MONITORING AN ENGINE CONDITION BASED ON TRIBOLOGICAL DIAGNOSTICS IN MILITARY VEHICLES

Glos J.[1], Sejkorova M.[2]
Faculty of Military Technology – University of Defence Brno, the Czech Republic [1]
Transport Faculty – University of Pardubice, the Czech Republic [2]

Abstract: *Tribological diagnostics uses lubricating oil as a source of information about processes and changes in mechanical systems. For that purpose a whole range of tribodiagnostic methods was developed. The procedures of the tribodiagnostic methods can range from simple ones to complex which require special instrumentation. In this paper there are described methods of engine oil quality assessment, engine condition evaluation and methods of wearing process estimation in the engine.*

Keywords: TRIBODIAGNOSTIC, TRIBOLOGIE, WEAR, PARTICLE OF ANALYSIS, LASER PARTICLE COUNTERS

1. Introduction

Tribology is the branch of science utilizing research knowledge of friction, wear and lubrication in order to decrease friction coefficient, i.e. to optimize friction progress and thereby reduce wear of two interacting elements. Tribological diagnostics is a non-destructive and non-disassembling diagnostic method that uses lubricating oil as a source of information about processes and changes in mechanical systems, to which it is applied.

Tribological diagnostics deals with two basic ranges of issues:

1. Determining condition, extending usable life and forecasting degradation of lubricating oils.
2. Determining mode, point and trend of mechanical system wear (combustion engine, transmission, hydraulic system and others) by way of evaluating foreign matters occurrence in the oil in terms of quantitative and qualitative points of view.

Traditional reputable methods and special tribodiagnostic methods are used for monitoring the operating degradation of oils. Determining wear of mechanical systems lubricated by oil is based on knowledge, that oil shows a certain percentage of foreign matter after some operating time. Especially metallic abrasive wear (wear particles), that are dispersed in oil and that after the quantification by some suitable method allows indirect monitoring of mechanical changes in the system that uses the oil. It is then possible to draw specific conclusions based on the determined amount of metallic abrasive wear, growth rate, shape, morphology, size and material composition. If the growth and other parameters are in accordance with nominal values stated for the given mechanical system, it is possible to legitimately deduce normal wear progress without an increased risk of system failure. An abnormal or sudden growth of metallic particles, or their size, indicates an exceptional process. From the size, shape, velocity of growth and other parameters it is possible to deduce the failure severity and necessity to take remedial measures. Knowing the material of all system parts lubricated and rinsed with oil, then according to the metallic abrasive wear type, it is possible to determine and localize the frictional pair with the rapid increase of degrading wear. If it is not possible to localize the position of the increased abrasive wear by this method, then some other technical diagnostics suitable for failure localization should be applied.

Tribological diagnostic methods are generally considered to be very significant for combat, special and transportation vehicles for these reasons:

- Wearing processes crucially affect vehicles and other machines lifetime, their failure-free operation time, maintenance costs, repairs etc. Tribological diagnostics positively affects the friction process and mechanical systems wear.
- Changing oil and lubricants in determinated periods based only on experiences and projected average oils lifetime is not optimal in terms of economical use of these substances. Monitoring the operating degradation of oils by the tribological methods allows significantly more intensive use of these oils until the end of their lifetime without any risk of failures from the aforementioned reasons.

Despite the considerable equipment purchase costs, the rational use of tribological diagnostics results in possible effective oil management. Therefore, it can prevent unnecessary change of oil that could still remain operational and whose replacement is consequently disadvantageous not only from an economic, but also an environmental point of view. On the contrary if the changing periods are adhered to very strictly, there is a risk of using an excessively worn-out oil that does not correspond to the requirements and whose further use might lead to machinery damag. Subsequent repair costs often exceed investments in preventive care including regular equipment condition monitoring using the tribological diagnostic methods.

Monitoring of chemical and physical changes that occur during operation provides a relatively accurate overview of the up-to-date lubricant state and its potential for further use. The basis for the evaluation of the dynamics of individual parameter changes are their values for a new oil. There exists a number of methods used for that purpose including infrared spectrometry or electrochemical methods. Wear progress and size of components that are lubricated by the relevant lubricant can be monitored also by a group of other methods suitable for morphology description and particle separation formed by metallic abrasive wear.

2. Machine Diagnostic

Metallic particles and other elements can get into the lubricating oil during the wearing process. Regular monitoring of a specific group of metals and elements allows the prediction of incipient failures. Different methods of instrumental analysis are used for determining the contents of metals and other elements in lubricating oils. The most commonly used methods are spectroscopy and polarography. Wear progress and size of components that are lubricated by the relevant lubricant can be monitored also by a group of other methods suitable for morphology description and particle separation formed by the metallic abrasive wear, by filter material fibres, environment contaminants and others. Particularly ferrography followed by image analysis. The objective of these diagnostic methods is to determine the type of material that issued the particles contained in the lubricating oil. Following with determination of a subgroup or respectively the frictional pair with the increased wear. For that it is necessary to be familiar with materials and construction of the system that is being diagnosed, the composition of the lubricating oil used and operating materials and liquids.

Oil analysis methods:

Atomic absorption spectrometry (AAS) is a method based on specific absorption of monochromatic radiation by free atoms of the monitored element in the ground electronic state. The energy of an absorbed photon corresponds to the transition of valence electron from the basic energy level to a higher one. The radiation source is a discharge tube with a hollow electrode containing the determined

element or combination of elements. This method is commonly used to determine the existence and content of some metals, especially Fe, Pb, Cu, Al, Zn, and others [1,2,3,].

Atomic emission spectrometry (AES) is a method that uses arc or spark sources to get the oil sample into the gaseous state and atomize it. As a result of atomic collisions or energy quantum absorption, the electrons of individual atoms are transiting from the ground state to the excited state. During the transition back to the ground state, atoms emit energy that equals the proportion of the energy levels in question in the form of luminous energy. The wavelength of light value is specific for each element [1,2,3,].

Fourier transform infrared spectroscopy (FTIR) is an analytical method designed primarily for identification and structural characterization of particularly organic compounds. Infrared spectrometry measures the absorption of infrared radiation of different wavelength by the analyzed material. The analytical output is the infrared-spectrum that is the graphic representation of energy dependence functions on wavelength of the incident radiation. During the Fourier transform infrared spectroscopy the interferometrically acquired signal is transformed by the Fourier transformation to the infra-red spectrum [1,2,3,].

X-ray fluorescence analysis (XRF) is a highly sensitive method that can detect concentrations up to 0.0001 % of Cu or 0.001 % of Fe, Pb, Si, Ti, Mn, Mo, Sn and others. This method is based on measuring energy of the fluorescent x-ray radiation. Each element has its typical fluorescent radiation energy, which is used for quantitative analysis. The principle of the quantitative analysis is measuring the intensity of outcoming secondary x-rays (their quantity) [1,2,3,].

Emission spectrometry with inductively coupled plasma (ICP-OES) is an analytical method used to determine the contents of individual elements in the analyzed sample. It allows the analysis of almost all elements of the Periodic table. The solution of the analyzed sample is nebulized and the produced vapour is transmitted by an argon stream into a burner, which contains argon plasma with temperature of 6 000 – 10 000 K maintained by a high frequency alternate magnetic field.

Polarography is a very sensitive electrochemical method studying effects originating on polarized electrodes placed in the measured solution. The system of electrodes consists of usually absolutely polarized measuring dropping mercury electrode (detector) and also an absolute reference non-polarizable electrode. Controlled electric voltage is then placed between the electrodes and the dependency of the originating electric current on the inserted voltage is being monitored. Pulse polarography is used in the first place because its current dependency on the inserted voltage has a pure shape of the base with sharply salient amplitudes of which location characterizes the type of substances contained in the solution. These methods can be used for determining a number of inorganic and organic substances in various matrixes. For example metal concentrations are determined by this method within the oil analytics [1,2,3,].

Methods of morphology assessment and distribution of abrasive particles

Experience shows that the determination of metal abrasive wear concentration is not always sufficient to evaluate the wear mode. For that reason methods were developed allowing the evaluation of the quantity, shape, size, coloring and morphology of the abrasive wear particles surface originating in the equipment.

Ferrography is a method based on separation of foreign substances contained in the oil filling of machines lubricating systems from the oil itself. It uses particles sedimentation on a special slide during oil sample flow in a strong inhomogeneous magnetic field. It describes the trapped particles circulating along with the oil and classifies them to the individual wear mechanisms. As a non-disassembling diagnostic method it allows us to objectively determine the wear mode of the oiled machine. Then on the basis of morphology analysis and quantity of abrasive wear particles it is possible to discover the approaching machine failure. In some cases it is also possible to determine the point of origin of the abrasive wear particles, which has an outstanding importance for machinery wear evaluation. Both Direct-reading ferrography and Analytic ferrography are used in practice these days. The bichromatic microscope can be used to examine; shape, color, surface character and other morphologic characteristics of the sedimentation particles that contain very important information about prevalent abrasion type and oil wear of the lubricated machine parts. Analytic ferrography shows the real technical condition of the lubricating system and lubricated parts as well as the wear nature of the individual frictional pairs. For these purposes it is beneficial to combine Analytic ferrography with Image analysis or also with Scanning electron microscopy [1,2,3,].

Image Analysis allows the gathering of quantitative information about different geometric and statistic parameters of particles (for example quantity, area and other quantitative parameters of individual particles), about their total area proportion on a ferrogram and others. This data can be used directly for the evaluation of isolated particles or as a basis for further Stereological analysis. Quantitative evaluation of the characteristic particle parameters is an important part of examination of the relationship between operating conditions and the method, intensity, or regularity of abrasive surfaces wear. Using computer technology and suitable software makes the work with digital image easier and allows a whole number of other operations. For example change contrast, brightness, do gamma-correction or other picture parameters, eliminate image objects smaller then a predefined limit, suppress displaying artefacts, group objects into classes according to chosen attributes etc. Good-quality, precise and correct results during visual data processing can be gathered only on condition that the microscopic visual display is accurate, the picture is sufficiently sharp and objects are easily identifiable [1,2,3,].

Particle Counter and Particle Shapes Classifier (LNF-C) is used for oils samples analysis from different types of machines and is unique for its multifunctionality. After sample preparation (homogenization and bubbles removal) the oil is sucked and circulated in a measurement cell. At the same time impulse laser rays are passing through the same cell and incident on a background scanned by a CCD digital camera that can catch an image contour of the oil sample particles flowing through the cell. During sample processing, the photos (pictures of the flow cell) are analyzed at 30 frames per second. The highly sensitive machine is able to register all particles up to 100 μm size. Numbers of particles are converted to codes of purity according to international and national standards. Furthermore it is possible to read off contents of free water and soot. All particles bigger than 20 μm are sorted according to their typical shape into categories: (depending on the origin of their wear type) abrasive, sliding, fatigue, non-metallic and then are statistically evaluated. For individual particle types are stated quantities per 1 ml, average size, standard deviation and maximal diameter. The result is not only analysis of the quantity and size of the particles contained in the oil, but also analysis of abnormal abrasive wear particles and an overview of previous results related to the same equipment. This allows the gathering of data about oil condition, but above all also about wear mode and technical condition of the equipment, from which the oil sample was taken [1,2,3,].

3. Oil Diagnostic

Quality and condition evaluation of the oil used is based on measuring a range of physicochemical parameters of the oil properties. For that purpose a whole range of methods was developed, from the simplest ones up to complicated and machine-demanding. Standardized methods with scientifically determined conditions and testing procedures are used for quality evaluation and measurement of oils and lubricants. Monitoring of chemical and physical changes that occur during operation provide a relatively accurate overview of the up-to-date lubricant state and its potential

for further use. The basis for evaluating the dynamics of individual parameter changes are their values for the new oil.

Examples of some typical oil quality evaluation tests

- **Viscosity:** The basic characteristic feature of the lubricating oil is viscosity. It is a result of the internal friction of the oil during its flow. It is basically the internal friction resistance by which the oil works against forces that try to mutually move its smallest particles. It causes shear stress on the contact area of two oil layers that are moving at different velocities. Shear stress is directly proportional to the velocity gradient and the proportionality constant is called dynamic viscosity η [Pa · s]. The ratio of dynamic viscosity η to density is called kinematic viscosity [mm2 · s-1]. The inverse value of viscosity is called fluidity. The kinetic viscosity is primarily measured in different types of viscometers. The best-known one is Ubbelohde capillary viscometer.
- **Water contents:** Water is an adverse substance in the lubrication oil that gets into the oil frequently through leaks in cooling systems or from the environment. Its presence causes oil emulsification and damage of the lubricating film. The water content also affects other oil additives, causes corrosion etc. It is possible to use the oil with some small amount of water (for example combustion engine – 0.2%), but on an overrun it is necessary to separate the water element or change the oil. Water content [ppm] is determined by distillation test or by Coulometric titration for better results.
- **Total Base Number (TBN):** This method is used to determine the total amount of alkaline elements including organic and inorganic bases, amino compounds, weak acid salts and heavy metal salts, that can affect the total alkalinity of the oil. This indicator is used for engine oils and its amount relates to alkaline-like contents – mostly additives of the detergent-dispersant type. Potentiometric titration by perchloric acid is used for determination and the measurement unit is [mg KOH·g-1]. TBN indicates the alkaline reserve that the engine oil can use for neutralization of acidic products of thermooxidation reactions and acidic products of fuel combustion and oil additives.
- **Total Acid Number (TAN)** defines the amount of acidic proportions in the oil, i.e. weakly acid-reacting proportions contained partly already in the fresh oil and partly resulted from the combustion process and oil oxidation. TAN is defined as the KOH amount (in mg) used for neutralization of all acidic elements included in 1 gram of the analyzed oil. Potentiometric titration is used for determination and the measurement unit is [mg KOH · g-1].
- **Total Solid Particles Contents:** Contaminating oils with solid particles causes a number of machine failures and breakdowns. Mechanical impurities most commonly include metallic particles and dust. Naturally, a range of other substances also causes the mechanical contamination of oils. The content of mechanical impurities is determined on a membrane filter with pore size of 0.8 μm or by automatic particles counters. The amount of impurities is expressed as milligrams per kilogram of the oil or the automatic particles counters determine the contamination code for liquid purity. Contamination code is determined according to size and quantity of particles in 1 or in 100 ml of the oil. Most often the contamination codes according to ISO standard 4406 and NAS 1638 are used.
- **Special tests of oil condition:**
- **Conradson Carbon Residue (CCR)** is determined by thermal degradation of the tested oil in an air-free environment followed with annealing treatment. Its size is determined by the tendency to create carbon residues on the hot parts of the machine. The ageing of oil in operation causes the creation of substances that increase the value of the carbon residue. CCR is expressed in % of unburnt hydrocarbons.
- **Ignition point** is an indicator related to the amount of volatile matter in the oil. It is primarily used for measurements of engine oils, where its value indirectly determines the fuel contents in the oil. Open-cup or close-cup method are used to determine the ignition point. The ignition point is expressed in degrees centigrade.
- **Soot** belongs to mechanical impurities that are produced in the combustion space during fuel combustion. Infrared spectroscopy is the most common method used for soot content measurement. Since soot and other mechanical impurities are dark and do not transmit light, they cause, during measurement of the infra-red spectrum, the elevation of the so called base line, which is measured at 2000 cm-1. The higher content of soot and other impurities, the higher the base line elevation.
- **Determining the contents of additives:** defines contents of elements contained in almost all currently used lubricants and oils, usually in the form of admixtures, that improve certain attributes. The amount of additives decreases during operation and once the given minimum limit is exceeded, the lubricant starts losing its capabilities. Some elements (Ca, Zn, Mg, Ba etc.) contained in additives are determined by Emission spectrometry with inductively coupled plasma (ICP-OES) or Atomic absorption spectrometry (AAS). X-ray fluorescence analysis (XRF) is most commonly used for S and P elements content determination. Fourier transform infrared spectroscopy (FTIR) is very often used for additives contents determination.

3. Example of Practical Application

Engine oil Ursa Super (20W/50) from UTD-20 engine was chosen as an example of measurement results. The engine was subjected to a demanding performance test in a testing room on an engine brake. This test was compounded of 48 stress cycles consisting of 10 operating hours each. [1 operating cycles = 10 operating hours]. Such test time and stress magnitude equals to double of normal given operating time for this type of engine. Standard maintenance was carried out in this test time – such maintenance scheme includes also oil addition, total oil changes according to rules and schedule giveny by engine producer. Oil samples were taken and analyzed during the whole test period (481 OpHrs) regularly in relatively short intervals. 62 engine oil samples were analyzed in total. The samples were analyzed by the infrared spectrometer FTIR, by atomic emission spectrometer AES and by an automatic computer and particles classificator LNF-C. For this analysis was chosen the contents of soot in the engine oil measured by the FTIR and LNF-C methods, concentration of abrasive wear metals (Fe, Cu, Pb) in the engine oil using the atomic emission spectrometry AES and the quantity of monitored particles was analyzed with LNF-C. Measurements of soot contents in a combustion-ignition engine oil during its operation measured by the FTIR method, automatic laser computer and particles classificator LNF-C (Fig. 1), showed a substantial oscilation affected mainly by the oil refilling and notably its changing. The soot contents during the operation did not exceed 0.4%. Monitoring of metals and particles quantities contents (Fig. 2) demonstrated increase of all monitored values within the period of 432 OpHrs, especially from the operation beginning to the first 22 OpHrs due to a running up, when a cooling liquid spread into the oil – due to a cylinder rupture and the elevated wear started. Water intrusion into the oil was acknowledged also by the FTIR method measurements. Testing of the engine continued after the engine head was repaired and oil added. However, the particles contents had been increasing even when following oil change was performed – this due to increased oild consumption and small contamination of the oil by cooling water. The total test time was 480 operating hours when test was finished due to a massive incursion of water into the oil. Increased wearing was observed during constant particles and metal pieces contents investigation especially in the running up period. Next significant increase of the particles and metal pieces came when wearing increased therefore the clearance of friction places increased too. This whole situation was perhaps also caused by the previous oil contamination by cooling water which affected the engine parts condition.

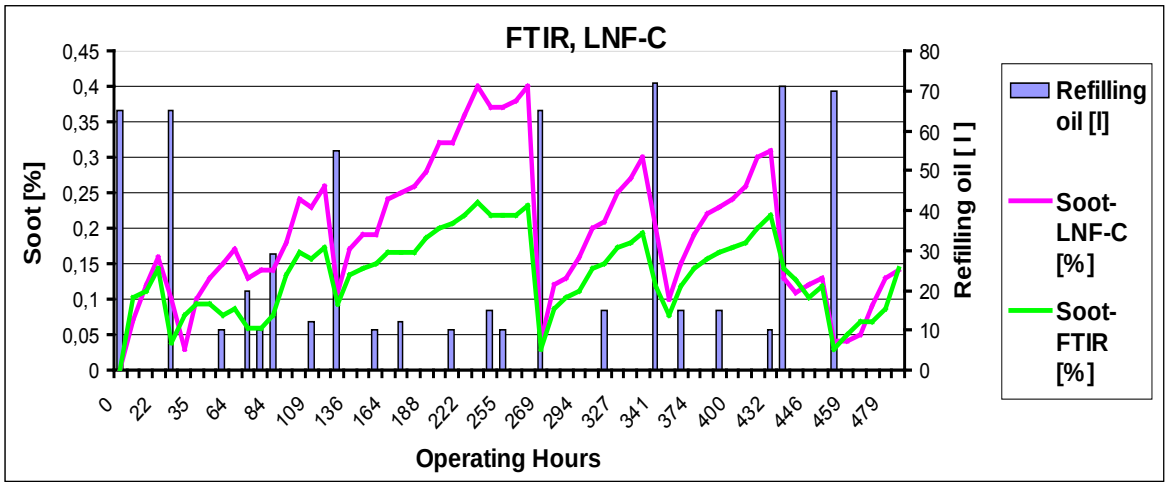

Fig. 1 *Dependency of the soot contents on engine operating hours and oil refilling.*

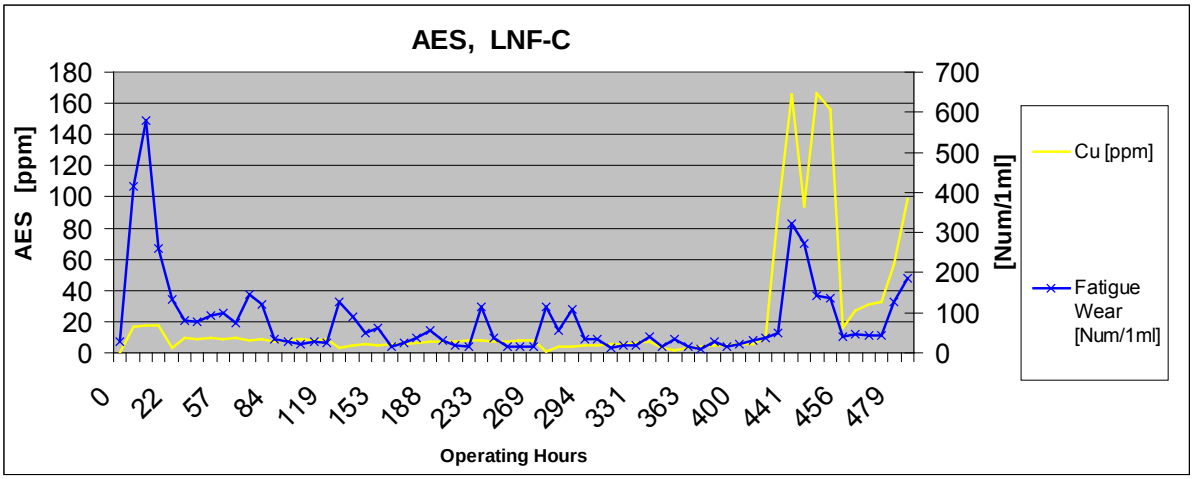

Fig. 2 *Dependency of Cu concentration and fatigue particles on operating hours.*

4. Conclusions

Monitoring technical equipment condition by means of lubricating oils is nowadays a very important part of technical diagnostics, especially because the oil analysis results of the monitored equipment is sufficiently reliable and also the return of investments in analysis is very good. If the analysis is carried out regularly, the oil changing intervals can be in most cases prolonged and therefore it is possible to get approximately 20 % of the total savings just on lubricating oil costs. The oil analysis costs are usually compared just with this amount but the biggest savings are provably in minimization of the monitored equipment downtimes, costs of repair or replacement parts and last but not least in increased general reliability of the monitored equipment. For monitoring individual equipment types it is convenient to use groups of tests according to equipment type in which the oil is used. The tests are chosen in a way to keep the basic preconditions for a successful tribological diagnostics, i.e. speed, comprehensive analysis evaluation and a fairly good price. In the future is possible to expect more and more use of instrumental analysis and computer technology to allow carrying out the analysis as well as evaluation of individual analysis types completely automatically. The next step to speed up the tribological diagnostics response will most probably be diagnostic elements and systems operating directly on equipments and their connection to the whole operation diagnostics of the monitored technical equipment with real-time results.

5. Literature

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