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Assessment of the quality factor of tribosystems and relationship with tribological characteristics

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Abstract

The definition of the quality factor of the tribosystem has been further developed, which, unlike the known one, takes into account not only the geometric dimensions of the tribosystem, thermal diffusivity of triboelement materials, lubricating medium and deformation propagation rate in the surface layers of the material, but also the function of changing the rheological properties of the surface layers of materials during running-in and their increase during running-in. Theoretical studies have established that three parameters have the maximum effect on the quality factor: sliding speed, roughness of friction surfaces and lubricating medium.

Experimental studies have established the relationship between the value of the quality factor, wear rate and coefficient of friction during steady-state operation of tribosystems. It has been shown that an increase in the figure of quality factor reduces the above parameters, and the criterion itself Q_{max} is a measure of the potential of the tribosystem adapt to the operating conditions.

Keywords: tribosystem, modeling, wear rate, coefficient of friction, material compatibility, quality factor of tribosystem, the criterion quality factor of tribosystem, internal friction of material structure

Introduction

The concept of the quality factor of a tribosystem was introduced by the authors of the work [1] and is defined as the ability of mating materials in the tribosystem (lubricating medium and rheological properties of the structure of materials of moving and stationary triboelements) convert the work of friction forces into thermal energy, thereby preventing energy reserves in the surface and subsurface layers of triboelements, which can be estimated by the deformable volume.

The greater part of the friction work will be converted into heat and less material will be involved in deformation, then there is a greater quality factor of the tribosystem.

The concept of the quality factor of a tribosystem complements the concept of material compatibility in a tribosystem, which is understood as the ability of contacting materials to adapt to each other and to changing friction conditions, taking into account the interaction of materials with the lubricant and the environment, ensuring the specified durability and stable operation over the entire range of operation.

As follows from the above definition, the quality factor of the tribosystem is influenced by the processes of formation of surface layers during friction, tribological properties of the lubricating medium, as well as the design of the tribosystem, rheological properties of the structure of conjugated materials and the nature of the applied load to the tribosystem.

For predicting the wear resistance of tribosystems, as well as for calculating the wear rate and friction losses, it is necessary to have a quantitative parameter for assessing the quality factor of the tribosystem, which is a multi-parameter function of processes, flowing in the surface and subsurface layers of materials and depends on the nature of the applied load.

Literature review

The problem of material compatibility in the tribosystem belongs to the works [2-4] which define the concept of material compatibility, which consists in the ability of contacting materials to adapt to each other and to changing friction conditions, taking into account the interaction of materials with the lubricant and the environment, ensuring the specified durability of the tribosystem and its stable operation without lubrication or in the mode of violation of the integrity of the lubricant. In later work [5], the concept of compatibility was clarified - as the ability of a tribosystem to provide an optimal state in a given range of operating conditions for the selected parameters.

Considering that friction is a dynamic and dissipative process, internal friction can serve as a quantitative characteristic of the relaxation properties of the surface layers of materials [6, 7]. Internal friction characterizes the ability of a material structure to dissipate vibration energy, related to the density, concentration and mobility of dislocations and point defects.

In works [8-10], it is shown that relaxation processes exhibit a higher structural sensitivity to changes in the stress-strain state of the material under dynamic loading compared with physical and mechanical properties. The main conclusion of the above works is that the rheological properties of the frictional contact can be represented in the form of four levels, in which the processes of contact interaction are concentrated.

Based on the performed analysis of the work we can conclude, that the relaxation properties of the structure of the materials from which the tribosystem is made affect the compatibility of materials, and are a function of wear resistance and running-in, which is proven in work [11]. In this work, a parameter is given - the attenuation coefficient of ultrasonic vibrations in the structure of the material, which characterizes the amount of internal friction and the method of its measurement.

Analyzing the presented material, we can conclude, that the development of a criterion that would more fully take into account the above factors is an urgent task.

Purpose

The aim of this work is to develop a criterion for assessing the quality factor of a tribosystem and assess its functional relationship with the wear rate, friction coefficient and running-in time.

Methods

According to work [1] the quality factor of the tribosystem can be estimated by the expression:

$$Q = \frac{K_f^2 \cdot a_{red} \cdot E_u}{\dot{\varepsilon}_{red}} \cdot \sqrt{\frac{\delta_{mov} \cdot \delta_{fix}}{\pi}}, J/m^3. \quad (1)$$

A parameter that takes into account the geometric dimensions of the tribosystem, the form factor Кf, according to work [12] is calculated by the formula:

$$K_f = \frac{F_{\min}}{V_{mov} + \frac{V_{fix} \cdot F_{\max}}{F_{\min}}}, \frac{1}{m}, \quad (2)$$

where F_{min} – friction area of a fixed triboelement, m^2;
V_{mov} – volume of material under the friction area of a movable triboelement, m^3;
V_{fix} – volume of material under the frictional area of a fixed triboelement, m^3;
F_{max} – friction area of the movable triboelement, m^2.

Significant parameters are also: thermal diffusivity of materials of triboelements a, m^2/s and the strain rate in these materials $\acute{\varepsilon}$, 1/s on actual contact spots. Considering that a movable and a fixed triboelement simultaneously participate in the tribosystem, we use the concepts of reduced values.

The reduced coefficient of thermal diffusivity of the tribosystem materials is determined by the expression:

$$a_{red} = \frac{2 \cdot a_{mov} \cdot a_{fix}}{a_{mov} + a_{fix}}, m^2/s, \quad (3)$$

where a_{mov} and a_{fix} – thermal diffusivity coefficients of materials of movable and fixed triboelements, reference value, m^2/s.

Tribological properties of the lubricating medium, according to work [13], can be taken into account using the parameter E_u, J/m^3 – specific work of wear per unit volume of test material (balls of steel ShH-15) in the tested lubricating medium. Formula for calculating values E_u based on the results of an experiment on a four-ball machine, is presented in work [13].

The reduced strain rate in the surface layers of the tribosystem materials is determined by the expression:

$$\dot{\varepsilon}_{red} = \frac{2 \cdot \dot{\varepsilon}_{mov} \cdot \dot{\varepsilon}_{fix}}{\dot{\varepsilon}_{mov} + \dot{\varepsilon}_{fix}}, 1/s, \tag{4}$$

where $\dot{\varepsilon}_{mov}$, $\dot{\varepsilon}_{fix}$ – deformation rate of materials of moving and fixed triboelements, 1/s. Based on work [14]:

$$\dot{\varepsilon}_{mov} = 75(1+\mu_{mov})(0,86-1,05\mu_{mov})\frac{\sigma_{acp} \cdot v_{sl}}{E_{mov} \cdot d_{acp}}, \text{ 1/s}, \tag{5}$$

$$\dot{\varepsilon}_{fix} = 75(1+\mu_{fix})(0,86-1,05\mu_{fix})\frac{\sigma_{acp} \cdot v_{sl}}{E_{fix} \cdot d_{acp}}, \text{ 1/s}, \tag{6}$$

where μ_{mov} and μ_{fix} – Poisson's ratios of materials of movable and fixed triboelements, reference value;
σ_{acp} – stress at the actual contact patch, calculated by the formula presented in the work [14], Pa;
v_{sl} – sliding speed, m/s;
E_{mov} and E_{fix} modulus of elasticity of materials of moving and fixed triboelements, reference value, Pa;
d_{acp} – diameter of the actual contact patch, m^2, calculated by the formula presented in the work [14], Pa.

The structure of conjugated materials in the tribosystem, according to the formula (1), is taken into account by values δ_{mov} and δ_{fix} – damping coefficients of ultrasonic vibrations in the structure of the material of the moving and stationary triboelements, dimensionless and constant values. These coefficients are directly proportional to the internal friction of the original structure of conjugated materials and do not change during running-in.

However, according to the conclusions of the work [15], the rheological properties of the structure of conjugated materials are not constant, but change (increase) during the running-in time for 30,7…33,9%. When studying transient processes in tribosystems and substantiating effective programs for their running-in [16], it is necessary to take into account the function of changing the rheological properties of tribosystem materials in time - $RS_{TS}(t_i)$.

To assess the rheological properties of the structure of conjugated materials in the tribosystem during running-in, when t_i varies from zero to t_r, let's use the expression:

$$RS_{TS}(t_i) = \sqrt{\frac{\delta_{mov}(t_i) \cdot \delta_{fix}(t_i)}{\pi}}, 1/m, \tag{7}$$

where $RS_{TS}(t_i)$ - values of rheological properties of connected materials in the tribosystem, as a function of running time, dimension 1/m;

$\delta_{mov}(t_i)$ - the value of the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the material of the movable triboelement, as a function of the running time, the dimension dB/m, is calculated by the expression given in the work [15];

$\delta_{fix}(t_i)$ – the value of the logarithmic decrement of the attenuation of ultrasonic vibrations in the structure of the material of the fixed triboelement, as a function of the running time, the dimension dB/m, is calculated by the expression given in the work [15].

The basis of the methodological approach when supplementing the criterion of quality factor of the tribosystem instead of constant values that take into account the initial structure of materials in the tribosystem is the formula (1), we use the function of changing the rheological properties of tribosystem materials in time - $RS_{TS}(t_i)$. Using the analysis of the dimensions of physical quantities, we write expressions for determining the quality factor during the transient process:

$$Q(t_i) = \frac{K_f \cdot a_{red} \cdot E_u}{\dot{\varepsilon}_{red}} \cdot RS_{TS}(t_i), J/m^3, \tag{8}$$

and after the end of the transition process:

$$Q_{\max} = \frac{K_f \cdot a_{red} \cdot E_u}{\dot{\varepsilon}_{red}} \cdot RS_{TS(\max)}, J/m^3. \tag{9}$$

The given expressions for evaluating the quality factor of the tribosystem during running-in, the formula (8) and after the completion of the running-in (at steady state), the formula (9), unlike the well-known (1), take into account not only the geometric dimensions of the tribosystem, the thermal diffusivity of the materials of the triboelements, lubricating medium and the rate of propagation of deformation in the surface layers of the material, but also the function of changing the rheological properties of the surface layers of materials during running-in and their increase during running-in.

The listed differences will improve the accuracy of modeling the wear rate and coefficient of friction during transient processes and at steady-state modes of tribosystem operation.

Results

As follows from the above expressions (8) and (9) the quality factor of the tribosystem is a quantitative parameter that characterizes the design of the tribosystem - the parameter K_f, thermal diffusivity of triboelement materials a_{red}, tribological properties of the lubricating medium E_u, strain rate in the surface layers of triboelements ($\dot{\varepsilon}_{mov}$, $\dot{\varepsilon}_{fix}$), which depends on the roughness of the friction surfaces and the elastic modulus of the materials of the triboelements (E_{mov} and E_{fix}), as well as the function of changing the rheological properties of the surface layers of materials during running-in $RS_{TS}(t_i)$ and their increase during the running-in time $RS_{TS(max)}$.

Dependences of the change in the value of the figure of merit on the change in the coefficient of the form of the tribosystem K_f, rheological properties of the structure of conjugated materials $RS_{TS(max)}$ their thermal diffusivity a_{red} and tribological properties of the lubricating medium E_u, are shown in fig. 1. These are parameters, an increase in which directly affects the figure of the quality factor, with the exception of the tribological properties of the lubricating medium. E_u and the reduced coefficient of thermal conductivity of the materials of triboelements.

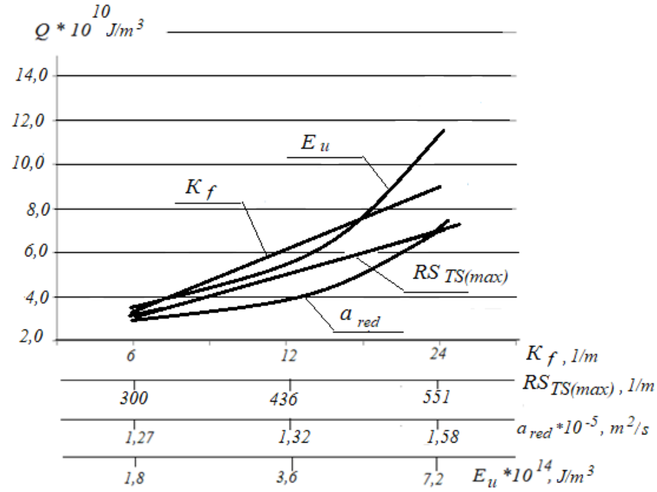

Fig. 1. Dependences of the change in the figure of the quality factor of tribosystems on the change in the shape factor, the rheological properties of the materials of the triboelements, their thermal diffusivity and the tribological properties of the lubricating medium

As follows from the analysis of the curves, the greatest influence on the figure of the quality factor is exerted by the tribological properties of the lubricating medium E_u, further, in decreasing order, the form factor, which characterizes the structure of the tribosystem, rheological properties of the structure of materials and thermal diffusivity of materials of triboelements.

The value of the reduced strain rate in the surface layers of materials of triboelements $\dot{\varepsilon}_{red}$, formula (4), is inversely proportional to the figure of the quality factor, the formula (8), (9). The parameters that are included in the expressions for the deformation rate of the materials of the fixed and movable triboelements are determined by the expressions (5) and (6), the influence of which is shown in fig. 2.

The analysis of the obtained dependences allows us to conclude that the greatest influence on the quality factor of the tribosystem is exerted by the value of the sliding speed, and then, in decreasing order, the roughness of the friction surfaces and the load.

The conducted theoretical studies allow us to evaluate the influence of the above parameters on the quality factor of tribosystems. At the same time, the range of parameter variation is selected within the limits of tribosystem functioning in normal wear modes, i.e. without damage. The ratio of the maximum value of the figure of the quality factor to the minimum value, when one of the parameters changes, makes it possible to determine how many times the figure of the quality factor indicator changes within the given modeling limits.

Two parameters have the maximum influence on the quality factor: sliding speed and surface roughness. In this case, sliding speed comes first – 11,2 times, and the surface roughness is the second – 6,5 times.

In the third place is the tribological properties of the lubricating medium - 4,7 times, the form factor – 3,0 times, rheological properties of materials and thermal diffusivity of materials of triboelements – 2,55 times.

Based on the performed rating, it is possible to justify the parameters that affect the quality factor, and consequently, the tribological properties of tribosystems. These are the sliding speed, the roughness of the friction surfaces and the lubricating medium.

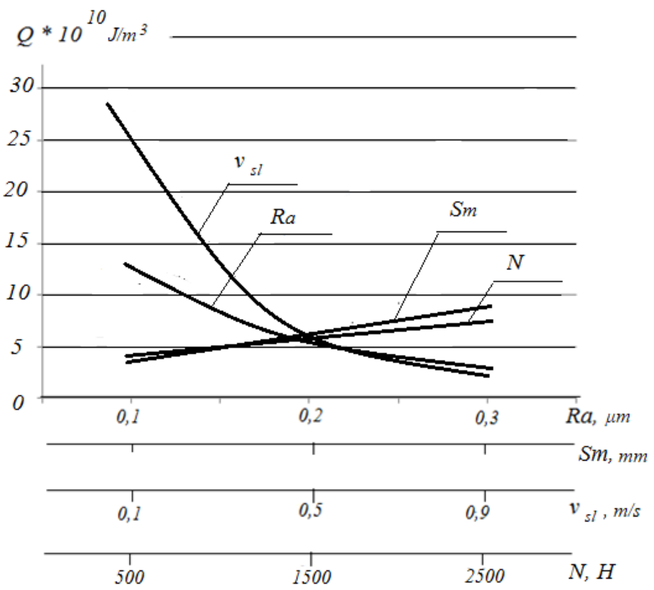

Fig. 2. Dependences of the change in the value of the figure of the quality factor of tribosystems on the change in the roughness of the friction surfaces, load and sliding speed

The form factor of the tribosystem does not change during the running-in process. This is a value that is determined during design and is a constant during the running-in and operation of the tribosystem.

The value of roughness is also formed in the process of manufacturing tribosystems, however, in the process of running-in and operation, it changes and comes to an equilibrium value. The tribological properties of the lubricating medium also do not change during the running-in process, however, they change during operation. Based on the foregoing, we can conclude that the running-in process can be controlled by changing $\dot{\varepsilon}_{red}$, formulas (5) and (6), in the direction of decreasing. To do this, it is necessary to reduce the sliding speed υ_{sl} and load N. Analysis of the dependencies shown in fig.2 allows us to state that the change in load N insignificantly affects the figure of the quality factor, and the sliding speed υ_{sl}, is an effective parameter, changing which you can control the running-in process.

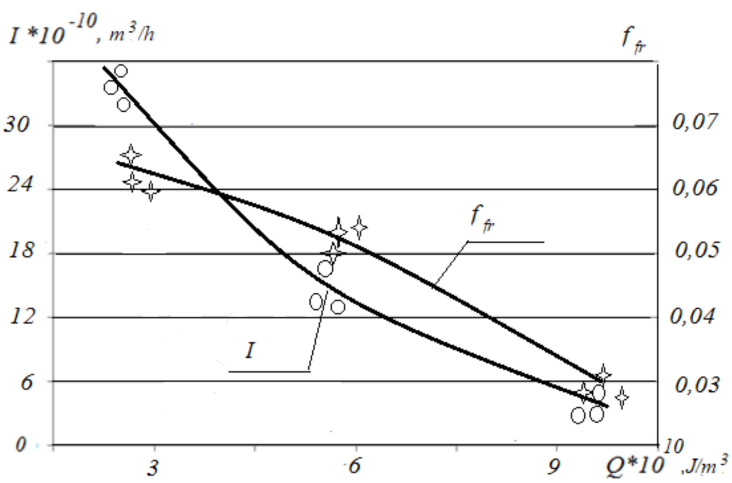

Fig. 3. Dependence of the change in the volumetric wear rate and the coefficient of friction in the steady-state mode of operation on the value of the quality factor of the tribosystems

In the fig.3 experimental values and curve fitting (solid lines) changes in volumetric wear rate *I* and coefficient of friction f_{fr} in the steady-state operating mode of tribosystems with different quality factors are presented. Analysis of the obtained dependences allows us to conclude that an increase in the quality factor of the tribosystem by 4 times reduces the rate of volumetric wear by 9 times and the coefficient of friction by 2,4 times.

The obtained experimental results allow us to conclude that there is a functional relationship between the volumetric wear rate, friction loss and the quality factor of tribosystems. The presented experimental studies allow us to conclude that the quality factor of tribosystems Q_{max} can act as a measure of the potential of the tribosystem adapt to the operating conditions providing the maximum resource.

Conclusions

1. The definition of the quality factor of a tribosystem was further developed, which, unlike the known one, takes into account not only the geometric dimensions of the tribosystem, thermal diffusivity of triboelement materials, lubricant medium and the rate of propagation of deformation in the surface layers of the material, but also the function of changing the rheological properties of the surface layers of materials during running-in and their increase during running-in. Theoretical studies have established that three parameters have the maximum effect on the quality factor: sliding speed, roughness of friction surfaces and lubricating medium.

2. Experimental studies have established the relationship between the value of the figure of the quality factor, wear rate and coefficient of friction during steady-state operation of tribosystems. It is shown that an increase in the figure of the quality factor reduces the above parameters, and the criterion itself Q_{max} is a measure of the potential of the tribosystem adapt to the operating conditions.

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Войтов В.А., Войтов А.В. Оцінка добротності трибосистем і її зв'язок з трибологічними характеристиками

Отримало подальший розвиток визначення добротності трибосистеми, як здатність сполучених матеріалів в трибосистемі (мастильне середовище та реологічні властивості структури матеріалів рухомого і нерухомого трибоелементів), перетворювати роботу сил тертя в теплову енергію, тим самим перешкоджати запасам енергії в поверхневих і підповерхневих шарах трибоелементів, які можна оцінити об’ємом що деформується. Представлено вираз для розрахунку кількісної величини добротності, який на відміну від відомих враховує не тільки геометричні розміри трибосистеми, температуропровідність матеріалів трибоелементів, мастильне середовище і швидкість поширення деформації в поверхневих шарах матеріалу, а також функцію зміни реологічних властивостей поверхневих шарів під час припрацювання і їх збільшення за період припрацювання. Теоретичними дослідженнями встановлено, що максимальний вплив на добротність надають три параметри: швидкість ковзання, шорсткість поверхонь тертя і мастильне середовище.

Представлені експериментальні значення зміни об'ємної швидкості зношування і коефіцієнта тертя на сталому режимі роботи трибосистем з різною добротністю. Аналіз отриманих залежностей підтверджує, що збільшення добротності трибосистеми в 4 рази знижує величини швидкості об'ємного зношування в 9 разів і коефіцієнта тертя в 2,4 рази. Отримані результати дозволяють стверджувати, що збільшення добротності покращує трибологічні характеристики трибосистем, а сам критерій Q_{max} є мірою потенційної можливості трибосистеми пристосовуватися (адаптуватися) до умов експлуатації.

Отримані теоретичні та експериментальні результати доводять про наявність функціонального зв'язку між об'ємною швидкістю зношування, втратами на тертя і величиною добротності трибосистем.

Ключові слова: трибосистема, моделювання, швидкість зношування, коефіцієнт тертя, сумісність матеріалів, добротність трибосистеми, критерій добротності трибосистеми, внутрішнє тертя структури матеріалів