate and thus the possibility of excessive wear.

Figure 10 shows images from the Spectro T^2FM ferrograph at different stages of the combustion engine lifetime. Figure 10 a) presents an image of selected segments from the ferrographic trace of engine oil during the run-in period of an internal combustion engine, showing what is likely to be a bronze particle from the bearing; these are silver flake particles characterised by adhesive wear, in this case during the run-in. Figure 10 b) shows a larger number of shiny silver particles from soft metals such as tin, bronze, or PB-Sn bearing compositions. In the image that is the PSL 16 format magnified 1000x, coloured particles can be observed; they are probably from bronze alloys from plain bearing. Silicates (dark spherical shapes particulate) are also seen to a lesser extent. Figure 10 c) shows the presence of spheroidal artefacts (spheres). These are almost spherical particles that are formed during fretting-corrosion (grinding, etc.) and are fatigue wear, which, unlike other types of wear, indicates the deterioration of the material surface with the possible consequence of permanent damage to the respective parts of the combustion engine. This is an important signal for stopping the machine and preventing total damage to the combustion engine.

a) run-in b) 400 operating hrs c) at the end of service-life 950 hrs

Fig. 10. Spectro T2FM ferrograph images showing metal particles in engine oil over the lifetime of an internal combustion engine

5. Conclusions

In this paper, a model of tribotechnical diagnostics is made to determine the technical condition of an internal combustion engine within the life cycle for different equipment. In this case, an internal combustion engine Honda GCV 160 E was observed, sampled and analyzed in detail. These samples were taken at regular intervals of 50 hours of the machine operation. Based on the measurements and the design of the tribotechnical diagnostics model for determining the technical condition of the internal combustion engine within the life cycle Figure 3, the said internal combustion engine was periodically evaluated. Based on the measured values, the different life cycle stages were determined, and are described in the paper. Furthermore, limit values for the above combustion engine were determined and are presented in Table 1. All information from the measurements is presented in detail in the individual figures. Figure 4 presents the dependence of viscosity and viscosity index in engine oil on the operating time of the internal combustion engine using the basic tribodiagnostic test which is the determination of kinematic viscosity and viscosity index using the Spectro Visc Q^{300}. Furthermore, Figure 5 shows the dependence of the amount of fuel in the engine oil on the operating time of an internal combustion engine using the Fuel Sniffer Spectro FDM Q^{600}. Figures 6 to 10 show the results of measurements using advanced instrumental analytical methods which in this case were atomic emission spectrometry (Spectroil Q^{100}), ferrography (Spectro T^2FM), Fourier transform infrared spectroscopy (Spectro FTIR Alpha Oil Analyzer Q^{410}) and an automatic laser particle counter and classifier (Spectro LNF-C). Based on the design of the tribotechnical diagnostics model for determining the technical condition of the internal combustion engine within the life cycle according to Figure 3, the lifetime of the machine was determined to be 900 hours of operation. It is generally assumed that the life of the mower should be about 7 years, when the chassis corrodes, which becomes unsatisfactory. This corresponds to an average annual operation of 130 Mh, which also corresponded to the experiment when the chassis was rusted. The experiment clearly shows that extending the life of the engine by choosing a higher quality material is not desirable, because it becomes unsuitable mower chassis.

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