discriminative analysis, wear, tribodiagnostics, qualitative and quantitative parameter, complex technical state

Jiří STODOLA
University of Defence Brno, Faculty of Military Technology
Kounicova 65, 662 10, Brno, Czech Republic
Corresponding author. E-mail: jiri.stodola@unob.cz

DIAGNOSTICS OF COMBUSTION ENGINES USING WEAR AND DEGRADATION PROCESSES MODELING

Summary. The paper deals with ways of applying mathematical methods to evaluate the result of tribodiagnostics related to vehicle combustion engines. The idea is based on a discriminative analysis that makes possible to describe one qualitative parameter (complex technical state) by means of several quantitative parameters (i.e. quantity of diagnostic parameters). The results have been verified by means of considerable statistical data of T-3-930 engines made in the Czech Republic which are used in ground vehicles.

MODELOWANIE PROCESÓW ZUŻYCIA I DEGRADACJI W DIAGNOSTYCE SILNIKÓW SPALINOWYCH

Streszczenie. W artykule przedstawiono sposób wykorzystania metod statystycznych do oceny wyników badań tribodiagnostycznych silników spalinowych. Przyjęta metoda oparta jest na analizie dyskryminacyjnej, umożliwiającej opis jednego parametru jakościowego (złożonego stanu technicznego) za pomocą kilku diagnostycznych parametrów ilościowych. Wyniki badań zostały zweryfikowane na podstawie danych statystycznych silnika spalinowego T-3-930, wyprodukowanego w Republice Czeskiej, który stosowany jest w pojazdach drogowych.

1. INTRODUCTION – EVALUATION OF MACHINE SETS WEAR MODE

Generally, mechanical wear depends not only on the friction character but also on a complex physical-chemical process occurring on the sliding surfaces of a tribological unit. An external undesirable product of the friction system action is a very wide range of wear particles [1]. From the diagnostic point of view, it is important that wear particles carry nearly comprehensive information about the mutual connection among individual elements of such a system, that is, what the conditions for production of the particles in individual friction couples are. Mechanical systems are characterized by simultaneous contacts of many friction couples and, thus, also by simultaneous production of wear particles at all of these points. The problem is, on the basis of number, shape, size, or coloration of the particles, to determine what tribological processes are in progress in the machine. Wearing dynamics can be evaluated according to:

- intensity of particles production,
- material composition of particles,
- distribution of particles´ size groups,
- morphology and shape of particles´ surface features, etc.

Generally, the wear products can be categorized as follows:

Adhesive particles (rubbing wear particles Fig. 1 and Fig. 3). These are “one-dimensional” particles, whose length and width are approximately equal, to 5–15 μm, but are only 0,25–0,75 μm thick. These particles are characteristic for wear of steel components therefore they have very good magnetic characteristics. During the ferromagnetic analysis, these characteristics can practically always be recorded. Their genetic origin is in the Beilby layer, from which they gradually spell and are washed off by the lubricant. Their number and especially their size characterize the adhesive wear intensity.

Abrasive particles (cutting wear particles Fig. 4). They always characterize an improper mode of engine operation. From the tribo-technical point of view two origins of abrasive particles may be indicated:

a) Action of a heterogeneous particle between friction surfaces results in strong surface scratching, tribological mode changes, and rapid wearing of the friction surfaces. The abrasive wearing has its origin in, for example, siliceous powdery particles that leak into the engine through insufficiently tight of air filters.
b) Penetration of a harder material of the friction couple into a softer one. The probability of forming particles in this way increases when friction couples with a considerable difference in their surface hardness are contacting.

In any case, abrasive particles are of a characteristic of a “micro-cut” or of a coiled “thin wire” shape. The shape considerably differs for those abrasive particles that infiltrate into the engine after a partial or complete disassembly, that is, during running-in mode (cutting wear). They are shaped into crescents or swords with sharp protrusions on their ends. Generally, the size of abrasive particles ranges in the interval of 50-300 μm with a very short thickness of 0.25 μm.

Spherical particles (spherical debris Fig. 5). They belong to the main types of particles originating in fatigue wear of a rolling kind. Generally, they originate in consequence of Beilby layer fatigue on internal or external surfaces of bearings. The spheroids´ dimensions are relatively short ∅ 2-5 μm. In the Ferro scope lens, they appear like little black points; with better magnification, a polished surface with light reflection in the centre is evident. The presence of these particles on a ferrogram signalizes an ongoing failure of anti-friction bearings. It has been verified by experiments that one rolling element is able to produce 6-7 million of spheroids before a failure occurs.

Laminar particles (Fig. 6). Most often originate as a consequence of redistribution processes in lubricating systems. Repeated flow of oil and, therefore, also flow of particles through the system results in particles´ plastic deformation (for instance, between a rolling element and a ring path). Rolling out the spheroids and other tri-dimensional particles results in thin flat laminas of minute thickness. Their length ranges from interval 40 to 250 μm and their width from 10 to 50 μm. Particles are characterized by a plain surface and irregular edges. As a rule, the presence of these particles are attended by the presence of spheroids; in these cases, the process of a gradual failure of the anti-friction bearing has begun.

Fatigue particles (Fig. 7). They characterize the most common failure of tooth wheels. These are tri-dimensional particles with a comparable length, width, and thickness. The particles´ surface is irregular, scratched with irregular sectioned edges. Dimensions of these particles fluctuate from 10 to 150 μm. Fatigue particles can further be divided into two groups:

a) The “chunky” (micro-prism) type has an irregularly rugged surface and a size of 10-80 μm; on the surface, they usually have secondary originated inclusions.
b) The “scuffing” (high-temperature abrasion) type comes up on the teeth sides of tooth wheels during high pressure and temperature. The particles´ material is usually thermally affected, which is indicated by particles´ coloration of distemper tints.

Abnormal particles (severe wear particles). The extreme and breakdown wear particles that originate with seizing or a strong abrasion. They arise from mechanical deterioration of the Beilby layer under the action of an excessive load. In the touch-point of friction surfaces, this layer does not have the necessary loading capacity and is scratched off. The abrasion rate is so high that the Beilby layer’s restoration is impossible. During the diagnostic analysis, it is then impossible to register any adhesive abrasion particles that are replaced by tri-dimensional particles, always with a characteristic sharp edge and dimensions of 30-70 μm.

Non-ferrous particles. Their appearance may be similar to abnormal particles (severe wear particles), especially because of their shape and size. They always differ in their coloration and magnetic features. They originate as a result of contacting steel and nonferrous metals alloys during the adhesive mode of abrasion. Iron oxides-magnetite Fe_3O_4 originates under high temperatures and pressures, mainly owing to insufficient lubrication of the friction surfaces. The surface of these particles is black, plain, and of a shingle character; the size of these particles fluctuates around 5 μm. The high-temperature oxides presence relates to abrasion of the materials made of a high-strength steel or a bearing steel. Alpha-hematite Fe_2O_3 signals corrosion of the machine function surfaces by action of water. Pink or red hematite particles can be recorded by analyses of samples taken during the running-in mode of engine operation.

Corrosive and other particles. During tribodiagnostic analyses, the presence of secondary originated non-metallic particles (Fig. 8) can also be recorded, except for metallic abrasion. Dust particles – small spherical or prismatic particles-silicates with a size of up to 30 μm. They are translucent and clear. Tribopolymers – are shaped into spherical particles or tiny cylinders in the amorphous form. The tribopolymers core is always composed of submicronic steel particles. Organic substance of the particle can be dissolved with an appropriate solvent or by heating it at more than 300 °C. Fibres mainly originate from filtration materials. Cotton fibres are ribbon-like in shape; synthetic fibres are straight, with conspicuous luminous refraction on their edges.

Stated characteristics of the most important categories of particles signal the fact that there are two origins for particles indicated:

1. Primary particles – generated directly by the friction couples. They characterize directly the abrasion mode according to generally known findings.
2. Secondary particles – originate from a transformation of primary particles after repeated passage through the system. The relative rate of presence of primary and secondary particles depends on several factors, for instance, on the lubricating medium's volume, number and efficiency of oil filters in the system, efficiency of other processes of particles separation from the system, real thermal and mechanical load of the engine, number of tribological units, the type of lubricating oil used, etc.

The difference in effect of factors mentioned during evaluation of individual engines requires separate monitoring of each type and design type of the combustion engine.

For evaluation of the wear mode of machine groups (engines, gearboxes, etc.), in practice, two basic strategic approaches are used:

1. Trend evaluation of the wear mode using time series.
2. Multidimensional statistic monitoring and its evaluation.

Specific features characterize both of these approaches, and it is impossible to consider one as absolute and exclude the other one.

2. TREND EVALUATION OF THE WEAR MODE

During normal engine operation, a balanced concentration of the wear products develops in the lubricating medium. This means that the concentration speed of various origin wear products equalizes with the speed of mechanisms removing the wear products from the lubricating medium. Removal of these wear products is carried out mainly by filtration and sedimentation, followed by loss of oil from the system and chemical reactions. Owing to the complexity of the problems related to reactive kinematics of organic ingredients contained in the lubricant and generated here as a consequence of chemical reactions for the duration of lubricant exploitation, it is impossible to obtain the data needed for reactive kinematics calculation [2]. The balance equation expressing the substances balance between inflow of wear products from the friction points of the system into the lubricant and their decrease owing to the action of individual decreasing mechanisms can be derived from a deterministic model (Fig. 9). The basic differential equation expressing the dynamic balance in the model under consideration is:

$$V.c + m.dt - c.f.p.dt - c.Q.dt = (c + dc).(V - Q.dt) \tag{1}$$

where:
V – oil volume in the lubricating system (dm^3); c – concentration of wear products in lubricant medium at the time t (mg/dm^3); f – total coefficient of wear products decrease (mg/s); p – oil quantity delivered to the engine friction points (dm^3/s); Q – oil loss volume (dm^3/s).

The instantaneous volume of lubricant V varies during the time as a result of loss of lubricant in the system (caused by leakages, burning, etc.) according to the relationship:

$$V = V_0 - Q.t \tag{2}$$

where:
V_o – initial lubricant volume at the beginning of the given time period.

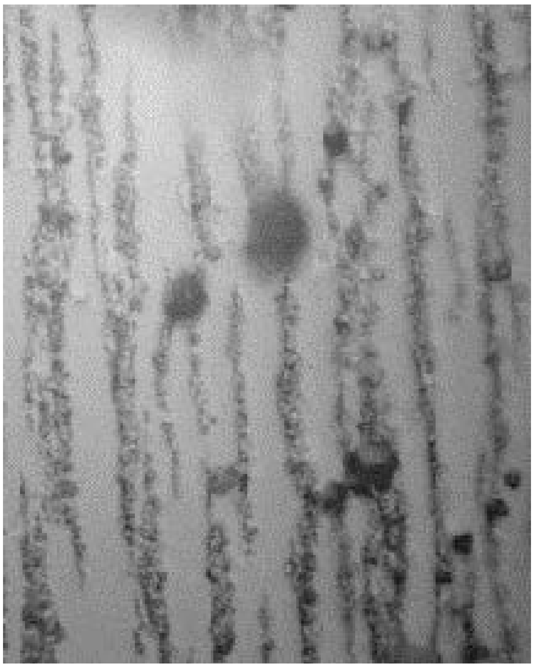

Fig. 1. Rings of sub-micro-sized ferromagnetic scraping from diesel engine. Rubbing wear, good condition of engine. Magnified 100x
Rys. 1. Pierścienie ferromagnetycznego złomu rozmiaru submikrona z silnika diesla. Ślady zużycia w postaci wytarcia, dobry stan silnika. Powiększenie 100x

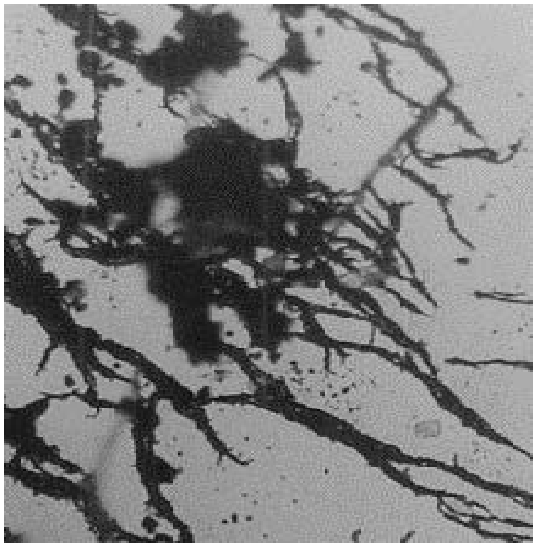

Fig. 2. Rings of para-magnetic particles (Pb-Sn composition of bearing metal) oil from car spark-ignition engine. Strong rubbing wear. Magnified 100x
Rys. 2. Pierścienie para-magnetycznych cząstek (kombinacja Ph-Sn w metalu nośnym), olej z samochodowego zapłonu iskrowego silnika. Silne zużycie w postaci wytarcia. Powiększenie 100x

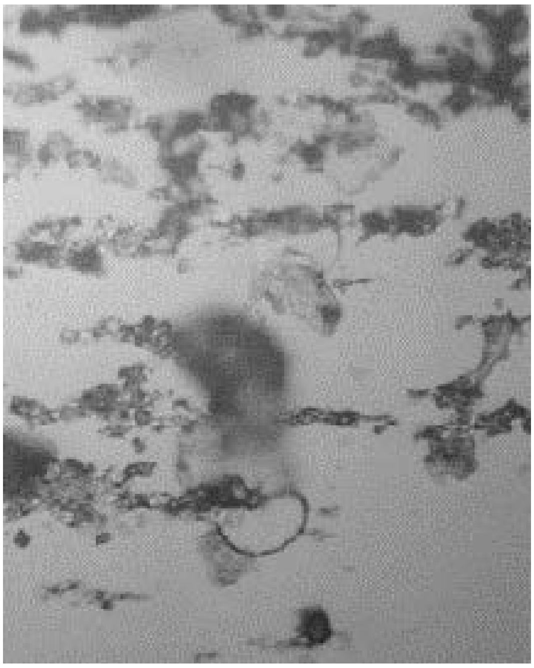

Fig. 3. Very long and slim wire-shaped particles can appear on the ferrograms during the device running-in by adhesion and light abrasion wear. Magnified 1000x

Rys. 3. Bardzo długie i wąskie cząstki w kształcie przewodu/drutu mogą się pojawić na ferrogramach podczas działania urządzenia przez przywieranie oraz zużycie w postaci ścierania. Powiększenie 1000x

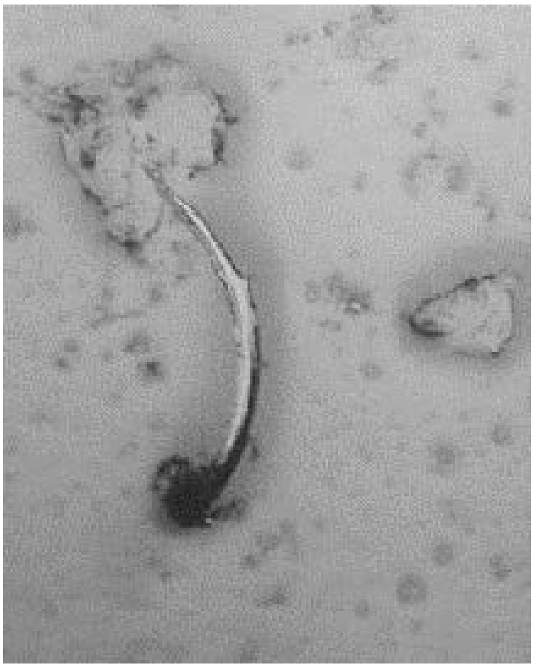

Fig. 4. Strong cutting wear steel particle, so-called two-point abrasion. Harder member of the friction pair penetrates into softer member of friction pair and separates chips from it. Magnified 1000x

Rys. 4. Silne zużycie w postaci cięcia/skrawania danej części stalowej, tak zwane dwupunktowe ścieranie. Twardszy element z pary ciernej penetruje miększy element pary ciernej i oddziela od niego wióry. Powiększenie 1000x

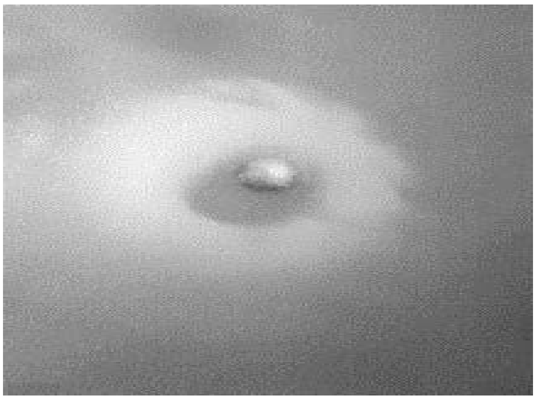

Fig. 5. Ferrogram from oil diesel engine. Spheroid always indicates the development of fatigue crack. Magnified 1000x

Rys. 5. Ferrogram z oleju silnika diesel. Sferoida zawsze wskazuje na rozwój pęknięcia zmęczeniowego. Powiększenie 1000x

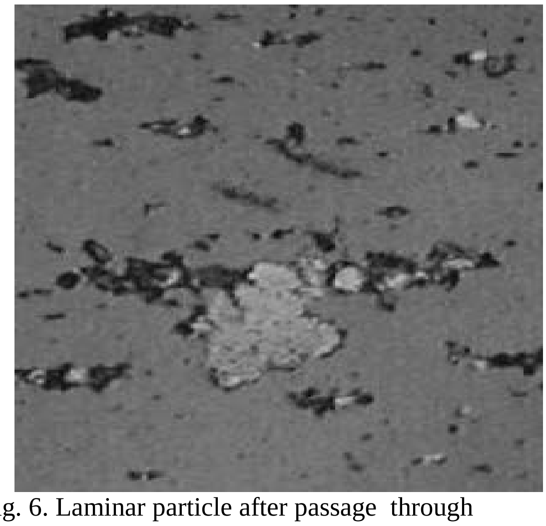

Fig. 6. Laminar particle after passage through the rolling contact. Typical is pitted surface and tracks of micro-inclusions during rolling of particle in the rolling contact. Magnification 1000x

Rys. 6. Uwarstwiony element po przejściu przez łożysko toczne. Typowa jest pełna wżerów powierzchnia ze śladami mikro inkluzji podczas walcowania części w kontakcie z łożyskiem tocznym. Powiększenie 1000x

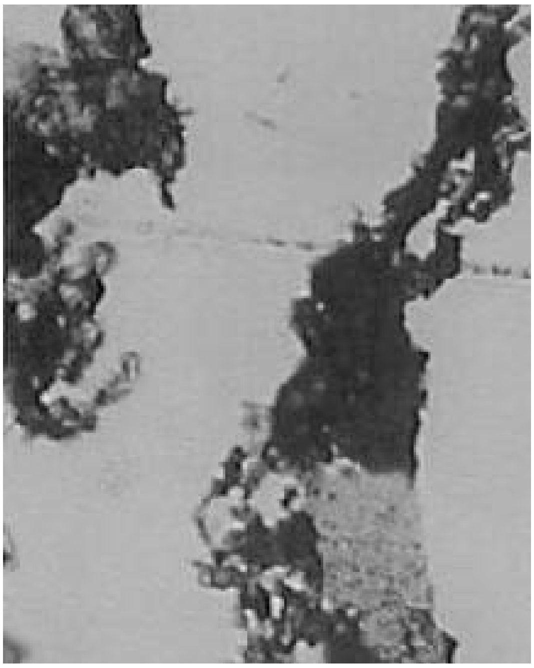

Fig. 7. Particles of ultimate wear, they have potting on the surface caused by repeated passage of zone of rolling contact, and they are produced at the end of fatigue wear. Magnification 500x

Rys. 7. Cząstki ostatecznego zużycia, mają one plamy na powierzchni spowodowane powtarzającym się przechodzeniem strefy łożyska tocznego, tworzą się na koniec zużycia zmęczeniowego. Powiększenie 500x

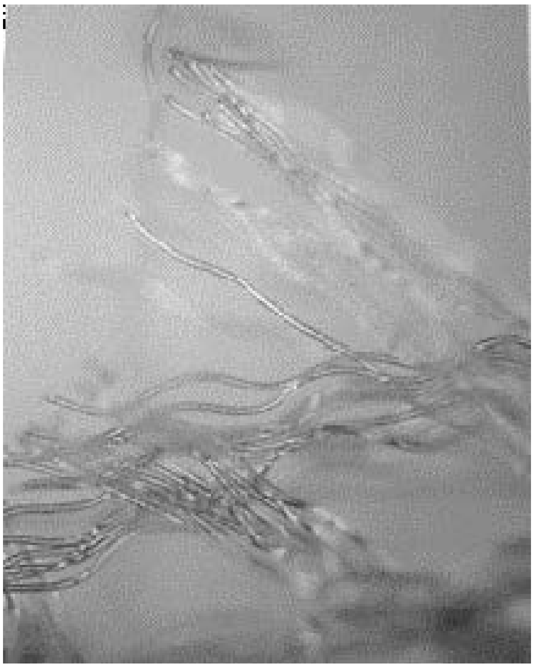

Fig. 8. Polyester (synthetic) fibres from some filtering elements. Magnification 100x

Rys. 8. Syntetyczne poliestrowe włókna z pewnych elementów filtrujących. Powiększenie 100x

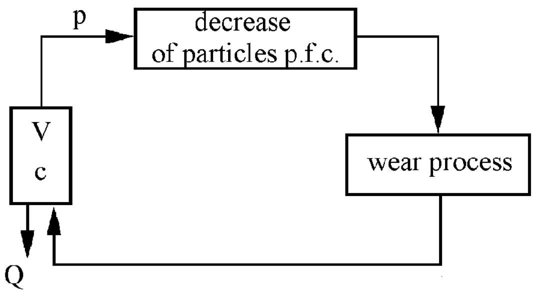

Fig. 9. Diagram showing the process of production and decrease of wear products in the lubricating system of a combustion engine

Rys. 9. Diagram ukazujący proces produkcji i zmniejszenie zużycia produktów w systemie smarowania silnika spalinowego

The general expression for this change is usually stated in linear dependence on the time *t*:

$$m = m_0 - a.t \tag{3}$$

where:

m_o - initial speed at the beginning of the time period, *a* - acceleration.

To enable the solution of the equation and to determine the resulting relationship for calculation of the speed of wear products generation, the following simplifications are recommended:

- in the given time period between two sequential sampling values, the *m* and *Q* are considered to be constant,
- the value of the coefficient *f* is estimated on the basis of oil filters´ pervious action and the speed of wear products´ sedimentation.

In the case of products of oil degradation reactions, the loss coefficient is not considered because as K matter is to determine the concentration of relevant substances dissolved in the lubricant [3]. After substitution for V according to the relationship (2), modification and dereliction of the expression of the second order (i.e. Q*dc*dt*), the equation transforms to the form:

$$(m - c.f.p).dt = (V_0 - Q.t).dc \tag{4}$$

which can be further modified as:

$$\frac{dt}{V_0 - Q.t} = \frac{dc}{m - c.f.p} \tag{5}$$

After integration in the limits c1 to c2 for c, t1 to t2 for t and after the final modification, we will get the final relationship for the mean speed of wear products generation:

$$m = \frac{\left(c_2 - c_1.e^A\right)}{1 - e^A}.f.p \tag{6}$$

$$A = \frac{f.p}{Q}.\ln\frac{\left(V_0 - Q.t_2\right)}{\left(V_0 - Q.t_1\right)} \tag{7}$$

However, during operation of real combustion engine vehicles, the lubricating medium is continuously refilled, and thus the calculation of m is correspondingly more complicated [4]. After each oil refilling by the volume V‘ to the original volume V0, the original concentration of wear products c changes to c‘:

$$c' = \frac{c.V}{V + V'} \tag{8}$$

During the number of n constant time cycles and the number of a refilling with a constant volume of oil to the V0 and on all of the premises mentioned above, the main speed of wear products generation can be calculated according to the relationship

$$m = \frac{\left(c_n - c_1.B^{2n-1}.e^A\right)^n.\left(1 - B.e^A\right).f.p}{\left(1 - e^A\right).\left(1 - B^2.e^A\right)} \tag{9}$$

where:

$$B = \frac{V_0 - V'}{V_0} = \frac{V_0 - Q.t}{V_0} \tag{10}$$

However, the stated theoretic calculations must be applied to conditions of factual operation of vehicles with combustion engines. To deduce appropriate conclusions and to describe long-term trends of monitored indices developments, it is necessary to determine their trend, that is, to replace the progression of empirical values with a progression of values without a random fluctuation and, thus, to equalize interval time series using a suitable method. For equalizing time series, an analytic equalizing is frequently used in technical routines [5]. This equalizing consists of describing the course of given time series by a simple theoretic and analytic function of the type *y = f(t,b)* where *t* is a time variable and *b* represents a vector of unknown parameters. In principle, this is a simple regression where the time series index features a dependent variable and time (time variable) an independent variable. To determine the “best” values of parameters, the minimum of sum of deviations (residua) squares of the measured and calculated magnitudes of a dependent variable is used as a regress criterion in technical routines most often.

$$U = \sum \left(y_i - Y_i \right)^2 = \min \tag{11}$$

where the function U is called the objective function, which is minimized during the calculation of parameters.

As the whole progression of nonlinear dependences can be transformed using an appropriate transformation to a linear dependence, the linear regression method is used most often:

$$y = \left(b_1 \pm s_{b1} \right) + \left(b_2 \pm s_{b2} \right).t \tag{12}$$

Coefficients of the regression linear equation will be determined providing that partial derivations of the objective function U must be zero; then, by solving them, the estimations will be obtained:

$$b_1 = \frac{\left(\sum y_i - b_2.\sum t_i \right)}{n} \tag{13}$$

$$b_2 = \frac{\sum t_i.\sum y_i - n.\sum t_i.y_i}{\left(\sum t_i \right)^2 - n.\sum t_i^2} \tag{14}$$

The trend value, as a criterion for serviceable condition of the engine and its lubricant medium, respectively the upper or lower limit of the interval of gradient of regression line reliability can be then considered:

$$L = b_2 \pm s_{b2}.t_\alpha \tag{15}$$

and parameters of the line:

$$s_{b2} = \frac{s_{y,t}.n}{\sum t_i^2 - \left(\sum t_i \right)^2} \tag{16}$$

$$s_{y,t} = \sqrt{\frac{U}{n-2}} \tag{17}$$

where:
s_{b2} – standard deviation of the coefficient, b_2, t_α – critical value of the “Student division” for selected level of importance, $s_{y,t}$ – standard deviation characterizing scattering of outcomes along the given regression line.

3. MULTI–DIMENSIONAL STATISTICAL EVALUATION

Modelling of stochastic magnitudes characterizing a real condition of equipment is an important element in tribotechnical diagnostics application [6]. Besides the trend approach, the probability model can also be used. Such a model enables us to define one qualitative variable u by means of several quantifiable parameters X_1, X_2, X_i…X_p. The primary set, as well as the informative selection which represent the primary set, are subsequently resolved into several groups (generally “k”). Individual groups have to correspond to variants of the variable “u”. A priori probability of belonging to groups is:

$$\pi_h \approx P\left(A_h \right),\ h = 1,2,\ldots,k \tag{18}$$

where:
π_h – probability of belonging to the group of number h; $P(A_h)$ – probability of the event A_h phenomenon.

It can be estimated according to the informative selection structure

$$\pi_h = \frac{n_h}{n} \tag{19}$$

where:
n_h – the number of elements in the h^{th} group; n – the number of selection elements.

After carrying out multidimensional observations "x" a-posteriori probability can be determined using the Bayes formula

$$P\left(A_h / x\right) = \frac{\pi_h .\, f_h(x)}{\sum_{h=1}^{k} \pi_h .\, f_h(x)} \tag{20}$$

where:
$P(A_h/x)$ – conditional probability of the phenomenon; A_h/x, $f_h(x)$ – conditional density of probability of the complex of "p" considered variables for h = 1, 2, .., m.; f'_h – vector of coefficients in the h^{th} group; x_i – vector of measured values.

To categorize unknown elements, it is necessary to provide for a decision-making rule for their classification within individual groups. The selection area is divided into "k" not-overlapping classification areas. Each element is categorized into such a group where the a-posteriori probability will be maximal, and, simultaneously, the incorrect classification probability will be minimized [7]. The total probability of incorrect classification can be described by the equation

$$\omega = \sum_{h=1}^{k} \pi_h \sum_{h' \neq h}^{k} P\left(\frac{x \in \varphi_{h'}}{A_h}\right) = \sum_{h=1}^{k} \pi_h \sum_{h' \neq h_{\varphi h}}^{k} \int f_{h'}(x).dx \tag{21}$$

where:
ω – total probability of incorrect classification, φ_h – area into which the object is incorrectly classified.

For objects classification, it is sufficient to search for the group where the numerator in the Bayes formula (20) is maximal, because the denominator is common for all groups:

$$\psi_h = \pi_h . h_h(x) \tag{22}$$

By expressing the probability of multidimensional normal classification by logarithmic calculation and omission of the addends, which are common for all of the groups, we obtain a quadratic discriminative score:

$$\psi_h^{(Q)} = x^{`} . \varphi_h . x + v_h . x + \rho_h \tag{23}$$

with a matrix of quadratic form:

$$\varphi_h = \frac{1}{2} \cdot \sum_h^{-1} \tag{24}$$

a vector of linear coefficients:

$$v_h = \mu_h . \sum_h \tag{25}$$

and a constant:

$$\rho_h = 1n\pi_h - \frac{1}{2}1n\left|\sum\nolimits_h\right| - \frac{1}{2}\mu_h.\sum\nolimits_h^{-1}.\mu_h \tag{26}$$

where:
$\Psi_h^{(Q)}$– quadratic discriminative score; x' – line vector of values; x - column vector of values, φ_h – quadratic form matrix in group h; Σ_h^{-1} - inverse matrix to covariant matrix in group h; v_h – vector of linear coefficients in group h; μ_h – vector of mean values in group h; ρ_h – quadratic discriminative constant of the group h; π_h – a posteriori probability of belonging to the group h; $|\Sigma_h|$ – determinant of covariant matrix of the group h; $\sum_h$ – covariance matrix of the h^{th} group.

If another condition of covariant matrices correspondence is observed, discrimination can be performed by means of a linear discriminative score:

$$\psi_h^{(L)} = \alpha_h.x + k_h \tag{27}$$

with a vector of coefficients:

$$\alpha_h = \mu_h.\sum\nolimits^{-1} \tag{28}$$

and a constant:

$$K_h = 1n\pi_h - \frac{1}{2}.\alpha_h.\mu_h \tag{29}$$

where:
$\psi_h^{(L)}$ – linear discriminative score in the h^{th} group; α_h – vector of coefficients in group h, K_h – linear discriminative constant (constant of the h^{th} group); ^ – over π_h it indicates the choice probability of belonging to the h^{th} group; $\overline{\mu}_h$ – vector of mean values in the h^{th} group.

The discrimination efficiency can be verified by means of re-substitution that is application of discriminative classification on a selective set and percentual expression of incorrectly classified objects.

4. RESULTS AND DISCUSION

The above methodology of evaluating multidimensional diagnostic signals has been applied to objective evaluation of results obtained by means of ferrographic analysis. Four basic groups of engines were indicated, as follows [8]:

1. Current wear **–** this group involves all the states characterized by absence of increased quantity of inadmissible particles.
2. Limit wear **–** this group is characterized by the presence of particles of an inadmissible type. Such an engine needs intensive examination.
3. Critical wear **–** this group involves an engine threatened by a serious defect of some part within the engine. Further operation of such an engine should not be allowed with respect to technical and/or economical viewpoints.
4. Running**–**In mode **–** this group is characterized by the phase presence of particles typical for this and inadmissible in other phases of the engine operation.

It was proven during engine operation that the above fully meets the demands on an operational diagnostic system. There are also conditions (28) to establish a flexible specification of operational norms for particular types of engines and their modifications.

All the modes of wear are modelled, according to the number of types of particles present in oil samples. It is known in advance what kind of engine they come from. The results are compared by considering the number of particle types in a 1 ml oil sample, used for preparation of the ferrogram. During analysis of the ferrogram, nine particle types were detected:
1–Cutting wear particles, 2–Laminar particles, 3–Fatigue particles, 4–Spherical debris, 5–Severe wear particles, 6–Corrosive particles, 7–Oxide particles, 8–Non-ferrous metallic particles, 9–Others.

For every particular group, the mean values of the number of particle types were determined and numbered as shown in Table 1. Using these mean values in compliance with Eq. (27) a parameter can be formed called the complex ferrographic parameter *F*. The parameter makes possible to describe the dependence of a latent implicit parameter of the current state of the engine wear by means of vector of measured values, i.e., number of particular types of particles Eq. (29).

Based on results of the selective set, the complex parameter can be written in the form:

$$F_h = f_h'.\, x_i - K_h \tag{30}$$

where:
F_h – values of the parameter F in the h^{th} group.

The vector of coefficients is an element, which involves internal coupling of selective statistical sampling. It is based on the relation:

$$f_h' = x_h.\, V^{-1} \tag{31}$$

where:
V^{1} – inverse of covariation matrix of the selective set.

The constant in Eq. (30) involves first of all the demands on vector ranging in accordance with a reselected criterion, i.e.

$$K_h = 1n\pi_h - \frac{1}{2}\, f_h - x_h. \tag{32}$$

In the above procedure, Eqs. (30) – (32), a selective set of oil samples has been worked out. For predesigned groups there were particular parameters numbered as shown in Table 2. Any unknown vector of measured values can be assigned to one of the indicated groups. This means it will be placed in the group of maximum parametric value.

Applying the ranging criterion to the original selective set, the quality of the assigning method and the quality of the description of particular indicated groups of engines can be evaluated. From the total number of samples (106) involved in the selective set, 98 samples were evaluated correctly, i.e., full compliance with the actual state of the engine, known before. Standard deviation of determination of the technical state of the engine is about 7,6 %. The standard deviation of each particular group is given in Table 3. Higher values of the relative standard deviation in the IVth group (running-in mode) are closely connected with poor knowledge of the course of tribological phenomena during running in of engine T3-930. To decrease this value it is necessary to consider a larger statistical set formed to describe all the indicated groups with the same validity. The above method of evaluating ferrographic analysis is suitable for a large number of ferrography users. It is rather difficult to count particular types of particles, but the counting is defined precisely and the results obtained are unambiguous. Once the ferroscopic evaluation of the ferrogram has been mastered, there is no other difficulty in using the above method. The group characteristics specified is valid for the T3 – 930 engines [9]. When dealing with an engine of another type, it is necessary to verify the validity by further research. An important factor to note is that the decisive feature for assigning an element to a certain group is not the value of the parameter *F*, but the maximum value of the parameter. This is the difference in application of discriminative analysis in comparison with applications published in the open literature [3] etc.

Table 1

Vectors of Mean Values in Particular Groups

Type of Particle Code	Mean Values of Number of Particles in Groups			
	Current I	Limit II	Critical III	Running–In IV
	pcs/ml	pcs/ml	pcs/ml	pcs/ml
1	1.560	4.539	6.979	5.426
2	1.501	3.934	6.548	0.917
3	0.737	3.207	6.827	1.170
4	1.208	3.238	5.110	0.629
5	0.486	2.543	5.117	1.046
6	0.971	2.508	4.102	2.510
7	0.489	2.533	5.681	0.719
8	1.809	4.005	5.636	0.464
9	0.789	2.649	5.100	1.874

Table 2

Ferrographic Characteristic of Groups

Vectors of Coefficients $f_{i,h}$ and Constants of Groups K_h				
Group Parameter	Current	Limit	Critical	Running–In
1	0.718	1.350	0.632	2.067
2	0.609	0.771	0.600	0.031
3	–0.839	1.236	–0.206	–1.175
4	0.703	1.179	0.644	–0.172
5	–0.787	–0.489	–0.501	–0.416
6	0.405	0.352	0.598	1.395
7	–1.175	–1.703	–0.553	–1.738
8	1.171	1.715	0.900	0.370
9	0.029	–0.135	0.459	0.876
K_h	1.921	5.425	7.195	6.696

Table 3

Standard Deviation of Groups

GROUPS	I	II	III	IV
S_d (%)	6.35	8.33	8.33	14.30

5. CONCLUSION

The considerably simplified model presented here enables applications of multidimensional classification of particular ferrographic (or other) oil analyses and shows the utilization possibilities of this method for interpretation of tribodiagnostic check-up results. However, the practical exploitation depends on particular tasks to be solved. The trend evaluation performs a methodical function during evaluation of tribodiagnostic measuring results. But interpretation of results still depends on the qualifications of the expert who can judge individual changes, their size, and deviations from normal state. These facts somewhat complicate putting tribodiagnostics into practice, because reliable results depend on the qualifications and experience of the expert.

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