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INVESTIGATION OF THE PROCESS OF AGEING OF HYDRAULIC OIL DURING ITS USE

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Summary

The problems of changes in the properties of hydraulic oils during their use in hydraulic systems of wheel loaders have been presented. The methods and results of examination of selected characteristics of a hydraulic oil of the HV quality class and VG 46 viscosity grade as functions of oil usage time have been described. The test results have been analysed in the aspect of the predominating processes of the ageing of hydraulic oils and of the monitoring of oil condition. It has been found that the criteria of reaching the limiting condition of a hydraulic oil, specified in the literature and by oil manufacturers, are incompatible with the present-day hydraulic systems. The limit values as regards changes in the viscosity, viscosity index, and acid number are too restrictive. The predominating criterion of reaching the limiting condition by modern oils used in hydraulic systems is the content and particle size distribution of solid contamination.

Keywords: hydraulic oil, ageing of hydraulic oils, monitoring of oil condition

1. Introduction

Hydraulic oils are used as operating fluids in a wide variety of technical devices, including hydraulic systems. They determine the functionality, durability, and reliability of such systems. The present-day hydraulic systems are characterized by increasing exertion and decreasing overall dimensions, they comprise less and less hydraulic fluid, have smaller and smaller cooling systems, and operate at higher and higher pressures. In consequence, the hydraulic oils undergo increasingly difficult mechanical, thermal, and chemical conditions of operation, which conduce to ageing and fast deterioration in functional properties

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of the oils unless they are of adequately high quality and are appropriately used in the hydraulic systems.

At present, the fluids used in most hydraulic systems are hydraulic oils of the HV quality class (according to PN-ISO 6743-4). They consist of mineral base oil and various improvers, such as oxidation and corrosion inhibitors, viscosity improvers and anti-wear additives. The range of applications of the hydraulic oils that contain not only the said improvers but also detergent-dispersant additives (the HVLPD class oils, according to DIN 51524) is widening as well.

The oils when used in hydraulic systems undergo ageing (degradation) in result of the following [1, 2, 4, 5]:

- oxidation, caused by the attack of atmospheric oxygen and intensified by heat, high pressure, and catalytic action of the metals (chiefly iron and copper) of which hydraulic system components are made;
- thermal decomposition, as the oil temperature can reach a level of up to 1 000 °C in microscopic spaces in result of micro-dieseling or electrical spark discharges caused by the generation of static electricity in oil [1, 2];
- UV radiation impact, e.g. during maintenance or the like works or due to inappropriate oil storage;
- contamination by particulate matter, either penetrating from outside or being the product of wear of system components or of oil ageing processes, or by water or other liquids.

The ageing during the use of the hydraulic oil causes a deterioration in oil quality, i.e. changes in the oil viscosity, acid number, and anti-wear properties, growing trend towards the building-up of deposits on system components, and increasing particulate matter content.

The use of a hydraulic oil whose one or more features have become considerably worse may result in accelerated wear of system components and in the formation of deposits, which translate into deterioration in the system reliability and durability.

To prevent such a situation, the hydraulic oil is changed after a predefined time of system operation (within the preventive maintenance planning) or the technical condition (quality) of the oil is monitored over the period of the oil being in service in the hydraulic system. At present, many different systems are used to monitor the oil condition or to determine the limiting oil characteristics, but the monitoring systems are not always appropriate for the modern highly-exerted hydraulic systems and oils having very good functional characteristics, including the detergent-dispersant properties [1]. The results obtained with the use of such systems, based on incorrectly selected analyses, may be misleading.

2. Subject, objective, and scope of the tests

The tests were carried out on samples of hydraulic oil of the HV quality class (according to PN-ISO 6743-4) and the HVLPD quality class (according to DIN 51524), of the VG 46 viscosity grade (according to PN-ISO 3448), with a complete package of improvers, including detergent-dispersant additives.

The oil was used in the hydraulic system of an articulated wheel loader, whose technical specifications were as follows:

- engine power rating – 35.7 kW;
- oil pressure in the hydraulic system – 45 MPa;
- operating pressure in the hydraulic working system – 21 MPa;
- oil pump delivery rate – 49 dm^3/min;
- oil volume in the hydraulic system – 75 dm^3;
- time between oil changes, according to the operation manual – 3 000 h.

The objective of the tests was to determine changes in the values of selected characteristics of the hydraulic oil as functions of the time of using the wheel loader (loader operation time).

The tests were carried out on samples of fresh (clean) hydraulic oil and on oil samples taken from the hydraulic system of loaders that had been operated for 200 h, 800 h, and 2 500 h. The following characteristics of the hydraulic oil were determined in the tests:

- oil appearance and colour;
- kinematic viscosity at 40 °C and 100 °C;
- viscosity index;
- flash point;
- acid number;
- corrosiveness to copper;
- particulate matter content;
- particle size distribution and appearance of insoluble contaminant particles.

3. Test methods

The hydraulic oil samples, 1 dm^3 each, were taken from the hydraulic system tank of the loaders and homogenized. Then, individual oil characteristics were determined with the use of the methods as specified below.

- The oil appearance and colour were defined by visual observation in the daylight.
- The kinematic viscosity at 40 °C and 100 °C was measured with the use of the Ostwald-Pinkevitch capillary viscometer, according to the method specified in PN-EN ISO 3104.
- The viscosity index was calculated from the values of the kinematic viscosity at 40 °C and 100 °C, in accordance with the principles described in PN-ISO 2909, procedure B.
- The flash point was measured in accordance with the method described in PN-EN ISO 2719, with the use of a Pensky-Martens automatic closed-cup tester HFP 360.
- The acid number was determined according to the method specified in PN-C-04049.
- The corrosiveness to copper was examined in accordance with the method specified in PN-EN ISO 2160.

- The particulate matter content was determined by the gravimetric method according to ASTM D4898.
- The grain size distribution of insoluble contaminant particles was determined according to ISO 11171, with the use of an automatic particle counter Pamas PPFM-4S.
- The appearance, shape, and structure of insoluble contaminant particles were observed with the use of a microscope Nikon Eclipse LV 100 under diascopic illumination (i.e. in the transmitted light), with determining the particle dimensions as well.

4. Test results and analysis

The organoleptic examination of the hydraulic oil samples did not reveal the presence of water, either dispersed or isolated in the form of a separate phase, or metal or other contaminant particles of considerable size. After a prolonged oil sample storage time, a small amount of deposit could be seen, which had settled in result of sedimentation of fine organic particles. The colours of the oil samples were diversified: the oil darkened with the oil usage time (Fig. 1).

The oil sample colours varied from light (fresh oil) to various shades of brown (used oils). The darkening of the oil resulted from the formation of oxidation products in it. The oxidation products had the nature of acid resins, partly soluble in oil. With increasing oil usage time, the amount of the resins formed and the resin condensation degree grew, too, and this was the reason for the oil darkening effect. The light brown colour of samples of the oil having been used for a long time (2 500 h) indicated that the oil was free of thermal oil decomposition products and only contained substances formed in result of oil oxidation.

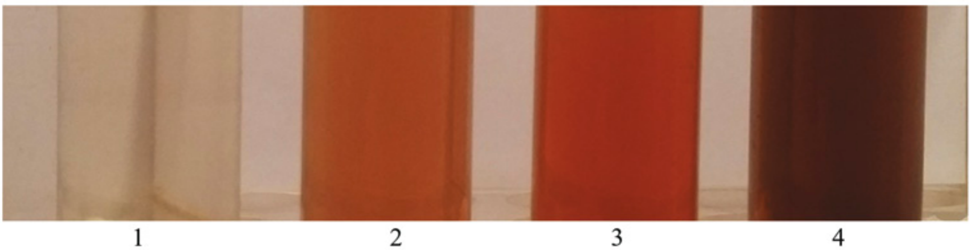

Fig. 1. Appearance of the hydraulic oil samples tested: 1 – fresh oil; 2 – oil having been used for 200 h; 3 – oil having been used for 800 h; 4 – oil having been used for 2 000 h

With increasing oil usage time, the values of important rheological characteristics of the oil changed as well: the values of the kinematic viscosity at 40 °C and 100 °C decreased and so did the value of the viscosity index (Fig. 2).

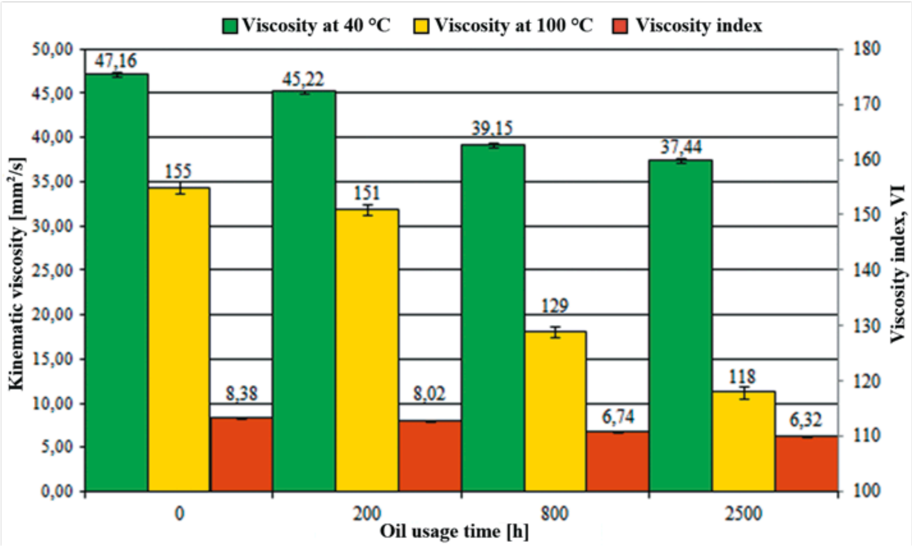

Fig. 2. Values of the rheological characteristics of hydraulic oil samples vs. oil usage time

When hydraulic oil is being used, its viscosity may increase, chiefly in result of the formation of products with high molecular mass in it (products of thermal decomposition and oxidation of the hydrocarbon base of the oil); on the other hand, the oil viscosity may rise due to the penetration of diluents into it (in consequence of neglects in system maintenance) or, in most cases, in consequence of shearing of long-chain hydrocarbon molecules of the oil base and viscosity modifiers. The actual change in the viscosity is the outcome of these two factors.

In the case under consideration, an unequivocal down trend was observed both in the viscosity values and in the viscosity index values. In the first phase of the use of hydraulic oil (up to 200 h of machine operation), the viscosity and viscosity index slightly declined (by about 4 % and 2.6 %, respectively), see Table 1. Then, after 800 h of operation, the viscosity declined by about 17-20 % in total and the viscosity index dropped by about 17 % in total, too, but with higher intensity. After 2 500 h of the oil usage time, the drops in the viscosity and viscosity index values became quite small in comparison with the very long period of operation. This resulted, on the one hand, from fresh oil refills and, on the other hand, from stabilization in the oil ageing processes. The kinematic viscosity values for the oil having been used for 800 h and 2 500 h were outside of the limits for the VG 46 viscosity grade.

Table 1. Values of the rheological characteristics of hydraulic oil samples and their relative reductions vs. oil usage time (in relation to the fresh oil)

Oil usage time [h]	Kinematic viscosity [mm²/s]		Viscosity index	Relative reduction [%]		
				in kinematic viscosity		in viscosity index
	at 40 °C	at 100 °C		at 40 °C	at 100 °C	
0	47.16	8.38	155	–	–	–
200	45.22	8.02	151	4.1	4.3	2.6
800	39.15	6.74	129	17.0	19.6	16.8
2 500	37.44	6.32	118	20.6	24.6	23.9

The oil under test is characterized by very good rheological properties, arising from the features of the mineral oil base and high viscosity modifier content (with long-chain polymers being used as the modifying agent). It also has very good detergent-dispersant properties. The conditions of oil operation in the hydraulic systems of wheel loaders do not conduce to thermal decomposition (the thermal loads are low). Conversely, the oil undergoes oxidation and the long-chain hydrocarbon molecules of the oil base and viscosity modifier are destroyed in result of the high values of shearing stresses and the contact with atmospheric oxygen. Thanks to very good dispersant properties of the oil, the oxidation products are kept widely dispersed without causing a growth in the oil viscosity. Therefore, an assumption may be made that the viscosity changes chiefly result from high and intensive shearing stresses, acting on the oil and causing a drop in the values of the rheological parameters.

The absence of intensive thermal loads and of diluents in the oil used in the hydraulic systems under test is indicated by the flash point value: for both the fresh oil and the samples of used oil with different usage time, these values fell within a range from 202 °C to 205 °C, determined with an accuracy of ±1.5 °C.

The thesis that the ageing of hydraulic oil is chiefly affected by the oxidation of the oil base has been confirmed by the results of measurements of the acid number. The value of this number linearly grew with increasing oil usage time (Fig. 3) and the absolute values of this parameter fell within a range from about 0.5 mg KOH/g to about 3 mg KOH/g for the oil that had been used for 2 500 h.

This very high value of the acid number of the oil sample did not translate into a growth in the corrosiveness of the oil: the copper strip test (carried out for 180 minutes at a temperature of 100 °C) did not reveal any corrosion attack for all the oil samples tested (the test result: corrosion class 1a). This may be explained by two facts:

- the organic acids that are oil oxidation products belong to the group of weak acids;
- the oil has very good anticorrosive properties.

The value of the acid number of hydraulic oils of the HVLPD class is 0.5-0.6 mg KOH/g; after an oil usage time of 1 000 h, it should be within a range 1.5-2.0 mg KOH/g. This shows the incompatibility of the current criteria of the limiting conditions with the HVLPD oils.

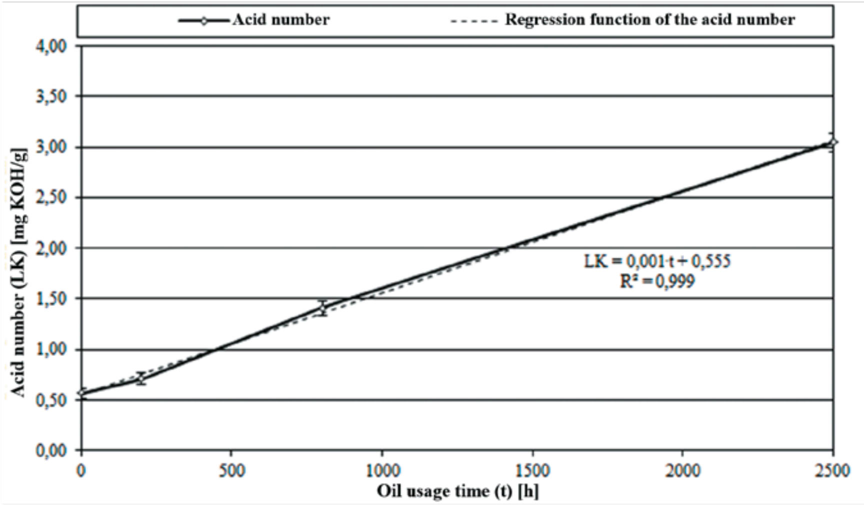

Fig. 3. Values of the acid number of hydraulic oil samples vs. oil usage time

One of the problems encountered when hydraulic oils are used is the accumulation of insoluble contaminant particles in the oil. This happens in spite of filters being provided in the hydraulic systems. The tests carried out have shown that the particulate matter content of the oil increased with the oil usage time (Fig. 4).

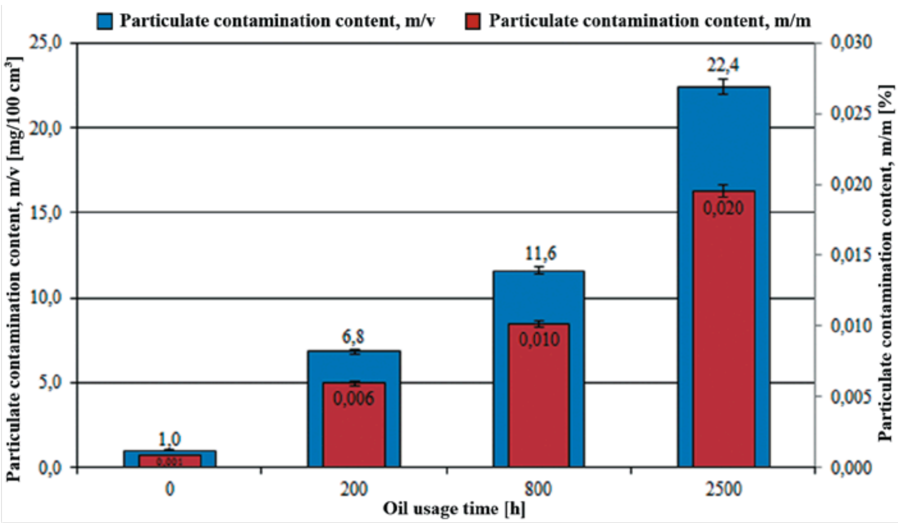

Fig. 4. Particulate contamination content of hydraulic oil samples vs. oil usage time

The particulate contamination content by mass increased tenfold for the first 800 h and twentyfold for the 2 500 h of the oil usage time in comparison with that of the fresh oil. The particle size distribution also changes with the oil usage time (Table 2).

Table 2. Particle size distribution in the hydraulic oil samples vs. oil usage time

Oil usage time [h]	Contaminant particles with dimensions over those specified below [μm] per 100 cm^3 of the oil							
	2	5	10	15	20	25	50	100
0	182 488	35 135	3 286	743	271	147	34	10
200	360 486	68 647	8 765	3 305	1 519	818	109	21
800	669 342	327 683	24 834	3 665	1 280	594	179	30
2 500	695 481	482 614	273 441	115 578	33 691	8 983	315	50

In general, the number of contaminant particles present in the hydraulic oil increases with the oil usage time. Noteworthy is the relatively low cleanliness of the fresh oil: although the total particle content in the fresh oil is low (0.001 % by mass), the percentage of fine particles (< 10 μm) is high. The fine particles make 98.2 % of the total particle count, while the fraction of larger particles is as little as 1.8 %.

A similar percentage distribution of particle sizes (but with a higher total particle count) was found in the samples of the oil having been used for 200 h (Fig. 5).

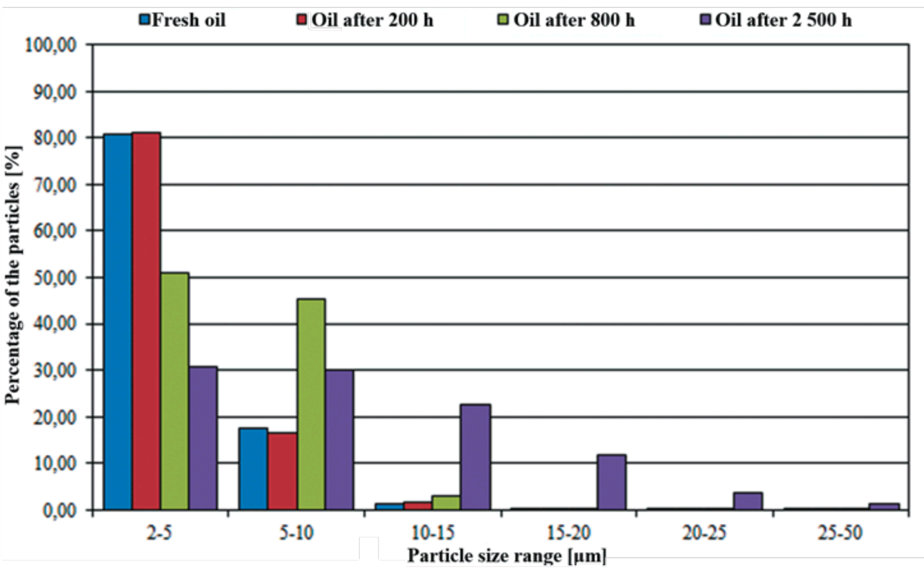

Fig. 5. Histogram of the percentage of contaminant particles of individual size ranges

For the oil samples taken after 800 h and 2 500 h of operation, the grain size distribution was completely different (Fig. 5): the samples contained much more contaminant particles, with increasing proportion of the particles of bigger dimensions. Such a trend holds with increasing oil usage time. In the last sample, the fraction of particles with dimensions within the range of 2-5 μm was more than two and half times lower than that in the oil having been used for up to 200 h. This indicates, on the one hand, intensification of the oil ageing processes (chiefly in result of the oxidation of the oil base) and good dispersant properties of the oil but, on the other hand, penetration of external contaminants into the oil and low efficiency of the hydraulic system filters.

The contaminants present in the oil used for 2 500 h include a significant number of mineral particles with irregular shapes and big dimensions, with dark organic substances (oil ageing products) having been deposited on them (Fig. 6).

The cleanliness of hydraulic oils is also defined in accordance with the requirements of standards NAS 1638 and PN-ISO 4406. In the NAS 1638 classification, 14 cleanliness classes are discerned, based on the particle counts per 100 cm^3 of the hydraulic oil for a specific particle size range. The higher cleanliness class codes indicate bigger particle counts. According to PN-ISO 4406, in turn, the cleanliness of a hydraulic oil is defined by the numbers of particles greater than 4 μm, 6 μm, and 14 μm per 1 cm^3 of oil, with assigning appropriate range numbers to the particle counts; the range numbers from 0 to 28 (the higher the code number, the larger quantity of the contaminant particles).

The hydraulic fluid cleanliness required for hydraulic equipment to operate is specified by the equipment designers. As an example, the required cleanliness of the hydraulic fluids for typical medium-pressure hydraulic systems should be as follows, according to the standard codes:

- for gear pumps, code 19/17/14;
- for double-acting hydraulic cylinders, pressure-reducing valves, flow control valves, distribution valves, code 20/18/15.

Table 3 presents the cleanliness classes of the hydraulic oils under test and the maximum oil contamination level acceptable for the hydraulic systems under test. The data show that the hydraulic oil cleanliness criterion set for the hydraulic system involved was met by the samples of the oil having been used for up to 200 h. The samples of the oil after 800 h and 2 500 h of operation did not meet the cleanliness criterion, chiefly because of excessive counts of the particles with dimensions bigger than 4 μm and 6 μm; for the oil sample taken after 2 500 h of oil use, even the counts of particles larger than 14 μm exceeded the acceptability limit.

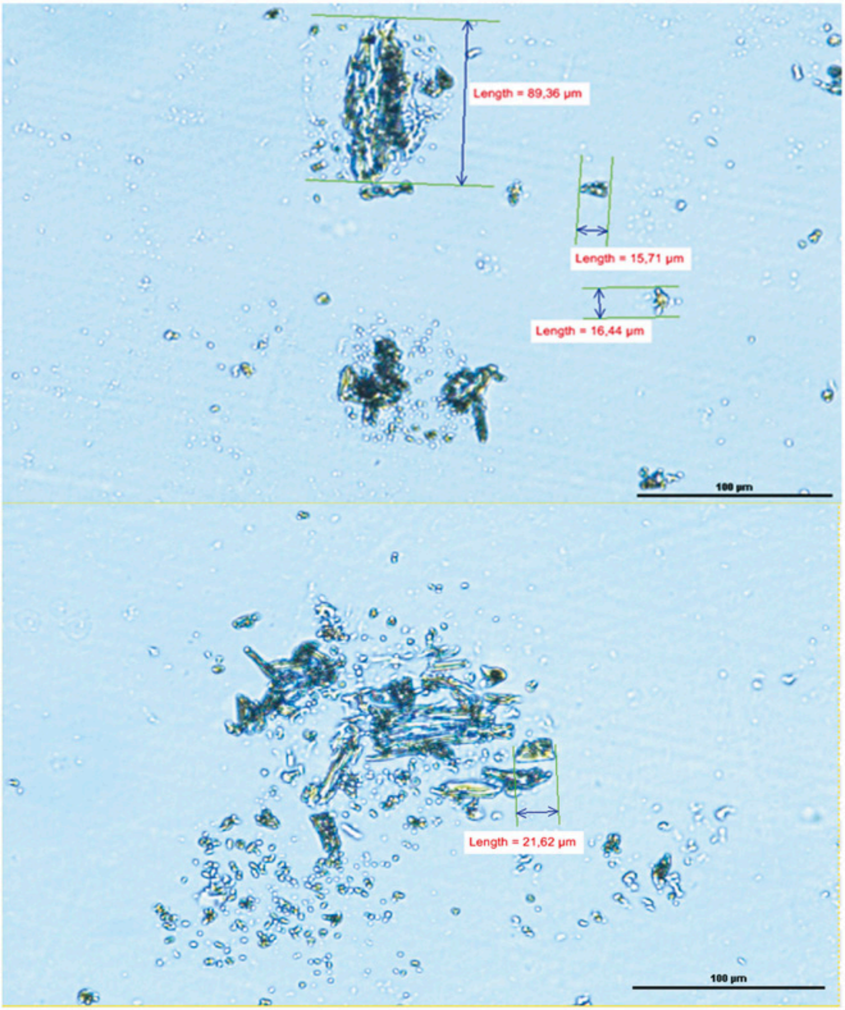

Fig. 6. View of contaminant particles in a hydraulic oil sample taken after 2 500 of use (magnification ratio: 20×10)

Table 3. Cleanliness classes of samples of the hydraulic oils under test

Oil usage time [h]	Cleanliness class to PN-ISO 4406		Cleanliness class to NAS 1638	
	Oil samples	Acceptability limit	Oil samples	Acceptability limit
0	18/16/10	20/18/15	7	8, 9
200	19/17/12		8	
800	20/19/12		10	
2 500	20/19/17		11	

Thanks to good detergent-dispersant properties of the oil, the organic contaminants (oil oxidation products) are kept in the form of fine-dispersed suspension (Fig. 7). In consequence, the hydraulic system components are free of deposits, but the quantity of contaminants suspended in the oil increases. This means that one of the important factors that have an impact on the hydraulic oil ageing process is the adequate oil filtration efficiency.

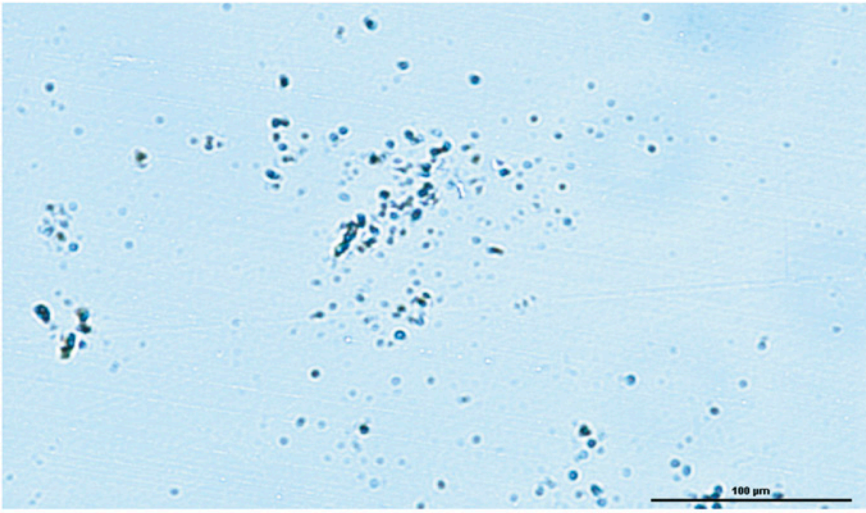

Fig. 7. View of fine-dispersed contaminant particles in a hydraulic oil sample (magnification ratio: 20×10)

5. Operational usability of the oils under test

The ageing processes result in a deterioration in the properties of a hydraulic oil during its use. An important issue is the determination when a hydraulic oil reaches its limiting condition and should be changed or subjected to reconditioning or re-refining. In most cases, this is done by determining the values of the main oil parameters that, when exceeded, define the oil as no longer usable (having reached and exceeded the limiting condition).

Based on literature data [3, 4, 5, 7], an assumption may be made that a hydraulic oil has reached its limiting condition when:

- its kinematic viscosity at 40 °C has changed by more than ±10 % in comparison with that of the fresh oil;
- its viscosity index has dropped by 15 % in comparison with that of the fresh oil;
- its acid number has risen by 0.3-0.4 mg KOH/g or has exceeded a value of 0.5 mg KOH/g;
- its particulate matter content:
  - has exceeded a value of 0.5 mg/100 cm^3 of the oil or

  - has reached the concentration and particle size composition worse than required for the cleanliness class prescribed for the hydraulic system involved (according to PN-ISO 4406);
- its flash point has dropped by 30 % in comparison with that of the fresh oil (this indicates penetration of solvent into the oil);
- its water content has exceeded a value of 0.1 %.

Moreover, the hydraulic oil is tested for the content of metallic elements, present in the products of wear of the metal parts of the hydraulic system. The metal concentration, especially a change in this concentration with increasing oil usage time, provides information about the technical condition of the system and it may only be used for indirect assessment of the technical condition of the hydraulic oil.

The limiting values are determined on a subjective basis; it is also difficult to rank individual parameters in terms of their importance. This is because of the fact that the ageing of oil in a hydraulic system is a random process determined by a multitude of various factors. At present, two basic systems predominate in the management of hydraulic oils during their use with respect to their technical condition:

- preventive maintenance planning, where the oil in a hydraulic system is changed as scheduled by the system manufacturer, without any examination of oil properties;
- monitoring, where oil samples are taken in specific oil usage time intervals and the values of selected oil characteristics are determined (by proximate field or laboratory test methods) and compared with limiting values determined on a subjective basis.

The results obtained from the tests carried out within this work have shown that the problem is not so obvious and the values of the characteristics under test not always indicate that the oil has reached its limiting condition. The predefined criteria of reaching the limiting condition are not appropriate, especially for the hydraulic oils with very good functional characteristics, including viscosity, anti-wear, and detergent-dispersant properties, as it was in the case described herein.

This has been confirmed by the tabulated summary (Table 4), which suggests that according to the literature criteria, the oil under test reached its limiting condition after 800 h of use, for the five oil parameters listed in the Table. This oil usage time, however, is much shorter than recommended by the equipment manufacturer (3 000 h).

Table 4. Exceedances of the limiting values of the examined parameters of the hydraulic oil

Item	Parameter	Unit	Limiting value, according to literature	Oil usage time after which the limiting value was exceeded
1.	Change in the kinematic viscosity at 40 °C as against that of the fresh oil	%	±10	exceedance by 17 %, between 200 h and 800 h
2.	Change in the viscosity index	%	–15	exceedance by about 17 %, after 800 h
3.	Acid number	mg KOH/g	– growth by 0.3-0.4 – value higher than 0.5	0.56 for fresh oil
4.	Particulate matter content	mg/100 cm^3	〉5	6.8 after 200 h
5.	Cleanliness class to PN-ISO 4406	code		20/19/12 after 800 h

Based on this, the following two theses may be proposed:

1. The parameters given in the literature as defining the limiting condition are too restrictive.
2. The values of the standard hydraulic oil usage time (time between oil changes) applied at the preventive maintenance planning are too high.

Such a situation arises from the fact that the oil parameter values defining the limiting condition as given in the literature are applicable to hydraulic oils with moderate and good functional characteristics, with mineral base, and having moderate rheological parameters and good anti-wear and anti-oxidation properties. Meanwhile, the hydraulic oils used at present (such as the oil under test) have very good rheological, anti-seizure, anti-wear, anti-oxidation, and detergent-dispersant properties.

The criteria defining the limiting condition for such hydraulic oils should be different. They must be compatible with the actual properties of such oils and with the conditions of operation of most hydraulic systems. The changes in the properties of hydraulic oils during their use are determined by the oxidation, impact of shearing stresses, and particulate contamination. These factors result in a decrease in the viscosity, an increase in the acid number, and a growth in the content of particulate contamination, chiefly organic substances with a very high degree of dispersion. The biggest hazard to the proper functioning, durability, and reliability of hydraulic systems is posed by the presence of contaminants in the oil (cleanliness of the oil). A deterioration in other oil properties, including viscosity, viscosity index, and increased acid number, does not cause major risks.

6. Conclusions

1. In the moderately-exerted hydraulic systems, the predominating hydraulic oil ageing processes that take place during the oil use are oxidation, deterioration in the rheological properties due to shearing of viscosity modifiers, and accumulation of insoluble contaminant particles.

2. The criteria of reaching the limiting condition of hydraulic oils, as specified in the literature and by oil manufacturers, are applicable to hydraulic oils of lower quality classes; they seem to be too restrictive and incompatible with the oils of higher quality classes.

3. A decisive parameter of the limiting condition of a hydraulic oil is the oil cleanliness class (content and grain size composition of insoluble contaminant particles).

4. For the hydraulic oils of the top quality classes, having very good rheological, anti-seizure, anti-oxidation, and detergent-dispersant properties, new values of the parameters defining the limiting condition should be determined by more extensive and accurate experimental investigations.

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