# TRIBOLOGICAL DIAGNOSTICS OF MACHINERY

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## Introduction

Tribological diagnostics as the ensemble of means and methods of continuous monitoring of the state of friction characteristics of moving junctions is playing an ever important part in the development of friction,lubrication,and wear theory and practice. The scheme presenting the main areas of tribological diagnostics is given in Fig.I. This growing part of TD is determined by the general tendency of modern technology,expressed in an attempt to organically combine the functions of measuring,evaluating,and predicting the parameters and characteristics of the processes taking place in the operating device. The logical result of this integration in future is the closed system correcting its operation in accordance with an established program.

Unfortunately, tribotechnical devices are still very far from such an ideal system at the present time. While in the friction assemblies with hydrodynamic lubrication it is possible in the first approximation to realize feed-backs in the lubricant circulation system with the aid of monitoring of the pressure,temperature and filtration, in the systems operating without lubrication and with boundary lubrication even the process of selection of the diagnostic parameters has not been completed.

The following parameters can be used for monitoring the friction assembly: friction coefficient,contact temperature,wear rate,vibration level,acoustic emission and electrical signals,generated in the assembly. The most efficient are the data enabling the automatic

## THE MAIN AREAS OF TRIBOLOGICAL DIAGNOSTICS

| MEASUREMENT OF TRIBOLOGICAL PERFORMANCES | TRIBOLOGICAL TESTING | ON-LINE MONITORING AND EXPRESS ANALYSIS |
|---|---|---|
| ↓ | ↓ | ↓ |
| FRICTION COEFFICIENT | STANDARDS ON SPECIMENS, TESTING CONDITIONS, AND TIME | BASIC PRINCIPLES OF ON-LINE SYSTEMS |
| WEAR RATE | SIMULATION AND ACCELERATED TESTING | ON-LINE HARDWARE |
| LOAD AND VELOCITY CHANGES | | METHODOLOGY OF THE EXPRESS ANALYSIS |
| TEMPERATURE | | |
| .................. | ................. | ................... |
| ↓ | ↓ | ↓ |
| DESIGN OF SIMPLE AND ADEQUATE EQUIPMENT FOR MEASUREMENT AND PROCESSING THE DATA ON FRICTION BEHAVIOUR | CREATION OF ADEQUATE METHODS IN SIMULATION OF REAL MACHINERY ELEMENTS AND DEVELOPMENT OF DATA BASES FOR CAD IN TRIBOLOGY | DESIGN OF NETWORK SYSTEMS COMBINING EXPRESS AND ON-LINE WEAR MONITORING |

Fig 1.

processing and analysis with the possibility of forecasting the wear of the assembly. Up to date acoustic and vibration analysis as well as electric and magnetic methods seem to be promising as very sensitive to small changes in friction behaviour, inertialess and presenting the data in the most convenient form from the point of view of processing.

## Wear Diagnostics

One of the most important problems arising in the development and maintenance of moving junctions of machines is the evaluation and prediction of the wear. The problem can be solved by measuring the change in mass of the parts or their dimensions. However, these methods require disassembly of the machine and, in addition do not yield complete data for establishing the wear mode. An important aspect of the problem is the fact that after each disassembly the the mechanism begins a new "run-in" cycle. A considerably larger amount of information on the type of wear and the degree of wear can be obtained by studying changes in the state and properties of lubricant containing the wear debris (see Fig.2).

At the present time various physical and physicochemical methods are used in this field. A classification of these methods and a comparison of their capabilities are shown in the Table I[1].

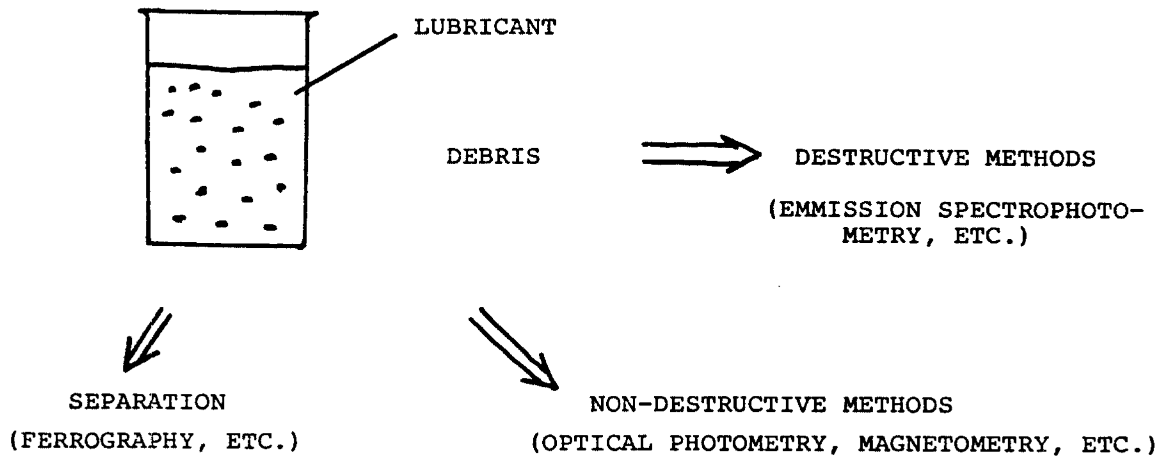
## Emission Spectrophotometry

This method has been used since the 1950s as a method for diagnosing the condition of internal combustion engines. The intensity of rubbing junctions is indirectly characterized by the concentration of metals in the oil which are present in materials of the rubbing parts. Emission spectral analysis is based on the emission spectra of the atoms and ions excited by electromagnetic radiation (usually by an electrical source light-electric arc,spark).

Emission spectral analysis is performed both for liquid oil spe-

## WEAR DEBRIS ANALYSIS

### SAMPLE ANALYSIS




### ON-LINE ANALYSIS

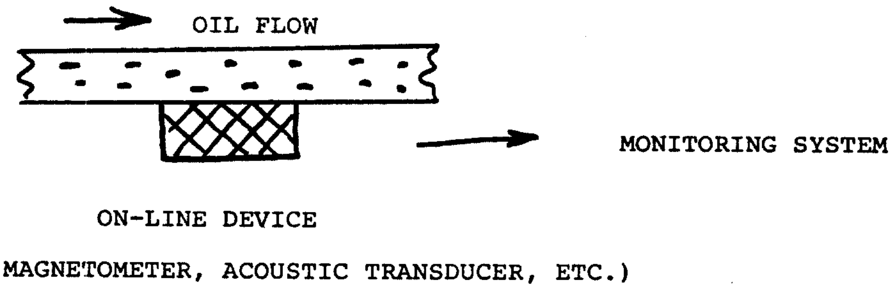



Fig 2.

Table 7

WEAR DIAGNOSTIC TECHNIQUES

| ANALYTICAL METHOD | CHARACTERISTICS AVAILABLE: COMPOSITION | MASS CONCENTRATION | SIZE DISTRIBUTION | MORPHOLOGY | TOTAL CONTAMINATION USE | POSSIBILITY OF ON-LINE ANALYSIS | POSSIBILITY OF EXPRESS ANALYSIS |
|---|---|---|---|---|---|---|---|
| EMISSION SPECTROPHOTOMETRY | + | + | - | - | - | - | - |
| ATOMIC-ABSORPTION SPECTROMETRY | + | + | - | - | - | - | - |
| ATOMIC-FLUORESCENCE SPECTROPHOTOMETRY | + | + | - | - | - | - | - |
| I.R. SPECTROSCOPY | - | - | - | - | + | - | - |
| ABSORPTION SPECTROPHOTOMETRY | - | + | - | - | + | - | + |
| DIRECT PHOTOMETRY | - | - | - | - | + | - | + |
| ELECTRO-OPTICS | - | + | + | - | - | - | - |
| MICROSCOPY & IMAGE ANALYSIS | - | + | + | + | - | - | - |
| LIGHT SCATTERING | - | + | - | - | - | - | - |
| FLOW ULTRAMICROSCOPY | - | + | + | - | - | + | - |
| FERROGRAPHY & MICROSCOPE | - | + | + | + | - | + | + |
| MAGNETOMETRY | - | + | - | - | - | - | + |
| N.M.R | - | + | - | - | - | - | - |
| NEUTRON ACTIVATION | - | + | - | - | - | - | - |
| ACOUSTIC ANALYSIS | - | + | + | - | - | + | - |
| SEDIMENTOMETRY | - | + | + | - | - | - | - |
| POLAROGRAPHY | + | + | - | - | - | - | - |
| CHROMATOGRAPHY | - | + | + | - | - | - | - |

cimens or for specimens with preliminary calcination of the sample. In the later case the sediment is first separated from the oil sample (by centrifugation, filtration, or calcination) and the ashy residue is burned in the spectral analysis. The sample calcination method has high sensitivity in determining small concentrations of elements in both used and unused oils. However, the process of calcination and preparation of the oil sample for analysis makes it difficult to carry out continuous monitoring of the engine condition. The basic advantage of liquid oil sample analysis is the speed of the method.The development of multichannel emission spectrophotometric systems makes it possible to perform large-scale multicomponent analysis of used oils.The sensitivity of quantitative analysis reaches $1\text{-}3 \cdot 10^{-4}$ mass%. This method is most widely used in engine diagnosis under laboratory conditions.

### Atomic Absorption Spectrometry

In this spectral analysis method the sample is vaporized in an atomizer (in flame or plasma), then we measure the intensity of the light from a discrete radiation source, passing through the vapor of the sample being studied. On the basis of the degree of attenuation of the intensity of the lines of the element being determined we evaluate its concentration in the sample.

Analysis of the effectiveness of determination of the wear debris content in the oil by the AAS method showed that this method reacts primarily to the small particles suspended in the oil sample and does not react to large particles of dimension more than 10 μm.

### Atomic Fluorescence Spectrophotometry

In this method the vapors of the sample are subjected to radiation that is resonant for the sought element and its fluorescence is recorded. Roentgen radiation is normally used to irradiate the oil sample. With the use of this method there are no limitations on the particle size, and we can rapidly determine the presence in the lubricant of large wear particles characterizing the onset of catastrophic wear. Atomic fluorescence spectrophotometry is applicable only for those metals which have realizable resonance radiation. The X-ray fluorescence method can serve foe determination of the same elements as the AAS method, except for lithium and magnesium.

### IR Spectroscopy

This method of qualitative molecular spectral analysis establishes the molecular composition of the studied specimen and is used to determine the content of oil oxidation products,carbonates, sulfates,and inorganic nitrites,based on the absorption spectra in the IR region.

### Absorption Spectrophotometry

This quantitative molecular spectral analysis method is based on the Bouger-Lambert-Beer law and establishes the connection between the intensities of the incident light and the light passing through the substance as a function of the absorbing layer thickness and the substance concentration. It makes it possible to determine the wear particle concentration in used oil.

### Direct Photometry

The degree of contamination is taken as the index characterizing oil quality. The degree of contamination is determined by the optical density of the oil,measured by photometry of oil samples.

### Electrooptic Method

This method is based on the phenomenon of optical anisotropy relaxation after removal of electrical fields orienting the dispersion. The particle size distribution function is determined from the recorded relaxation curve by solving the integral equation for the light flux intensity.The method sensitivity is $10^{-3}$ mass%. Thus, the electrooptic method makes it possible to determine the particle concentration and geometric dimensions. At the present time the method is used only under laboratory conditions.

## Microscopy

This method makes it possible to count the number of wear particles and also determine their size distribution. The wear mode is classified in accordance with the number, dimensions,and configuration of the particles. These particles are studied in optical and electron microscopes. Application of this method is possible only in combination with any other, resulting in getting the sediment of debris.

## Light Scattering

This method is used to determine the concentration of mechanical impurities in the oil on the basis of measurement of the magnitude of the optical radiation flux scattered by the mechanical particles present in the oil sample. Use of the method requires careful procedural development,associated with standardizing the sample preparation conditions and ensuring their stability.

## Flow Ultramicroscopy

This method makes it possible to determine the wear particle concentration and size distribution. However,we should note that the method requires a high level of sample dilution and complex equipment, and its application to contaminated motor oils is obviously possible only under laboratory conditions.

## Neutron-Activation Analysis

This method has high sensitivity to small metal concentrations and involves irradiation of the oil sample by a beam of neutrons; this excites the nuclei of the substance being analyzed. The energy of the radioactive radiation characterizes the concentration of the metal being analyzed in the oil sample. In spite of its high sensitivity this method has not yet been widely used because of the labour involved and the high cost of the analytic equipment.

## Acoustic Analysis

The possibility of using the acoustic method to evaluate the concentration and size distribution of the wear particles during lubricated friction was noted, but there are serious problems in processing of the signals corresponding to debris in the whole spectrum of acoustic emission.

## Nuclear Magnetic Resonance (NMR)

This method has high sensitivity to small ferro-magnetic particle concentrations ($IO^{-6}$ mass%) in used oils.The method is based on the resonant absorption of electromagnetic energy in substances due to magnetism. The analysis reduces to recording the NMR spectra of unused oil, and used oil with the mechanical particles removed. The particles concentration is determined by comparing the relative broadening of the spectrum line. The NMR method can also determine the paramagnetic particle concentration with sensitivity $IO^{-4}$ mass% and the diamagnetic particle concentration with sensitivity $IO^{-2}$ mass%. This method is quite complex and laborious, but an advantage is the prospect for use in early wear diagnosis.

## Sedimentometry

The method is based on determining the diameter of the particles from their rate of settling in the oil. The process of settling of the particles in the oil is realized either under action of the gravity force, or (for acceleration of sedimentation) centrifugal force (centrifugation).During centrifugation the particles position themselves along the radius of the centrifuge in accordance with their dimensions. Further analysis is accomplished with the use of optical devices.

## Polarography

This method utilizes the phenomenon of depolarization at one of the electrodes of an electrical cell during electrolysis of the studied solution, containing the wear products.

The polarographic analysis techniques are applicable for the analysis of used oil and determining its chemical and concentration composition under laboratory conditions.

### Chromatography

The method involves separation of the components in liquid phases ; in the first stage of the chromatographic study the multi - component liquid system is fractionated, and in the next stage the separated components are analyzed.

A technique has been developed which makes it possible to determine the quality and degree of contamination of the oil. Additional procedural development is necessary for use of the method in wear diagnosis.

### Magnetometry

This method is used to determine the concentration of magnetic wear particles in the oil. The operation of the magnetometric devices is based on recording the change of the magnitude of an applied magnetic field as it interfaces with the magnetic moment of the sample being measured. This method makes it possible to determine ferromagnetic impuriries in concentrations from $10^{-4}$ to 60 mass%.

The technique listed above have been used mostly in laboratory conditions and their review has been carried out upon the data presented in scientific publications. Only spectroscopy is standardized in some industrial countries where it is used as the field method in diagnostics of vehicles,airplanes, and helicopters. There is another method which has been widely used during last ten years throughout the world,- ferrography, and it's necessary to describe it more carefully.

### Ferrography and other Related Techniques

The ferrography method , proposed by Seifert and Westcott is widely used for sample analysis of the oil./2/ This method is based on obtaining the ferrogram by passing the oil sample along the substrate that is inclined at a small angle. The deposited particles arrange themselves on the surface of the substrate in chains that are perpendicular to the direction of lubricant flow, with the large particles located at the beginning of the substrate and the small particles located at the end. The ferromagnetic particles deposit first, while the paramagnetic and diamagnetic particles deposit later on the substrate. After the entire liquid sample drains from the substrate a solvent and a fixing solution are passed over the substrate. Qualitative study involves observation of the morphology of the particles in a microscope or determination of the wear particle type with the aid of a biochromatic microscope (the use of red and green light filters makes it possible to determine the presence of oxides on the basis of their coloration) or by heating the ferrogram and observing the particles under a microscope (at 330°C the particles of low-alloy become bluish, further heating leads to the iron particles becoming covered with blue spots). Two basic methods are used for quantitative analysis of the particles. One is the direct counting method, consisting in calculation of the wear index D, which is usually expressed by the relation:

$$D = (A_L + A_S)(A_L - A_S) = A_L^2 - A_S^2 ,$$

where $A_L$, $A_S$ are the optical densities of the precipitate at the beginning and end of the ferrogram; $(A_L + A_S)$ is the wear particle concentration index (characterizing the wear rate); the quantity $(A_L - A_S)$ is the index of the degree of shift of the particle size distribution toward the region of large particles (characterizing the degree of wear).

The second quantitative ferrogram analysis method involves the use of statistical analysis of the images. This method is used to obtain information on the number, size, and distribution of the wear particles. The ferrography method is widely used to determine and predict the wear of jet engines, diesels, helicopter transmissions, hydraulic systems, and so on. In spite of its wide use, ferrography is characterized by the following drawbacks. A large part of the wear products deposits on the first 5-10 mm of the substrate, which sometimes leads to significant compaction and hinders study of the individual particles. High dilution is required in order to obtain a deposit suitable for study in the case of highly contaminated samples. This dilution reduces the validity of the analysis. In studying oils that are highly contaminated with non ferromagnetic particles (for example, soot) the deposit becomes contaminated, which makes it difficult to study the wear products. In addition, the use of ferrography is limited by the cost of the substrate, containing the barrier made of fluorinated polymer.

These drawbacks were overcome in the rotary particle depositor (RPD), developed in the 1980s /3/. The special configuration of the magnetic field and the selection of the rate of rotation of the substrate with the sample lead to deposition of the particles present in the oil in three concentric circles. The RPD is used with success in monitoring the condition of gearboxes, diesel engines, aircraft piston engines, and hydraulic systems. A specially developed "particle counter", consisting of an alternating current magnetometer, is normally used for quantitative analysis of the precipitate obtained with the aid of the normally used RPD. The particle counter can be used under both laboratory and field conditions for rapid determination of the particle concentration in the oil. One drawback is the influence of wear particle size on the counter indications.

## On-line Methods

A very promising direction in the development of moving junction condition diagnostics is the development of real-time monitoring methods, i.e., the use of on-line devices that provide continuous tracking of the mechanism wear intensity. While in the case of sample analysis of the oil the sampling is usually performed after termination of operation of the mechanism,in the case of analysis correct selection of the sensor location relative to the junction is important in ensuring minimal distortion of the obtained data.

One example of the on-line analysis device is the device developed on the basis of direct-redout ferrography (Fig.3)./4/ The device consists of a direct-redout ferrograph, two membrane pumps for the oil and solvent, three cut-off valves for controlling the flow, a signal converter, and a microprocessor, which controls the operation of the entire device and the output of the mechanism condition information. The ferrograph itself is constructed with the use of a light source and optical fibers,through which the information characterizing the number of fine and coarse particles is supplied to the signal converter,where the optical signal is converted with the aid of a photocell to an electrical signal and enters the microprocessor for further processing. This system makes it possible to obtain information on the overall wear particle concentration and characterize the particle size distribution.

A new method for evaluating wear particle parameters in real time has recently been proposed /5/. The oil is tapped from the oil line into a special line and passed through a small cell, around which there are positioned four electromagnets, creating a rotating magnetic field by supplying to the winding of each electromagnet impulses that are shifted by a quarter of a period relative to one another (Fig.4). The rotating magnetic field causes rotation of the particles in the cell. The particles are illuminated by laser radiation with the aid of a single-filament optical fiber. The radiation reflected from a particle is applied by means of the fiber to the signal converter[2] where it is converted to an electrical signal and enters the microprocessor[3]. A signal that is modulated in amplitude and frequency forms as the particle rotates. The particle shape and size are determined from the Fourier spectrum of the modulated signal with the aid of the microprocessor. However, it is apparent that the accuracy of determination of the wear particle characteristics will be determined by several parameters - the size of the optical fiber aperture, the location of the particle relative to the fiber aperture, the reflectivity of the individual particle facets, and the influence of reflections of the radiation from the neighboring particles.

The forementioned built-in wear particle analysis methods are complex, both in their configuration and in the processing of the results. It is obvious that such devices are advisable for use in critical and expensive devices, such as airplane engines.

A built-in analysis device whose operation is based on accumulating the wear particles from the lubricant is going to be described./6/. The device contains a sensor that consists of an ensemble of electromagnets and a permanent magnet that is exposed to the lubricant stream. this leads to change of the magnetic flux in the measuring coil, that is proportional to the mass of the captured particle. The signal from the sensor is fed through the preamplifier to the data processor, where the input pulses are separated into two categories, characterizing particles that are larger than 200 μm and particles that are larger than 1000μm. After separation the pulses are applied to counters, which determine the pulse repetition rate and the total number of particles. In spite of its relative simplicity this device can be used only for monitoring wear processes that are accompanied by the formation of large particles (  200 μm), which is determined by the sensor sensitivity.

In those cases when the problem is to determine the maintenance cycle on the bases of the wear particle content in the oil, quite simple built-in devices that are also based on particle accumulation can be used./7/ An example of one such device is the device containing a permanent magnet a pair of installed pole pieces, and two temperature matched thermistors MkI, Mk2, which form the arms of a Wheatstone bridge (Fig.5). A nonferromagnetic spacer is installed in the oil line and the measuring device is mechanically connected with a motor that is used to displace it. When the device is brought near the nonferromagnetic spacer wear particles accumulate on the unit. This causes change of the magnetic flux, which leads to reduction of the flux density in the magnetoresistive sensor MkI and increase in the sensor Mk2. The bridge output voltage will increase linearly with particle accumulation to some level. Upon reaching a certain level the linearity is disrupted, the motor is energized and moves the metering device away from the spacer on which accumulation took place. The wear particles leave the accumulation surface. Then the measuring cycle repeats. This device can be used in relatively clean systems, in which the number of wear particles is critical. However, in measuring the particle content in the oil the particle whose size does not exceed 6 μm are not taken into account, since the magnetic flux gradient is not sufficient to capture them from the lubricant stream.

The comparison of the capabilities of the methods based on particles detection is given in the Table 2./8/.

## Problems in Wear Diagnostics

It is obvious that the further research and development is necessary in order to provide maintenance of machinery by the adequate and efficient techniques of diagnostics. There are some scientific problems in the area of particles detection.

Study of an oil sample containing wear particles makes it possible to provide early diagnosis of the condition of lubricated assemblies. In the general case the concentration of these particles in the oil sample and their size distribution characterize the wear

Wear Diagnostic Devices Based on Wear Particles in the Lubricant

Table 2

| Instrument | Analyzable particle size | Advantage | Disadvantages |
| --- | --- | --- | --- |
| | | Sample analysis | |
| Ferrograph | 0.1-100 $\mu m$ | Quantitative and morphological analysis | Accuracy reduction due to possible overlap of particles<br>Need for use of solvent for highty contaminated samples<br>Relatively high cost |
| Rotary particle deposition system (RPD) | Determined by selected rotation rate | Quantitative and morphological analysis | An additional measuring system ("particle counter") is required for quantitative analysis |
| Particle counter (PQ) | No limit | Quantitative analysis | Output parameters nonlinearity arises as a function of size of particles in sample |
| | | Simplicity of realization | Low information content |
| | On-line analysis | | |
| Ferrograph | 0.1-100 $\mu m$ | Quantitative analysis | Accuracy reduction due to possible overlap of particles<br>Relatively high cost<br>Impossibility of use in systems with high contamination of the oil |
| Device with rotating magnetic field | Lower limit is determined by optical fiber aperture | High information content | Complex implementation<br>Large error |
| Sensors based on wear particles accumulation | $>6$ $\mu m$ | Relative simplicity of realization | Low information content<br>Low sensitivity to fine particles |

rate and the degree of wear.

An equilibrium concentration of fine particles corresponds to the normal steady-state regime of mechanism operation. With increase of the load (thinning of the oil film) scuffing develops,and the number of wear particles increases abruptly and their size distribution shifts toward the region of large particles. The sudden appearance of large particles in the oil indicates the onset of the catastrophic wear. The most important problem lies in establishing the connection between the particle parameters and the regime of wear.

The wear mechanisms were initially studied by qualitative analysis of the wear particles on the basis of microscopic observations. The following basic problems must be solved in order to establish a quantitative evaluation of wear based on the particles. It is necessary to establish the relationship between the particle concentration in the oil and the wear magnitude or the wear rate. In the initial stage of run-in the particle concentration in the oil increases. However, the following particle loss paths exist: deposition in the filter, deposition on the bottom of the oil tank, adhesion to the wall in the form of gel-like deposits, grinding into fine particles by moving parts, and removal together with the lubricant that is drained from the system. If the machine operation under constant conditions (constant particle generation rate), then the particle concentration in the oil increases untill the equilibrium state is reached. The use of a filter in the system imposes an additional problem, since it removes from the oil the large particles that are important witnesses for analysis of the wear process. This leads to reduction of sensitivity of the oil analysis methods based on measuring the concentration of the particles present in the oil.

For quantitative wear evaluation it is important to correctly determine the place and time of taking of the oil sample in order that the sample be typical for the given wear conditions. In the case of oil sampling in the process of machine operation good intermixing is ensured, but at the same time the particle concentration in the oil changes with the change of loading parameters. therefore the sample is usually taken from an accessable location that is closest to the pair being studied, after stopping the machine but soon enough that the large particles do not settle out. In addition it is necessary to ensure the possibility of separation of the metallic wear particles from the particles of other types (particles of silicon, soot, and so on). The magnetic diagnostic methods based on the action of magnetic fields on ferromagnetic particles most completely satisfy this requirements.

Summarizing the survey of the diagnostic methods, we note that they make it possible to evaluate the condition of machines and predict their wear on the basis of characteristics such as the wear particle concentration and the wear particle size distribution. On the other hand, direct observation of the wear particles yields information on the type of wear, often with the specific location of the part that is wearing. If the purpose of diagnosis is the optimization of the design parameters of the mechanism in the development stage, then it is necessary to have maximum information on the wear particles and it is convenient to use methods such as ferrography and RPD. The sample analysis methods can be also used in the large maintenance centers. The complex on-line systems are efficient for use in expensive and critical equipment.

In these cases when complete information on the wear particles is not required and it is sufficient to determine the particle formation rate, the simpler and less expensive field diagnosis methods are suitable. However, field diagnostics should be based on an appropriate data relating to tribotechnical tests, created with the use of more complex informative diagnosis methods.This information data base for each specific machinetype, oil type, and external operating conditions makes it possible to use in field diagnostics the relatively simple methods based on the determination of some one characteristic of the oil (for example, the optical density, magnetic permeability, and so on). From our point of view the most promising field diagnostic methods are the magneto-optical methods with the use of instruments combining simplicity and portability with adequate accuracy of determination of the characteristic being measured. In selection of the particular diagnostic method it is necessary to consider the design of the mechanism, its cost, the mechanism operating conditions (loading regime, degree of contamination of the oil) and the diagnostic objective.

The list of the problems requiring solution in the development of reliable diagnostic neans can be continued. However, the rapid development of the instrument base of machine diagnostics and the appearance of simple, miniature physical parameter sensors and microprocessors make it possible to hope for successful solution of these problems associated with development of the methodology of tribotechnical diagnostics come to the foreground, i.e., the problems of the development of diagnostic criteria that adequately reflect the wear mechanism with account for the great variety of processes of damage and mass transfer during friction.

## Methods of Tribological Diagnostics Developed in MPRI

I. Topography and morphology evaluation using the SEM-computer system for three-dimensional analysis of surface and wear debris/9/

The system consists of the SEM interface and IBM PC XT/AT (Fig.6). The basic principle is the use of secondary electrons image for quantitative analysis. There is a package of software realizing a number of procedures in surface topography analysis:

- surface quantative three-dimensional reconstruction (Fig 4)
- calculation of standard roughness parameters, heights and slopes

distribution( Fig 8 ).

- calculation of specific surface area( Fig 9 )
- construction of binary images and analysis of surface anisotropy (orientation of surface relief)( Fig 10, 11 )

Morphological analysis is realized as a set of programs calculating the total area, perimeters of wear debris, approximate number in the area of particle, average diameter, shape factor, and particle size distribution( Fig 12 )

Application of the system has been realized to different friction assemblies and interesting findings which have been carried out, e.g. correlation between the initial surface roughness and wear debris size distribution. Usage of various magnifications in the SEM makes it possible to evaluate some specific features of wear debris distribution related to wear mechanism.(Fig.I3 ).

All the software programs can be used in any other system of image analysis, for example in combination with optical microscope, videocamera, laser scanner, etc. There are some prospects in using this approach for combining the morphology analysis system with the diagnostic device like RPD for automatic quantitative analysis of debris sediments.

2. Acoustic emission analysis for wear evaluation.

This method is used in MPRI for monitoring the tribological behaviour of friction assembly as well as the analysis of wear as a real-time process /IO/.

Installation for measuring AE consists of piezoelectric transducers (1), amplifier (5), detector (6,8), pulse normalizer (7,9), pulse analyser (10) and recording units (Fig.I4). The frequency range of the system is 50-2000 kHz, rate of AE pulse counting $0-5\cdot IO^5$, sensitivity can be changed in wide range according to the specific conditions of testing. this system has been used for friction behaviour monitoring in metal-polymer assemblies. Rate of AE pulses formation has been found to be efficient parameter in evaluation the wear mode, dominant wear mechanism, and other parameters related with the material removal (Fig 15). Wear debris formation rate and their size were also found to be correlated with AE performances.

Some attempts have been made to create the expert systems based on the analysis of the acoustic emission data in correlation with load, velocity, temperature and friction coefficient of the friction assembly. this assembly is considered to be a dynamic probabilistic system and multi-dimensional statistical analysis has been used for evaluation of friction and wear behaviour. The basic problem in this development is the necessity of finding the correlation of wear type and dynamic performances of the assembly.

3. Opto-magnetic detector for wear debris analysis.

The principles of opto-magnetic analysis applied to lubricants contaminated by wear debris have been discussed earlier /II/. Application of non-linear magnetic field has been found to be efficient in getting information on the total contamination of lubricant, concentration of magnetic particles, part of relatively small and large particles in lubricant, etc.

A prototype of simple opto-magnetic detector hasbeen developed for using both as a field device and laboratory device (Fig.I6). Its most productive use seems to be in combination with other diagnostic techniques as ferrography, RPD and spectroscopy. This device is now being developed by the joint efforts of MPRI, KIST and Swansea Tribology Center in UK.

4. Electrical methods of friction and wear monitoring.

As it has been mentioned earlier, the electrical methods seem to be very efficient in getting information on the state of the friction contact /I0/. In the MPRI these methods are used now mostly for evaluation the effect of lubricant on the friction and wear performances. One of the systems frequently used is the scanning of the lubricated surface by the electrical probe in order to find the state of lubricant field on the surface (Fig.17). Needles made of noble metals are used as probes and the automatic computer processing of data gives the ability of quantitative evaluation of lubricant ability to wet the surface and form the film protecting the contact against wear.

Composition of surface films on the surfaces as well as heterogeneous composition of different materials can be evaluated by the same technique.

Application of electrical methods found to produce reliable data in evaluation of tribological problems occuring in electronics.

5. Tribological testing of friction assemblies, standardization and data base formation.

MPRI has become one of the main centers in USSR of tribological testing in the area of polymer and composite materials. The main attention is devoted to automation in friction and wear testing, formulation of standard procedures providing reliable test data for collecting the data base. MPRI takes part in the International Standard Organization activity for preparing testing standards in wear of polymers [12].

The Testing Center of the MPRI has ten standard testing machines combined with the computer (Fig.18). A new machine has been developed in MPRI as a basic system for making tests according to the ISO standards (Fig.19). From the point of view of production geometry of specimens is simple (Fig.20).

Collection of data on friction,coefficient, wear rate, limit load, velocities and temperatures provides information for data base. Today this data base is oriented for use with the conventional IBM PC XT/AT. The MPRI data base is created as a part of the SOVTRIBO data base system directed to join all data for design, selection of materials, information search and CAD.

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# CONCLUSIONS

ALL THE AREAS OF TRIBOLOGICAL DIAGNOSTICS ARE PROMISING FOR INDUSTRIAL APPLICATIONS. BEST PROSPECTS ARE CONSIDERED TO BE IN THE FIELD OF WEAR DEBRIS ANALYSIS AS WELL AS IN FIELD EXPRESS SYSTEMS AS IN ON-LINE MONITORING SYSTEMS.

ELECTROMAGNETIC METHODS ASSUMED TO BE MOST FLEXIBLE AND FRUITFUL BOTH IN EXPRESS AND ON-LINE APPLICATIONS.

WEAR TESTING TECHNIQUES ARE IMPORTANT AS PROVIDING DATA FOR TRIBOLOGY DATA BASES AND CAD.

FURTHER RESEARCH IS DESIRABLE IN DEVELOPMENT DIAGNOSTICAL CRITERIA ADEQUATE TO REAL WEAR PROCESS IN MACHINERY.