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LUBRICANT ANALYSIS AS THE MOST USEFUL TOOL IN THE PROACTIVE MAINTENANCE PHILOSOPHIES OF MACHINERY AND ITS COMPONENTS

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Abstract:
Condition monitoring and fault diagnosis of engineering systems are critical for the stable and reliable operation in various areas as mobile technology (primarily agricultural, forestry, mining and construction machinery), railways, airlines and large fleets. Thus, to achieve a satisfactory level of reliability for the life of a machine, proactive maintenance strategy is the only key. This means that the application of classical reliability methods suitable for components with sudden failures can be complemented by technical diagnostic methods which have the potential to provide the information about the system condition. In this article we focus on the diagnostic signal related to the used oil – tribodiagnostic measures and is an interesting theoretical item related to the evaluation of the quality of lubricants in the aspect of operation. This is because the oil is in direct contact with single parts of the assessed technical systems. Results tests were reviewed and derived from various parameters of lubricants and their limits that highlight the condition and state of the lubricants under varying categories which include, physiochemical, elemental (wear), contamination and additive analysis.

Key words: *engineering system, lubricant condition monitoring, proactive maintenance strategy, used oil analysis program*

INTRODUCTION

Reliability of machines or its components (expressed service life) relies not only on the operating conditions, time of operation, but also on the actual properties of oil refills [21]. As the oils age, changes in oil refills can be well characterized by a gradual change (degradation) of some parameters during operation. Changes in the lubricating oil are mainly influenced by the ongoing oxidation process, thermal degradation (hot spots) and the chemical reactions that occur under the real operating conditions of the machinery [12]. These phenomena occur in contact with atmospheric oxygen at elevated temperature, often in the presence of water, metallic and non-metallic impurities. The oxidation process itself is accompanied by the presence of less stable molecules that rapidly oxidize and produce acidic products [9, 25]. Every change of parameters of lubricants that exceed threshold upper and lower limit accepted for them, bring negative impacts in the form of potential faults [5]. Some authors [8, 13, 24] report that by further oxidation these are converted to more complex compounds, which in production plant oil systems is a prerequisite for the formation of various sludges, lacquers, resins, and unsuitable polar substances that settle on functional metal surfaces of machine components of work systems, thereby degrading functionality lubricated parts as well as heat dissipation from friction knots. In addition, the lubricant in operation is also influenced by other factors such as operating temperature, operating pressure, circulation number and oil fill size, required and sufficient filtration but also care of the lubricant during operation. However, careful inspection, assessment of the physicochemical properties of the oil refills and determination of the impurities and additives in the oil require some practical experience. Practical experience in oil analysis teaches us that the most successful programs are those that arise after careful evaluation and in conjunction with the objectives set [7, 18, 20]. The basis is to develop a quality concept at the outset so that it does not have to be modified later. The condition-based maintenance (CBM) presents four distinct maintenance strategies, outlined in Table 1. The strategy with the highest failure rate is breakdown (reactive) maintenance; the strategy with the lowest failure rate is proactive maintenance (PaM). PaM is also referred to as prognostic maintenance.

Table 1
Comparison of Maintenance Strategies

Maintenance approach	Applicability	Technical requirements: Specialized knowledge	Technical requirements: Specialized equipment	Cost requirements: Cost to implement	Cost requirements: Repair after failure	Cost requirements: Downtime and extended damages
Reactive	low impact of failure	low	low	low	highest	highest
Preventive	increased impact of failure	high	average	average	average	average
Predictive	simple prediction of failure	high	high	high	low	low
Proactive	multiple prediction of failure	highest	highest	highest	lowest	lowest

RESEARCH METHODOLOGY AND IMPORTANCE OF INDIVIDUAL MONITORED PARAMETERS

For the most accurate and objective monitoring of the condition of parts of the production equipment, the monitoring is based on both the limits of individual values of oil parameters and their trends [2, 19]. Limits are used primarily at the beginning of monitoring and then as the "last instance" during trends when trends are already decisive. It is based on detailed information about the machine, respectively parts and operating conditions. Furthermore, when setting limits, account is taken of the machine manufacturer's recommendations, experience with similar machine types as well as the values found in the analysis of new unused oil. If any value achieves a limit state, it means that oil does not meet its full functions and should be changed. With this data we can then compare the results of a specific analysis, but also the historical results of this machine or its part. Only in this way can we assess the condition of machine parts based on lubricating oil analysis [3].

Despite the large number of measured parameters, there is not always a guarantee of a proper assessment of the condition of the oil fill and the equipment when misinterpreted. It is therefore necessary to know the 'normal' and limit values of the individual parameters as well as the relationships between them. It should also be noted that each group of lubricating oils has its own specific properties. The condition of oil is compared to the condition of fresh oil and refers to the threshold values which should not be exceeded. Only when we know what the individual values of the monitored parameters mean can we make an objective assessment of the oil filling and the equipment from a tribodiagnostic point of view [22]. Otherwise, the result of the analyzes would only become a worthless mixture of numbers.

Kinematic viscosity is as one of the most important parameters of liquid lubricants determines the formation of liquid friction or lubrication, the magnitude of the resistance to starting of moving parts, the sealing ability of the lubricant, its pumpability and thermal conductivity. It is a measure of fluidity and internal oil friction. The thickness of the lubricating film depends on it. By measuring the kinematic viscosity of the oil during operation, it is monitored whether the oil its function in the lubrication system, thus preventing excessive wear of the friction parts. The limit value for kinematic viscosity change is within ±10 to 20% depending on the type of oil. For each machine, the manufacturer specifies the viscosity range for the given lubricant, which must reduce friction and prevent excessive wear on the lubricated parts of the machine. In the oil used, the viscosity increases due to the formation of impurities, either by penetration from the outside or by wear and aging of the oil. Its decrease may be due to e.g. by diluting the oil charge with fuel, or by contamination with another medium. Authors [17] state that viscosity decrease may be also due to shear instability of viscosity modifiers, especially at the beginning of the use of a lubricant. Its increase may signal e.g. severe oxidative changes in oil (industrial oils), or contamination by flue gas or soot (motor oil).

BN (Base Number) is the alkaline reserve value for engine oils. The oil should be changed when it is half the initial BN value of the new oil.

TAN (Total Acid Number) is a very important indicator of the quality of the oil filling used. It also talks about the free acid content of the oil resulting from its oxidative changes and thus directly determines the degree of degradation of the oil. Engine oil and gas engine oil should be replaced when the TAN and BN values equalize. For others, it is necessary to know the limit value of TAN, or to confront it with the infrared spectrum, which in the case of oxidation changes shows a significant presence of the carbonyl group C = O (it is presence of oil oxidation products - aldehydes, ketones, carboxylic acids).

Deemulsification refers to the breaking down of emulsion into it's component incompatible phases (i.e. water and oil).

Water content is an important parameter in most oils, as contamination of oil with water can cause problems such as corrosion, loss of oil lubrication, sludge and sediment formation. Most oils are hygroscopic, so they absorb moisture from the environment. In some oils, moisture is one of the critical parameters affecting the application properties of the oil, e.g. breakdown voltage for transformer oil. Excessive water content results in increased abrasion and wear of the friction pairs, which can cause bearing failure, clogging of the filters, and engine baking. Due to the increased water content of the environment, it is often necessary to use oils with detergent dispersing properties which can absorb more water without losing the lubricating properties of the oil (hydraulic oils, oils for pneumatic systems).

Total Pollution talks about oil contamination by mechanical impurities. These impurities can adversely affect the lubricating properties of the oil, act abrasively in the system, clog the lubrication channels, valves, and contribute to the formation of sludge and deposits in the system. This parameter is particularly important e.g. for hydraulic and turbine oils. In these cases, however, a better image of the contamination will provide a purity code (measured by a laser particle counter or manually using a microscope and a scanning grid).

Purity code is especially important for hydraulic and turbine oils. Today it is measured mainly by laser particle counter, the method of light beam interruption. It provides data on the number of particles in the oil by size category. These are different for the ISO and NAS methods, as well as the form of the code number that is reported as the result of the measurement.

Corrosive effect on steel and copper is defined as the formation of metal oxides, sulfides or hydroxides compound on the metal surface itself as a results of a chemical oxidation process. The corrosion is typically occurring when the ferrous metals are exposing to either some stronger oxidizing agent than Fe_2+ or any environment that consisted with water and oxygen.

Inductively Coupled Plasma Spectrometry Optical Emission Spectrometry (OES – ICP) – a frequently used method for the determination of additive, contaminant and abrasion elements in oil.

a) Additive elements – the most important are zinc, phosphorus, sulphur, calcium, barium and magnesium. It is necessary to know the composition of the oil and the content of the elements in the fresh oil in order to monitor their loss. In general, the content of EP-additives which have a direct influence on the anti- attrition properties of the oil is thus determined.

b) Contamination elements – are elements that should not normally be present in the system. Silicon, which speaks of dust particles contamination of the oil, is most often monitored.

c) Wear elements – the most important abrasion elements to be determined are iron, aluminium, chrome, lead, copper and tin. There is a need to know the design of the system or equipment to assume where the individual wear elements may come from, as well as experience in the field (e.g., copper may come from engine wear from bearings, cams, connecting rods, but also from the cooling system).

Infrared spectrometry is an optical non-destructive analytical method that provides fast and comprehensive information about the condition of the lubricant used and is used to determine oil changes, e.g. for gas engine oils, this method determines the oxidation, nitration and sulfation of the oil. This method can also detect contamination of the oil with another oil or product, but also with water. By comparing the IR spectra, one can find the agreement of the oils or the differences between them. Today, spectrum libraries allow, with a certain probability, to accurately identify an oil.

RESULTS OF RESEARCH

The choice of parameters for oil refills analyzes depends on whether the oil fill used is analyzed for lubricant research and development or is routine analyzes within the maintenance strategy. In the first case, the aim is to obtain as many parameters as possible from the oil filling as well as from the machinery for their possible use in new improved lubricant oil formulas. In the case of routine analyzes, it is very important to select the dominant parameters so that they provide an accurate picture of the condition of the oil filling and the machine at the lowest possible operating costs [16]. A combination of classical and modern instrumentation methods is also very suitable. Based on practical experience, we can determine a summary of commonly tested and reported properties in lubricant condition monitoring for individual groups of oil fillings, see Table 2.

Table 2
Key parameters for individual groups of oil fillings

Common parameter	Hydraulic oils	Turbine oils	Gear oils	Compressors
Kinematic viscosity at 40 and 100°C	A	A	A	A
Viscosity index	A	N	A	A
Presence of water or coolant	A	A	A	A
Total pollution	N	N	A	A
Alkaline reserve	N	N	N	N
Acid number	A	A	N	A
Deemulsification characteristics	N	A	N	N
Content of wear, contamination and additive metals	A	A	A	A
Infrared spectrum	A	A	A	A
Code of cleanliness	A	A	N	N
Corrosive effect on steel and copper	N	N	A	N

Note: A – *parameter is monitored,* N – *parameter is not monitored.*

Ensuring the smooth and reliable operation of machines and equipment is one of the main reasons for conducting lubricant analysis [4]. In this context, attention should be paid to the three procedure for analysing lubricating oil refills. These are:

1. Analysis of physico-chemical properties of lubricating oil (proactive approach) – the quality parameters checked include kinematic viscosity, acidity and alkalinity AN/BN, elemental analysis (elemental spectroscopy) and infrared spectroscopy FTIR (additives);

2. Analysis of contamination of lubricating oil (proactive approach) – the controlled quality indicators include e.g. water content, moisture, number of particles and flash point;
3. Analysis of the wear of machine parts and friction knots (predictive approach) – controlled quality indicators include mainly particle density (Fe), ferrography and elemental (wear) analysis.

The check of the individual qualitative indicators according to Table 3 is aimed at determining specific measured values that give an overall picture of the condition of the oil charge and the individual friction nodes of the equipment. These are some of the maximum permissible deviations from the required values in the units of measurement, which are subject to analysis, evaluation and are given as warning and limit values respectively limits. When evaluating some indicators, upper limits are given, e.g. particle number and wear level. Other indicators are those where only the lower limits are given, such as BN alkalinity number, additive rating (FTIR). Other indicators have both upper and lower limits, especially kinematic viscosity and infrared spectroscopy (FTIR). Table 3 shows some qualitative data and their evaluation according to the individual measured values as a basic indicator, durability indicator, change and statistical indicator.

Table 3
Qualitative indicators of oil fillings

Parameter	Basic indicator	Durability indicator	Change indicator	Statistical indicator
Kinematic viscosity				
at 40°C	UL, LL	UL, LL	–	–
at 100°C	UL, LL	UL, LL	–	–
Cleanliness oils	UL	–	VI	UL
Water according to Karl-Fischer	UL	–	VI	UL
RPVOT	–	LL	VD	LL
Acid number	LL	UL	VI	–
FTIR/oxidation, nitritation	–	UL	VI	UL
Wear content	–	–	VI	UL
Contamination content	UL	–	VI	UL
Additives content	–	LL	VI, VD	LL, UL

Note: UL – *upper limit,* LL – *lower limit,* VI –*value of increase,* VD – *value of decrease,* RPVOT – *Rotating Pressure Vessel Oxidation Test according to ASTM D 2272,* FTIR – *Fourier-transform infrared spectroscopy.*

Over time, each device wears out, its condition deteriorates, and performance decreases. Then, after some time, it stops operating and gets into a fault condition [10]. The origin and course of failure development can be illustrated in the Fig. 1.

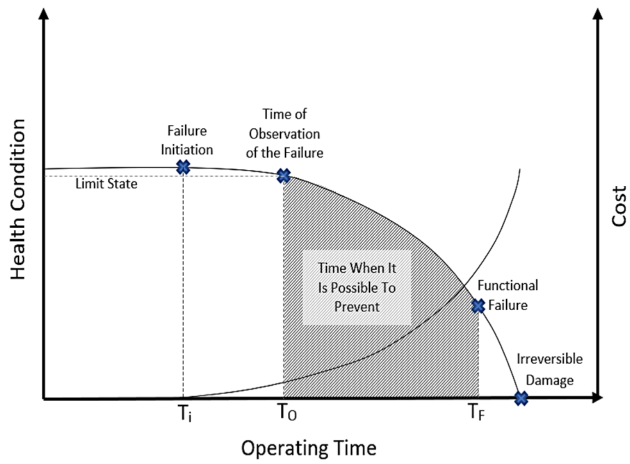

Fig. 1 The development of a failure from its initiation to the time of irreversible damage
Source: Developed on the basic of [9, 11].

At time T_i, during the operation of the device, an event occur which results in the initiation of a failure. This disorder does not occur immediately, but it continues to spread over time. The fault may still not be detected at this time. Under conditions of operation, stress reasons, or other circumstances, the fault develops further. It will take effect when the limit state is exceeded. If maintenance is not intervened in time, unexpected shutdown of the equipment may result in an accident. According to the figure, it is evident that, in the time interval between T_o and T_F by suitable intervention, an emergency machine shutdown can be avoided. If the measurement interval, the checks are set inappropriately, or the checks are not consistent, exceeding the limit state will not be detected and the equipment will shut down unexpectedly until the accident. In the interval between T_o and T_F, there is a time slot for warning, a space for detecting a fault before T_F.

CONCLUSION

The process of diagnosis of used lubricants can be defined as the determination of the acceptability, or unacceptability, of a particular results by the application of target or ageing limits interpreted in the context with the operational environment in which the components operates. Interpretation of the limits too should take into account duty cycle, age of production equipment, lubricant aging, productivity of the manufacturing process, maintenance procedures and environmental conditions [1]. Based on the analysis of the oil condition, the intervals of oil replacement can be expanded, allowing increased availability.

If proactive maintenance is to be effective, it is necessary to ensure success in oil analysis:

- establish a target level of machine cleanliness (limit values), which is resulting in a significant lifetime extension,
- identify care methods for oil fillings to remove contaminants, which is resulting in the removal or reduction of sources of input pollution.
- implement an oil and machinery contamination monitoring program, resulting in filtration at earlier intervals.
- the limits themselves are more proactive than predictive, which results from the actual maintenance and repair activities of machines and equipments. Proactive signals are often critical to determine the suitability and quality of measured values [6, 14, 15, 23]. In practice, the following are used:
- relative limits used in the assessment of the number of particles of ISO 4406:2017 for the determination of the presence of water and additives in oil fillings, the acid number AN and the like,
- absolut limits for the determination of the oil life (replacement intervals), which result from the operating conditions in question and from the chemical and physical properties of the lubricants, which play a critical role. The most commonly used are the AN/BN acid and alkalinity numbers, kinematic viscosity, oil oxidation stability test (RPVOT), elemental spectrometry, infrared spectrometry (FTIR) for the determination of nitration, oxidation and additives, dielectric constant and others.

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