International Journal of Engineering & Technology, 7 (4.3) (2018) 25-29

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

The Quality of the Tribosystem as a Factor of Wear Resistance

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Abstract

The purpose of this work was to develop a criterion for estimating the quality factor of the tribosystem and to assess its effect on wear rate, friction coefficient and run-in time. The basis of the methodological approach when developing a criterion for the quality of the tribosystem is the parameters that take into account the construction of the tribosystem, the thermal diffusivity of materials and the loading conditions of the tribosystems.

The definition of the quality of the tribosystem has been further developed, which, unlike the known one, takes into account the geometric dimensions and kinematic scheme of the tribosystem, the thermal diffusivity of materials and the rate of propagation of deformation in the surface layers of the triboelement materials during their contact interaction. Theoretical and experimental studies established the relationship between the quality value, wear rate and the friction coefficient in the process of running-in. It is shown that the increase in quality helps to reduce the above-mentioned parameters.

The relationship between the running-in time and the quality value is established. It is shown that the process of running-in can be controlled. To reduce the running-in time, it is necessary to reduce the sliding speed during the transient process and to increase the tribological properties of the lubricating medium. The presented theoretical and experimental studies allow us to state that the quality of tribosystems Q can be a measure of the potential ability of the tribosystem to adapt (adapt) to operating conditions, providing the maximum resource.

***Keywords**: frictional force; material compatibility; modelling; the quality of the tribosystem; the criterion for the quality factor of the tribosystem; tribosystem; wear rate.*

1. Introduction

The concept of the coefficient of soundness of the tribosystem was introduced by the authors of [1] and defined as the ability of the mating materials in the tribosystem (the lubricating medium and the rheological properties of the structure of the materials of mobile and immobile triboelements) to transform the work of friction forces into thermal energy, thereby impeding energy reserves in surface and subsurface layers of triboelements, which can be estimated by a deformable volume.

The concept of the soundness of the tribosystem (quality of the tribosystem) complements the concept of material compatibility in the tribosystem, which refers to the ability of the contacting materials to adjust both to each other and to the changing conditions of friction, taking into account the interaction of materials with the lubricant medium and the environment, ensuring target durability and stable operation in the whole range of operation.

To predict the wear resistance of tribosystems, as well as to calculate the rate of wear and friction losses, a quantitative parameter for quality assessment of the tribosystem is required, which is a multi-parameter function of the processes occurring in the surface and subsurface layers of materials and depends on the nature of the applied load.

2. Analysis of Recent Studies and Publications

Works refer to the problem of material compatibility [2-4]. In these works, the concept of material compatibility is defined, which is the ability of the contacting materials to adjust both to each other and to the changing conditions of friction, taking into account the interaction of materials with the lubricant medium and the environment, ensuring target durability of the tribosystem and its stable operation either without lubrication or when the integrity of the lubricant is violated.

Since friction is a changeable and dissipative process, internal friction can be used as a quantitative characteristic of the relaxation properties of surface layers of materials [5, 6]. Internal friction characterizes the ability of the material structure to dissipate the oscillation energy associated with density, concentration and mobility of dislocation and point defects.

In [7] it is shown that relaxation processes have higher structural sensitivity to the change of the stress-strain state of the material under non-static loading vs. the physicomechanical properties.

The conducted analysis suggests that the relaxation properties of the structure of materials, which the tribosystem is made of, affect the material compatibility and are a function of wear-resistance and during running-in ability which is proved in [8].

The authors of [1] introduce a parameter for quantitative evaluation of quality of the tribosystem:

$$Q = E_y \sqrt{\frac{\delta_{п} \cdot \delta_{н}}{\pi}}\text{, J/m}^3, \qquad (1)$$

where E_y – tribological properties of the lubricant medium, J/m^3, defined in accordance with [1];

$\delta_{п}$ and $\delta_{н}$ – ultrasound subsidence ratio in the structure of materials of both movable and fixed triboelements, non-dimensional value, are defined in accordance with [1].

According to formula (1), coefficient of quality of the tribosystem is a dimensional value which takes into account tribological properties of the lubricant medium (presence of surface active agents and chemically active substances in the lubricant medium), as well as internal friction of the structure of materials of both movable and fixed triboelements. However, formula (1) does not take into account the geometric dimensions (structure) of the tribosystem, thermal diffusivity of materials of the triboelements and the loading conditions.

Analysis of the presented material allows concluding that the development of a criterion that would more take into account all the above factors, is an relevant task.

3. The Basic Part of the Study

3.1. Purpose of the Study

Development of a criterion to evaluate soundness (quality) of the tribosystem) and assess its effect on the wear rate, friction coefficient and the running-in time.

3.2. Methodoloical Approach in Conducting the Study

The methodoloical approach for complementation of the quality criteria for a tribosystem is based on using the parameters which take into account the design of the tribosystem, thermal diffusivity of its materials and loading conditions.

The parameter which takes into account geometrical dimensions of the tribosystem, shape factor K_f, according to [9] is calculated using the formula:

$$K_f = \frac{F_{\min}}{V_n + \frac{V_\text{н} \cdot F_{\max}}{F_{\min}}}, \frac{1}{m}, \tag{2}$$

where F_{min} – friction area of a fixed triboelement, m^2;

V_n – volume of the material under the friction area of a movable triboelement, m^3;

$V_\text{н}$ – volume of the material under the friction area of a fixed triboelement, m^3;

F_{max} – friction area of a movable triboelement, m^2.

Relevant parameters also include thermal diffusivity coefficient of the materials of the triboelements a, m^2/s and deformation rate in these materials $\acute{\varepsilon}$, 1/s.

Since the performance of the tribosystem involves a movable and a fixed triboelement simultaneously, we used the reduced values.

The reduced thermal diffusivity coefficient of the materials of the tribosystem is defined using the expression:

$$a_{np} = \frac{2a_n \cdot a_\text{н}}{a_n + a_\text{н}}, m^2/s, \tag{3}$$

where a_n and $a_\text{н}$ – thermal diffusivity coefficients of the materials of the movable and fixed triboelements, reference value, m^2/s.

The reduced deformation rate in the subsurface layer of the materials of the tribosystem, which depends on the loading conditions, is defined using the expression:

$$\dot{\varepsilon}_{np} = \frac{2\dot{\varepsilon}_n \cdot \dot{\varepsilon}_\text{н}}{\dot{\varepsilon}_n + \dot{\varepsilon}_\text{н}}, 1/s, \tag{4}$$

,

where $\acute{\varepsilon}_n$ and $\acute{\varepsilon}_\text{н}$ – deformation rate of the material of the fixed and the movable triboelement s, 1/s.

According to [10]:

$$\dot{\varepsilon}_n = 75(1+\mu_n)(0{,}86-1{,}05\mu_n)\frac{\sigma_{TCA} \cdot v}{E_n \cdot d_{TCA}}, \tag{5}$$

$$\dot{\varepsilon}_\text{н} = 75(1+\mu_\text{н})(0{,}86-1{,}05\mu_\text{н})\frac{\sigma_{TCA} \cdot v}{E_\text{н} \cdot d_{TCA}}, \tag{6}$$

where μ_n and $\mu_\text{н}$ – Poisson ratios of the materials of the movable and fixed triboelements, reference value;

σ_{TCA} – stress on the actual contact patch, Pa;

v – sliding speed, m/s;

E_n and $E_\text{н}$ modulus of elasticity of the materials of the movable and fixed triboelements, reference value, Pa;

d_{TCA} – diameter of the actual contact patch, m^2.

When characteristics of the true contact area (TCA) and stresses on the actual contact patch are simulated, the following parameters are determined successively.

Mean absolute error of the surface profile points of the movable *Ran* and fixed *Raн* triboelements (equivalent roughness parameters [10]):

$$Ra = \sqrt{R^2 an + R^2 a\text{н}}, \text{ m}, \tag{7}$$

Mean roughness width on the surface mean line of the movable *Smn* and fixed *Smн* triboelements (equivalent roughness parameters [10]):

:

$$Sm = \frac{Ra}{\sqrt{\left(\frac{Ran}{Smn}\right)^2 + \left(\frac{Ra\text{н}}{Sm\text{н}}\right)^2}}, \text{ m}. \tag{8}$$

The measuring unit used for calculations in formulas (7) and (8) is *m*.

Surface gradient is defined according to [10]:

$$q = \pi^2 \frac{Ra}{Sm}. \tag{9}$$

The reduced Young's modulus of the contacting materials is defined using the expression [10]:

$$\frac{1}{E} = \frac{1-\mu_n^2}{E_n} + \frac{1-\mu_\text{н}^2}{E_\text{н}}. \tag{10}$$

The set of conditions of the surface contact according to [10] is defined using the expression:

$$K = \frac{2{,}22\sigma_n}{Eq}, \tag{11}$$

where σ_n – rated stress which is equal to the ratio of load N, N, to lesser nominal area of the friction surface, F_{min}, m^2, dimension unit Pa.

Relative true contact area, according to [10]:

$$\eta = 1 - \exp(-K). \tag{12}$$

True stress in the contact area [10]:

$$\sigma_{TCA} = \frac{\sigma_n}{\eta}, \text{ Pa} \tag{13}$$

The deformation level of the material is defined according to [10]:

$$h = \begin{cases} 3{,}95\ln\left(5{,}25 - \ln K\right) - 6{,}982, & \text{K} \leq 0{,}6827 \\ \dfrac{0{,}422}{\ln K + 1} - 0{,}845, & \text{K} > 0{,}6827. \end{cases} \quad (14)$$

Density of contact patches is defined according to [10]:

$$d_c = \frac{1}{S_m^2}\left(\frac{\pi}{2}\right)^{\frac{1}{2}} \cdot \exp^{-\left(\frac{h^2}{2}\right)}\left(\sqrt{h^2 + 0{,}4} + h\right), \ \frac{1}{m^2} \cdot \quad (15)$$

Mean area of an individual contact patch is defined according to [10]:

$$A_c = \frac{\eta}{d_c}, \ \text{m}^2. \quad (16)$$

Mean diameter of an individual TCA is defined according to formula:

$$d_{TCA} = \sqrt{\frac{4A_c}{\pi}}, \ \text{m}. \quad (17)$$

Tribological properties of the lubricant medium, according to the above works, can be taken into account using the parameter E_y, J/m^3 - specific work of wearing of a volume unit of the tested material (ShH15 steel balls) on the tested lubricant medium. Physical content of this parameter follows from expression:

$$E_y = E_1 + E_2 + E_3 = \frac{f_1 P_1 L_1}{D_u^3} + \sum_{i=196}^{P_к} \frac{f_i P_i L_2}{D_i^3} + \sum_{j=P_к}^{P_{c-1}} \frac{f_j P_j L_2}{D_j^3}, \quad (18)$$

where E_1 - value of specific work of wearing, which characterizes the presence of anti-wear properties in the lubricant, J/m^3;
E_2- value of specific work of wearing, which characterizes the performance range of extreme pressure additives, J/m^3;
E_3- value of specific work of wearing, which characterized the presence of extreme pressure additives in the lubricant and their performance range, J/m^3;
f_1- friction coefficient under load P_1= 196 N;
P_1– load of 196 N to determine the wear factor on the four-ball friction and wear machines, GOST 9490-75;
L_1– sliding distance when the wear factor is determined, 2,119 m;
D_u– mean diameter of wearing patches of three lower balls when the wear factor is determined, m;
$\sum\limits_{i=196}^{P_к}$ - total number of tests from the load of 196 N to the critical load, according to the first load range as specified in GOST 9490;
f_i- value of the friction coefficient under loads from 196 N to P_K;
P_i– load according to the first load range from 196 N to P_K, N;
L_2– sliding distance at the test time 10 sec, 5.88 m;
D_i– mean diameter of wearing patches of three lower balls under loads from 196 N to P_K, m;
$\sum\limits_{j=P_к}^{P_{c-1}}$ - total number of tests from P_K to the load preceding the weld load P_{C-1};
fj– value of the friction coefficient under loads from P_K to P_{C-1};
Dj– mean diameter of wearing patches of three lower balls under loads from P_K to P_{C-1}, m.

The finding have been obtained experimentally, on the four-ball friction and wear machines, which were used to calculate E_1, E_2, E_3 values, which are included into formula (18).

Table 1: Tribological properties of engine oils

Engine oil type	API class	$E_1 \cdot 10^{14}$, J/m^3	$E_2 \cdot 10^{14}$, J/m^3	$E_3 \cdot 10^{14}$, J/m^3
M-10G$_{2к}$	CC	2.73	0.47	0.009
Schell-Rotella X	CC	2.73	0.82	0.094
ESSO ULTRA	SL/CD	3.89	0.99	0.012
M-10DM	CD	5.82	0.9	0.11
Schell-Rimula D	CF/CD	5.82	0.908	0.104
ESSO ULTRON	SL/CF	5.82	0.950	0.095
Schell-Rimula C	CD	5.82	0.96	0.090
Schell-Rimula X	CF-4	7.62	0.85	0.014
ESSO ULTRA Turbo Diesel	CF-4	8.39	1.005	0.016

In view of the above complementation, the quality of the tribosystem can be estimated by expression:

$$Q = \frac{K_f^2 \cdot a_{np} \cdot E_y}{\dot{\varepsilon}_{np}} \cdot \sqrt{\frac{\delta_n \cdot \delta_{н}}{\pi}}, J/m^3, \quad (19)$$

The above expression of the quality of the tribosystem, unlike the known one (1), takes into account:
– geometrical dimensions of the tribosystem which affect the running-in time;
– thermal diffusivity of the materials of triboelements which affects the thermal stress levels in the subsurface layers;
– rate of propagation of deformation in the surface layers of the materials of triboelements, which takes into account the loading conditions.
The above differences have an effect on the running-in time of the tribosystem, and consequently on the course of transient processes in tribosystems.

3.3. Results of the Study

Dependence of the change of the quality value on the changes of the shape coefficient of the tribosystem $K_ф$, rheological properties of the structure of interfaced materials $\delta_н \cdot \delta_п$ their thermal diffusivity a_{np} and tribological properties of the lubricating medium E_y, are shown in Fig. 1. These are parameters the increase of which affects in direct ratio the quality value, except for the shape coefficient.

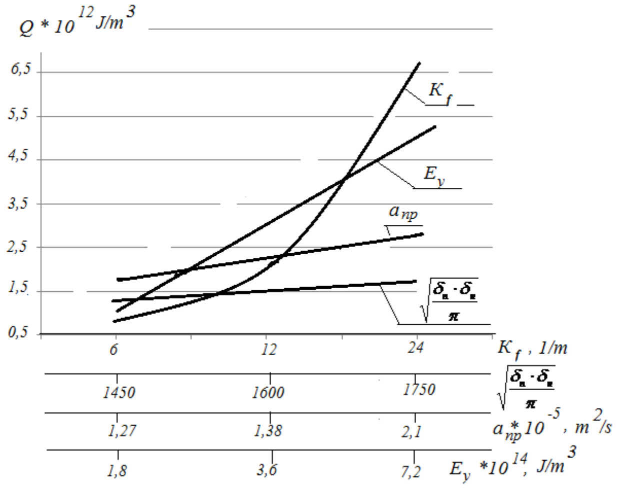

Fig. 1: Dependence of the change of the quality value of tribosystems on the change of the shape coefficient, rheological properties of the materials of triboelements, their thermal diffusivity and tribological properties of the lubricating medium.

According to the analysis of the curves, the design of the tribosystem has the greatest effect on the quality, formula (2), which takes into account such values as friction areas of the fixed and movable triboelements, their ratio and volumes of the material located under the friction areas. Then, in descending order, tribological properties of the lubricating medium, thermal diffusivity of the materials of triboelements and rheological properties of the structure of materials.

The value of the deformation rate in the surface layers of the materials of triboelemets $\dot{\varepsilon}_{np}$, formula (4), is in inverse proportion to to the quality value. Parameters which are included into the expression of the deformation rate of the materials of the fixed and movable triboelements are determined by expressions (5) and (6), the effect o which is shown in Fig. 2.

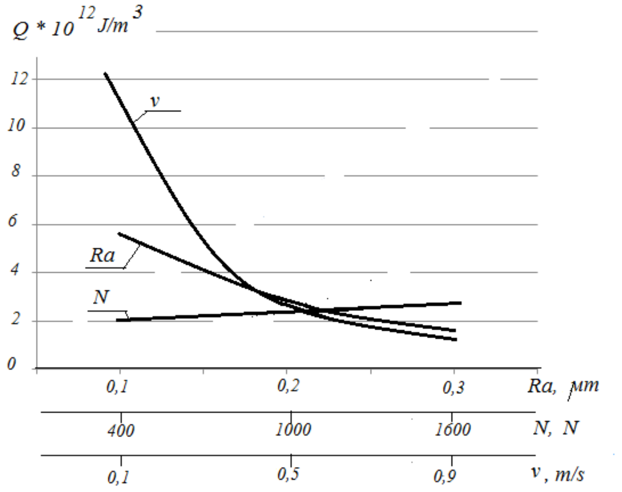

Fig. 2: Dependence of the change of the quality value of tribosystems on the change of roughness of friction surfaces, load and sliding speed.

According to the analysis of the obtained dependences, the sliding speed has the greatest effect on the quality of the tribosystem, and then, in descending order, roughness of the friction surfaces and load.

The conducted theoretical studies provide for rating the effect of the above parameters on the quality of the tribosystems. Therewith the range of changing for the parameters was chosen within the operation of tribosystems in the normal wear modes, i.e. without damaging.

The prepared rating can be used for substantiation of the parameters that affect the quality, and thus, the time of the transient process in the tribosystems. Those are sliding speed, roughness of the friction surfaces and lubricating medium. The shape coefficient of the tribosystem does not change during running-in. This value is determined by designing and is constant during running-in and operation of the tribosystem.

In view of the above, it can be concluded that the punning-in may be controlled by changing $\dot{\varepsilon}_{np}$, formula (4), decreasingly. For this purpose, the sliding speed υ and load N should be decreased. Analysis of the dependences shown in Fig. 2 enables to state that the change of the load N only slightly affects the quality value, and the sliding speed υ is an effective parameter, so the running-in process can be controlled by changing this parameter.

Simulating the changes of wear rate and friction coefficient for various tribosystems, theoretical dependences of the change of the above parameters on the quality value Q have been obtained.

In Fig. 3, theoretical curves (full lines) of the changes of the maximum value of the wear rate during running-in I_{max} and the steady-state value of the wear rate after completion of running-in I_{const} for tribosystems with different quality are shown. According to the analysis of the obtained dependences, the increase of quality of the tribosystem decreases the wear rates, both during running-in, and after completion of running-in, i.e. in the steady-state mode.

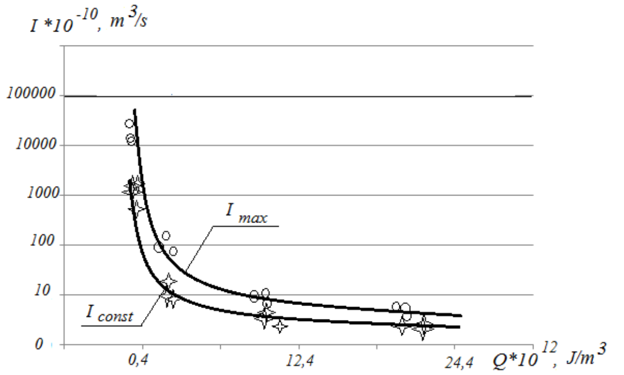

Fig. 3: Dependence of the change of the maximum value of the wear rate during running-in and the steady-state one, after completion of running-in, on the quality value of the tribosystems.

Similar studies have been conducted for the friction coefficient, Fig. 4, which also suggests the presence of the functional correlation between the maximum and steady-state values of the friction coefficient during running-in and the quality value of the tribosystems.

The obtained theoretical curves were validated experimentally. In Fig. 3 and Fig. 4, experimental points for tribosystems with different quality values are shown. For example, for the kinematic pairs of higher degree, with the line contact and the coefficient of mutual overlap <0.1 and combination of materials: 40X steel + 40X steel, quality of the tribosystem $Q \leq 0.4 \cdot 10^{12}$ J/m^3. For the kinematic pairs of lower degree, with the area contact and the coefficient of mutual overlap >0.5 and combination of materials: 40X + Бр.АЖ 9-4 steel, quality of the tribosystem Q =(12 to 24)$\cdot$ 10^{12} J/m^3.

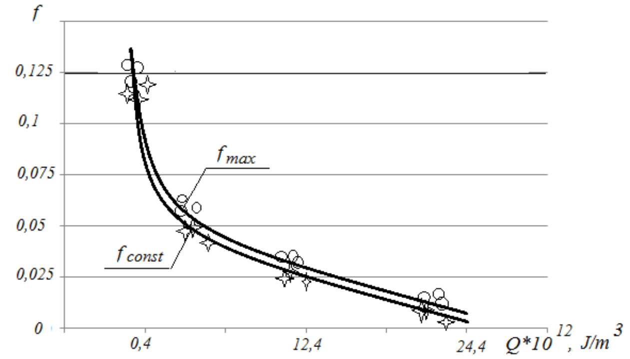

Fig. 4: Dependence of the change in the maximum value of the coefficient of friction during running-in and the steady-state one, after completion of running-in, on the quality value of the tribosystems.

Calculation of the relative simulation error between the theoretical and experimental values of the wear rate allows stating that the relative error was: e_I =7.2 to 8.3%, e_f = 7.9 to 9.3%, which is a satisfactory result for simulation of friction and wear processes.

The simulation results and the experimental validation of functional correlation between the running-in time t_{np} and quality of the tribosystem Q are shown in Fig. 5.

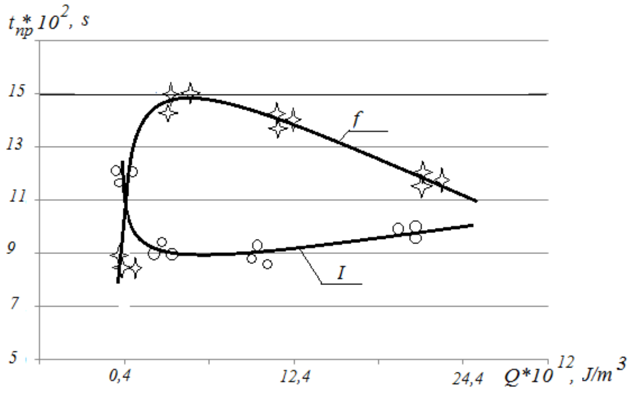

Fig. 5: Dependence of the change in the running-in time by the wear rate and the coefficient of friction on the quality value of the tribosystems.

The tribosystem with the values $Q \leq 0.4 \cdot 10^{12}$ J/m^3, which are mainly kinematic pairs of higher degree, have the minimum running-in time by the friction coefficient and simultaneously the maximum running-in time by the wear rate. With the transition to the kinematic pairs of lower degree $Q > 0{,}4 \cdot 10^{12}$ J/m^3, where contact takes place on the area, shorter running-in time correlates with the wear rate parameter, while longer time correlates with friction coefficient. As the quality of tribosystem increases, the running-in time for the friction coefficient shortens significantly, however, at the same time, the running-in time by the wear rate parameters increases slightly.

The obtained results suggest that with the certain quality value $Q = 30 \cdot 10^{12}$ J/m^3 the running-in time by two parameters will be equal.

Based on the calculation of the relative simulation error of the running-in time it can be stated that e_t = 8.2 to 9.4%.

The presented theoretical and experimental studies allow concluding that the quality value of tribosystems Q can be a measure of the potential ability of the tribosystem to adjust to operating conditions providing the maximum service life.

4. Conclusion

The definition of the quality of the tribosystem, which unlike the known one takes into account the geometric dimensions and kinematic scheme of the tribosystem, the thermal diffusivity of materials and the rate of propagation of deformation in the surface layers of the triboelement materials during their contact interaction, has been further developed. Theoretical and experimental studies have established the correlation between the quality value, wear rate and friction coefficient during running-in. It is shown that the increase in quality contributes to reduction of the above parameters, and the Q criterion itself is a measure of the potential ability of the tribosystem to adjust to operating conditions.

The correlation between the running-in time and quality has been established. It has been shown that the process of running-in can be controlled. Sliding speed should be reduced while the tribological properties of the lubricating medium should be enhanced during the transition process to reduce the running-in time.

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