APPLICATION OF TRIBODIAGNOSTICS IN THE MAINTENANCE OF VEHICLES

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Tribotechnical diagnostics use lubricants as media that help obtain information about processes and changes in the systems that they lubricate. If tribodiagnostics are applied properly and thoroughly, they result in significant savings in many areas; for example, they contribute to an increase of the lifetime of vehicles as well as other machines and devices, to a decrease of consumption of energy, to limiting the idle time due to failures and subsequent repairs, to a decrease of investment as well as operational costs (especially the machine maintenance and repair costs), to an increase of the safety of operation and to a reduction of negative influences of transport on the environment. They are based on monitoring the course of progressive wear of lubricants as well as mechanical parts.

The paper deals with possibilities of using modern instrumental methods in particular: infrared spectrometry with Fourier transformation, analytical ferrography with consequential image analysis, scanning electron microscopy, local electron microanalysis and voltametry in the area of vehicle lubricant analysis.

The first part of the paper presents the results of a study of the course of wear of engine, gear and hydraulic oils and plastic lubricants used for lubricating the vehicle parts.

The second part of the paper deals with the abrasion particles isolated from oil filters in different types of vehicles. The evaluation of their number, size, shape, colour, surface characteristics and other morphological attributes helps obtain information about the part they come from and about the mechanism of their creation. This knowledge can thereafter contribute (especially in connection to the knowledge of the chemical structure of the particles) to an elimination of the hazard of a damage or a breakdown of the machine.

The combination of the methods presented above helps monitor the evaluation of the course of processes related to the wear of particles of vehicles as well as steady mechanisms and obtain its complex evaluation.

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1 Introduction

Tribodiagnostics is based on regular collecting of samples of lubricating oils from the mechanisms monitored, and on analyses and tests of these samples. The aim of such diagnostics is to find out the condition of both the lubricating oil and the lubricated mechanism. The analysis of oil is focused on determination of changes of its physical and chemical properties which occurred during operation (these changes are mainly due to thermo-oxidation processes and the decrease in the amount of additives) and on identification and/or determination of contaminants (water, glycols, fuel, mechanical impurities drawn into the combustion area together with air, nitro compounds formed by the contact of the oil with combustion gases etc.). The oil also contains particles resulting from wear of the lubricated components; their analysis can provide information about processes that take place in the system.

Monitoring of chemical and physical changes which occur in the oil allow us to form a relatively precise idea about current condition of lubricant and possibility of its further use [1, 3, 11, 12, 14]. The starting point for evaluation of the dynamics of changes of individual parameters is the values of these parameters in unused oil. Numerous methods that are used for this purpose include infrared spectrometry or electrochemical methods. A group of other methods enable monitoring of the course of wear of component parts which are lubricated with the respective lubricant: these methods are suitable for description of morphology and distribution of the particles resulting from abrasion of metals, fibrous particles from filtration materials, contaminants from outer milieu etc. In particular, these methods include analytical ferrography with consequential image analysis and with additional study of morphology of the individual particles by means of scanning electron microscopy with the possibility to analyse composition of the particles by means of a local electron microanalyser.

2 Experimental

2.1 Experimental Methods Used

Infrared spectrometry: The analyses were performed using an FTIR spectrometer Vector 22 (Bruker) in the spectral range of 600-4000 cm^{-1}, with the resolution of 4 cm^{-1} and with the scan number 32 by means of the ATR technique (ZnSe crystal).

Ferrography: The separation of particles on a plastic support was carried out with a ferrograph REO 1 (Reo Trade Ostrava). The ferrograms were evaluated by means of a set composed of bichromatic triocular microscope, type H 6000, and digital camera Micrometrics 318 CU connected to a PC equipped with the system of image analysis LUCIA G, versions 4.82 and 5.1 (Laboratory Imaging Ltd. Prague).

Voltammetry: A method was developed for voltammetric determination of antioxidants in lubricating oils. Voltammetric analyses of selected antioxidants − 2,6-di-*tert*-butyl-4-methylphenol (BHT, purity 99 %, AppliChem) and *N*-phenyl-1-naphthylamine (FNA, purity 98 %, Acros Organics) – were performed by means of an electrochemical analyser EP 100 (HSC service, Bratislava) in three-electrode arrangement. The electrochemical oxidation of antioxidants made use of DC method with linear change of potential (Linear sweep voltammetry). The indication electrode in the form of gold disc (AuDE) was polarised in the range of potentials from 0 mV to 1400 mV, at the scan speed of 40 mV/s.

Scanning electron microscopy and local electron microanalysis: Using a scanning electron microscope TESCAN VEGA TS 5130 with an EDX spectrometer Quantax 200 (Bruker), we investigated the particles isolated from oil filters of various vehicles. The surface of mounts was covered with a conducting layer of gold in a sputtering instrument SC7620 (Quorum).

2.2 Experimental Results

The experimental work included analyses of samples of fresh and used engine oils and gearbox oils. The course of service wear of the oils was monitored in the samples taken from engines and gearboxes of various types of vehicles, such as buses, cars, heavy lorries and road tractors, locomotives of Czech railways, off-road and road motorcycles, agricultural tractors and machinery. The analyses also included hydraulic oils, oils for industrial gearboxes and plastic lubricants.

The aim of the work done was

- to optimize the procedures and experimental conditions of selected methods,
- to verify the possibility of their application to tribodiagnostic purposes,
- to evaluate the experimental results and formulate recommendations for users on the basis of their interpretation.

2.2.1 FTIR spectrometry

This method enabled monitoring of changes taking place in the oils due to the effects during operation. Such changes include, e.g., depletion of additives in engine and gearbox oils: a significant absorbance decrease in the region about 960 cm^{-1} indicates depletion of lubrication-enhancing and anti-seizure additives (Fig. 1).

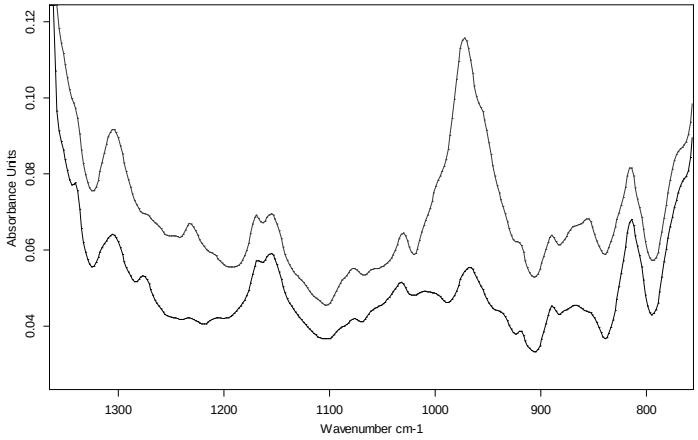


Fig. 1 A part of FTIR spectrum of engine oil SAE 15W 40 (tractor ZETOR)
sample no. 1 − lower spectrum (worn away oil)
sample no. 2 − upper spectrum (new oil)

The oil whose spectrum is presented in Fig. 2 exhibits a distinct decrease in the content of lubrication-enhancing and anti-seizure additives in the region of 990-960 cm^{-1} and a decrease in the content of high-temperature antioxidant on based on sulfur compounds, which is connected with the high temperature load of the engine. The peak in the region of 890 cm^{-1} is due to the presence of fuel in the oil as a result of poor tightness of the fuel system, and the peak in the region of 1610 cm^{-1} is connected with serious lack of tightness of the piston group, which causes blowing-by of combustion gases containing nitrogen oxides.

Degradation of the plastic lubricant LV-2,3 packed in a bearing, which was caused by electric current, is documented in Fig. 3; the erosion effect of electric current also damaged the material of the bearing.

The results of these analyses and others were published, e.g., in Refs [5, 6, 8].

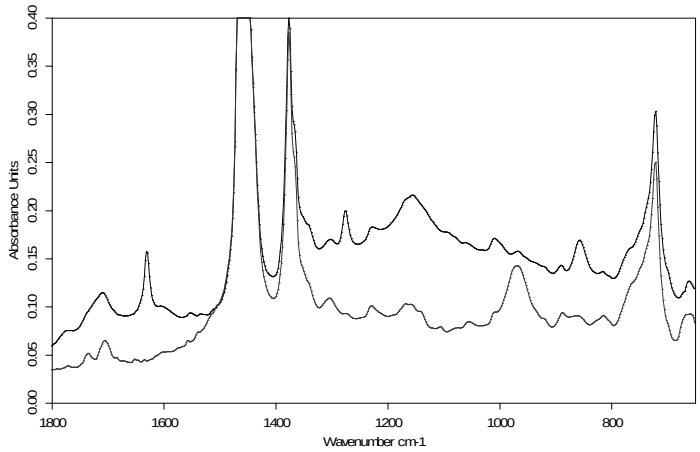


Fig. 2. A part of FTIR spectrum of engine oil (CITYBUS 3380)
sample no. 1 − lower spectrum (new oil)
sample no. 2 − upper spectrum (used oil)

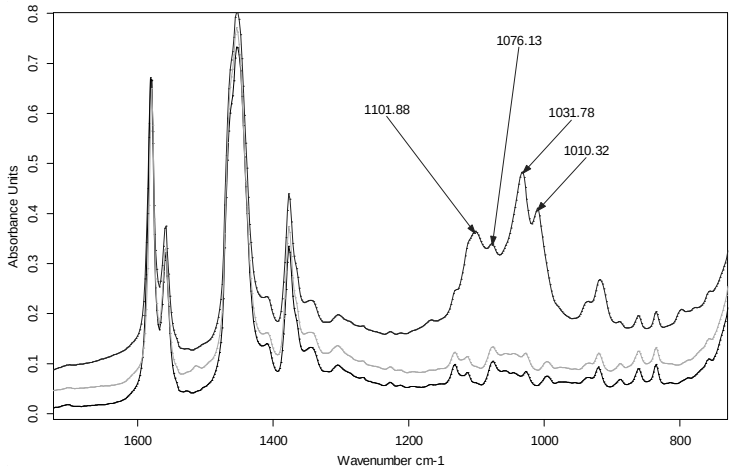


Fig. 3 FTIR spectra of samples of plastic lubricant LV 2,3
sample no. 1 − lower spectrum (lubricant from undamaged part of bearing)
sample no. 2 − upper spectrum (lubricant from damaged part of bearing)
sample no. 3 comparison − middle spectrum (unused lubricant)

2.2.2 Voltammetry

In the framework of experimental work done in voltammetry, suitable conditions were found for simultaneous determination of phenolic and amino antioxidants. The antioxidants based on phenols can be electrochemically oxidized at the polarisation of gold disc electrode AuD in the range of potentials from 0 mV to 1400 mV in 0.2 M H_2SO_4 in the presence of ethanol and acetonitrile (3: 1).

If a mixture of amino and phenolic antioxidants is analysed, an acidic solution of H_2SO_4 in the presence of acetonitrile must be used; in this medium the half-wave potentials of individual waves are markedly differentiated. The half-wave potential, $E_{1/2}$, of phenylnaphthylamine has the value of 805 mV, and $E_{1/2}$ of BHT is 1070 mV. Secondary amines can be determined directly in this basic electrolyte; the presence of BHT does not interfere with their determination. The determination of BHT in samples

containing comparable amounts of secondary aromatic amines requires elimination of the amines because their presence interferes with the determination of phenolic compounds.

A procedure was suggested and optimized for masking aromatic amines by means of their reaction with nitrous acid. The nitrosamines produced can be subsequently used for sensitive and selective determination of amino antioxidants by cathodic reduction at hanging mercury drop electrode (HMDE) with the help of differential pulse voltammetry fast scan (DPV FS). The method was applied to practical samples of oils. The results and their detailed discussion were published, e.g., in Ref. [4].

2.2.3 Ferrography with Subsequent Image Analysis

This method was applied to determination of surface portion of particles in a defined locality of ferrogram and estimation of the shape factor *S* of abrasion particles

$$S = 4\pi \cdot A/P^2,$$

where P and A stand for circumference and for surface area of the particle, respectively. Also other morphological parameters were determined on ferrograms on the micrographs (Table 1), namely elongation = MaxF/MinF, where MaxF/MinF (maximum/minimum Feret diameter) is the largest/smallest distance between two parallel tangents of the object.

A program module was created enabling, after initial delimitation of object, further modification of the image in binary representation by pulling it through. Thereafter, the whole surface area or the individual particles can be analysed. The results of measurements of the fields provide a table of values. This is followed by a cycle of separation of the objects using mathematical morphological methods. After separation of the particles, a measurement frame is defined which limits the area of further analysis (that is advantageous in particular with imperfect segmenting or if a selection of analysed particles from partial segment of image is required). Another possibility is manual modification by selecting from the commands offered for processing of binary image. The representation is accompanied by information about the total number of selected objects.

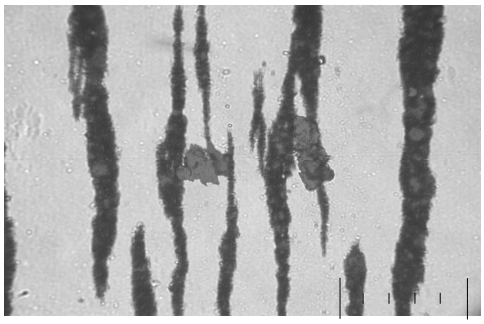
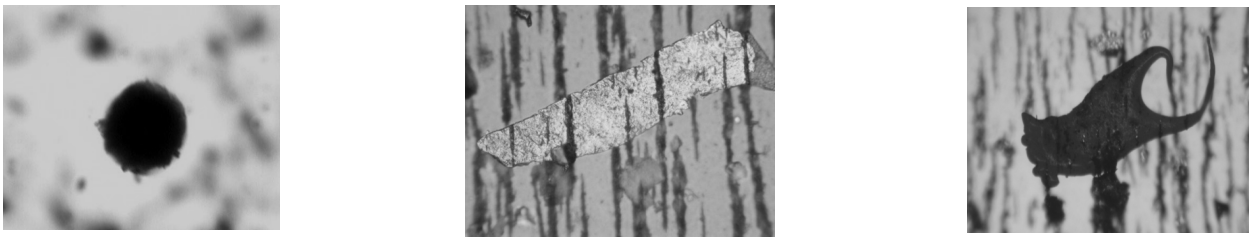


Fig. 4 Ferrogram with chains of particles from adhesive wear and large particles formed by separation from surface layer of lubricated component
(1 division line ~ 10 μm)



a b c

Fig. 5 Typical particles ferrographically separated from oils
a − Wear particle of typical spherical shape (diameter ca 20 μm)
b − Laminar particle with visible traces of abrasion wear (length ca 150 μm)
c − Indented particle of cutting wear (max. dimension ca 100 μm)

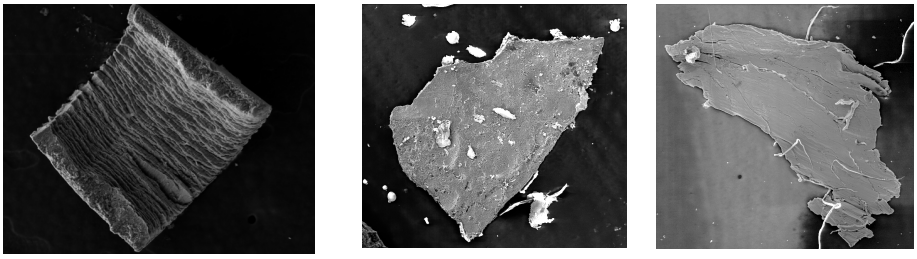


Fig. 6 Laminar particle with traces of abrasion wear
(REM, max. dimension of particles 200-500 μm)

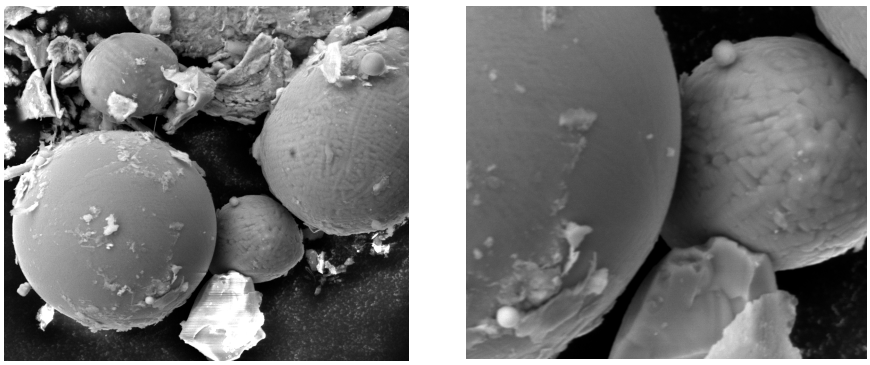


Fig. 7 Wear particle of typical spherical shape (REM, diameters of particles 10-50 μm)

The experimental work carried out so far leads to the conclusion that a complex evaluation of wear of motor oils and of the engine components lubricated with them should appropriately be complemented also by a study of the particles trapped on oil filters. Although this information is of qualitative rather than quantitative character and is obtained *ex post* (usually during simultaneous exchange of oil and filters), nevertheless, it can bring additional important findings about the processes that have taken place since the previous exchange.

The program module was tested on particles typical of the individual kinds of wear; for the examples, see Figs 5-8.

The authors published a number of papers dealing with the problem of study of abrasion particles from the standpoint of quantitative description of morphology of the particles and analysis of their composition; see, e.g., Refs [2, 7, 9, 10].

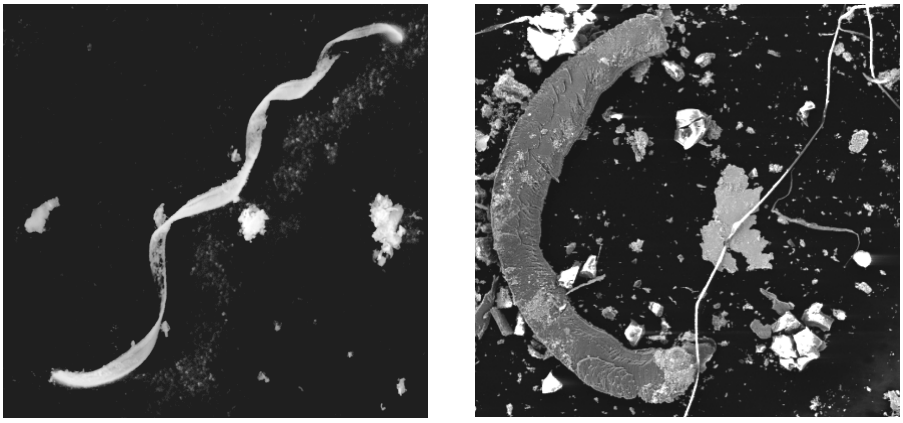


Fig. 8 Particles of cutting wear (length 200-600 μm)

2.2.4 Analysis of Particles from Engine Oil Filters

Selected typical particles isolated from filtration cartridges of oil filters from engines of various types of transport vehicles were analysed on REM with local electron microanalyser. According to their chemical composition, the particles investigated can be divided into five groups, which are described in detail in previous Refs [2, 7−10].

Type 1: fine particles, usually with rounded shapes and with poor conductivity; the non-dominant elements can be residuals of additives, impurities from outside etc. – these are either carbon deposits (porous friable formations) or morphologically miscellaneous particles of biological origin which contain carbon

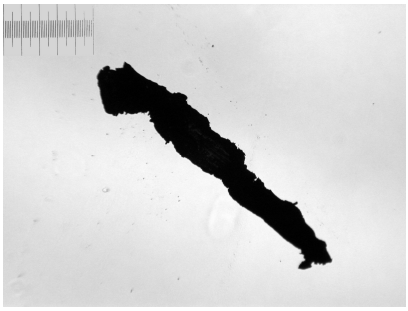


Fig. 9 Example of output from the program module (photograph: 1 division line = 10 μm)

Symptom	Value of symptom
surface area [μm^2]	3058.37
equiv. diameter [μm]	62.4
circumference [μm]	425.17
length [μm]	197.07
width [μm]	15.52
max. feret [μm]	164.82
min. feret [μm]	34.98
shape factor S	0.21
elongation	4.71

and other biogenic elements (pollen dust, fine fragments of plants coming from the environment, particularly from the air drawn in). Dominant elements (D): C (55-85 %), O (30-40 %); minor elements (N): Fe (traces), Na, Mg, Al, Si, S, K, Ca

Type 2: glossy particles often with deep furrows, with embossed edges; the main component is tin – particles from inner lining of bearings. D: Sn (~80 %); N: Pb, Cu, O, P, Fe (traces)

Type 3: flat thin particles with sharp edges, whose chief components are zinc and aluminium; alloys on this basis are used for increasing of the resistance against corrosion and abrasion; the particles are peeling off surface layers of engine component parts. D: Zn (30-45 %), O (40-47 %), Al (~15 %); N: Fe, Si, S, Cl, Ca, Cr. Particles of aluminium bronzes were newly included into this group (D: Cu up to 95 %, Al 5 % a above).

Type 4: commonly occurring particles composed predominantly of iron, often having oxide surface layer (the only significant components are Fe and O; traces of Cr, Mn) − this is the material of basic construction elements. D: Fe (60-70 %), O (30-40 %); N: traces of Si, Ca, Cr, Mn, P

a) type 4.1: spherical particles with the most frequent diameters of 10-50 μm; these spheroids result from wear processes

Table 2: Particles from oil OTHP-3 taken from gearbox H750M (the material of turbine blades, predominantly aluminium)

b) type 4.2: narrow flat to needle-shaped particles or spiral coiled formations, particles with embossed deformations coming from cutting wear

c) type 4.3: large flat particles having cracks and pitting on their surfaces – they are produced by peeling off the Beilby layer

Type 5: non-conducting particles of silicon(IV) oxide or silicate etc. which can get into the lubricating oil from outside together with the air drawn in. D: Si (20-30 %), O (60-70%), Al (6.46 %); N: Fe, Na, Mg, K, Ca.

Minor elements (Cl, S, Ca, Na, P aj.) can be present in residues of EP-additives sticking to the particles.

The EDX analysis of oil from gearbox H750M (Table 2) proved that predominating portion of particles come from the material of turbine (aluminium was the dominant element). Only sporadically

found were the particles with predominant content of iron. The abrasion can be due, first of all, to the direct contact of rubbing surfaces; another cause can be the intensive action of oil on the surface of turbine blades during rotation of the turbine rotors. The particles present in oil can attack the surface of blade and cause its increased wear. If such attack worsens the original quality of blade surface (which is then coarser), then the flow situation of filling changes too, which can result in lowered effectiveness of power transfer.

3 Conclusion

Instrumental methods that can bring a considerable body of data about the course and degree of wear of lubricants for transport vehicles are intensively developed at present. A valuable fact is that this methodology supplies beside diagnostic also prognostic information, i.e. it allows anticipation and prevention of emergency situations. Optimization of exchanges of oil fillings represents a serious economical and ecological problem; it is just this area where tribodiagnostics finds broad applications.

Its main advantage lies in the fact that this diagnostic method does not necessitate disassembling of the engine. On the basis of analysis of particles in exploited lubricant it allows evaluation of the wear regime in the given mechanism. The evaluation of number, morphology and composition of the abrasion particles permits prediction about onset of limit or emergency wear; in some cases it is also possible to determine the origin of abrasion particles and differentiate between the types of materials from which the abrasion particles were produced. The degradation of oils during their service life can be monitored by means of spectrochemical and voltammetric methods. Their combination enables a complex evaluation of the changes that occur in the lubricant and in the mechanism lubricated with it.

Reference literature

1. CLARK, D. A New Approach to Assessing Wear Problems Using Oil Analysis. Practicing Oil Analysis Magazine. September 2004. [online]. [cit. 2008-09-10]. Available from WWW: <http://www.practicingoilanalysis.com/article_detail.asp?articleid=653>.
2. ČORNÝ, Š.; MACHALÍKOVÁ, J.; KRTIČKA, F. Monitoring of the Wear Process and Wear Quantity. In: BORKOWSKI, S., BENEŠ, L. (Editors). Improvement of Machines Exploitation and Quality Products: Saint-Petersburg: Saint-Petersburg Polytechnical University Publishing House, 2008. Pp. 24-32. ISBN 978-5-7422-1784-8.
3. EBERSBACH, S. The Investigation of the Condition and Faults of a Spur Gearbox using Vibration and Wear Debris Analysis Techniques. Wear, Vol. 260, Issues 1-2, January 2006, pp. 16-24.
4. CHÝLKOVÁ, J.; ŠELEŠOVSKÁ, R.; MACHALÍKOVÁ, J.; DUŠEK, L.; WEIDLICH, T. Voltammetric Determination of Antioxidants in Motor oils Using Gold Working electrode. 12th Int. Conf. on Electroanalysis, ESEAC 2008. June 16-19, 2008. PP033. Chem. Listy 102, (2008). Pp. 79-80. ISSN 0009-2770.
5. MACHALÍKOVA J., CHÝLKOVA J., ŠELEŠOVSKÁ R. Advanced Instrumental Techniques, in Tribotechnical Diagnostics. Int. journal ”Machines, Technologies, Materials“, 2-3, 2007, 165-168, ISSN 1313-0226.
6. MACHALÍKOVÁ, J., CHÝLKOVÁ, J., OBRŠÁLOVÁ, I., ŠELEŠOVSKÁ, R. Advanced Instrumental Analytical Methods and Their Application for Sustainable Transport. WSEAS Transactions on Environment and Development, 2006, Issue 11, Volume 2, pp. 1390-1395. ISSN 1790-5079.

7. MACHALÍKOVÁ, J., M. SEJKOROVÁ, M. LIVOROVÁ, F. KRTIČKA. Assessment of Morphology of Wear Particles in Oils for Vehicles. Transactions on Transport Sciences. Vol. 1, No 4, 185-192. ISSN 1802-971X.
8. MACHALÍKOVÁ, J.; CHÝLKOVÁ, J; ŠELEŠOVSKÁ, R. Tribotechnical Applications of FTIR-Spectrometry, Ferrography and Voltammetry (in Czech). In Proceedings of International Conference "Wear – Reliability – Diagnostics". Brno 25. – 26. 10. 2005. Brno: University of Defence. Pp. 199-124. ISBN 80-7231-026-7.
9. MACHALÍKOVÁ, J.; SEJKOROVÁ, M.; BAŽANT, L.; SCHMIDOVÁ, E. EDX Analysis of Abrasion Particles (in Czech). Proceedings of the 15th international conference REOTRIB 2009 − Quality of Fuels and Lubricants. Velké Losiny Mai 27-29, 2009. Prague: VŠCHT Prague, 2009. Pp. 104-110. ISBN 987-80-7080-715-6.
10. MACHALÍKOVÁ, J.; SCHMIDOVÁ, E.; SEJKOROVÁ, M.; ČORNÝ, Š. Morphology of Wear Particles from Motor Oils and Oil Filters. Proceedings of the 5th Russian Conference POLYTRANSPORT SYSTEMS, Krasnoyarsk, 21-23 November 2007: Krasnoyarsk: Siberian Federal University, Polytechnic Inst., 2007. Part I – 398. Pp. 21-30. ISBN 987-5-7638-0766-0.
11. MIHALČOVÁ, J.; AL HAKIM, H.; ČORNÝ, I. Evaluation of Properties of Used Oils in Tribodiagnostics (in Slovak). Výrobné inžinierstvo. Vol. 6, No. 1 (2007), pp. 30-34.
12. NOVÁČEK, V.; TURAN, T. Modern Methods of Monitoring of Wear of Machines (in Czech). Proceedings of Conference on Lubrication in Modern Industrial Plant. 2006, p.72, ISBN: 80-02-01808-7. [online]. [cit. 2008-09-10]. Available from WWW: <http://www.alsglobal.cz/filedownloadservlet?userPath=fiutowskaj&file=Moderni_metody_sledovani_opotrebeni_stroju_sbornik.pdf>.
13. OBRŠÁLOVÁ, I., MACHALÍKOVÁ, J., CHÝLKOVÁ, J., ŠELEŠOVSKÁ, R.: Used Oils Management and its Relation to Environmentally Sustainable Transport Development. The 2006 WSEAS Int. Conf. on ENERGY, ENVIRONMENT, ECOSYSTEMS, SUSTAINABLE DEVELOPMENT. Vouliagmeni Beach, Athens, Greece, July 11-13, 2006. In WSEAS TRANSACT. Issue 6, Vol. 2, June 2006. Pp. 867-870. ISSN 1790-5079.
14. PODSIADLO, P.; STACHOWIAK, G. W. Development of Advanced Quantitative Analysis Methods for Wear Particle Characterization and Classification to Aid Tribological System Diagnosis. Tribology International, Volume 38, Issue 10, October 2005, pp. 887-897.