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Mathematical model of running-in of tribosystems under conditions of boundary lubrication. Part 2. Simulation results

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Abstract

The paper presents the results of mathematical modeling of tribosystems running-in processes when various factors are changed: design parameters of tribosystems, which are taken into account by the form factor; tribological properties of the lubricating medium; rheological properties of composite materials in the tribosystem; roughness of friction surfaces; load and sliding speed. By comparing the theoretically obtained results, by modeling according to the developed models, with experimental data, it was established that the mathematical model adequately reflects the running-in processes taking into account the changes in constructive, technological and operational factors. Applying the Cochrane criterion, it was established that the obtained experimental results are homogeneous and reproducible. The maximum value of the coefficient of variation of the values of the volumetric wear rate and the coefficient of friction is within the limits v = 12,3 - 26,5%. The value of the simulation error is within the limits v = 7,7 - 12,9%.

A rating of factors that maximally affect the processes of running-in of tribosystems in the conditions of extreme lubrication has been obtained. In the first place is the roughness of the friction surfaces, the coefficient of variation v = 26,5%. In the second place – the load on the tribosystem during running-in, the coefficient of variation v = 20,8%. In third place is the value of sliding speed during running-in, the coefficient of variation v = 18,6%. The conclusion made must be taken into account when developing a rational program for running-in tribosystems in conditions of extreme lubrication.

The methodical approach of applying the acoustic emission method in the study of tribosystem running-in processes is presented. It is proved in the work that in order to determine the volume rate of wear during tribosystem running-in, it is necessary to register and analyze the fourth cluster from the general acoustic emission signal. The sources of signal generation of the fourth cluster are microcutting and plastic deformation of protrusions of the roughness of the friction surface, which is characteristic of the first stages of running-in.

Key words: tribosystem; practice; mathematical model of training; marginal lubrication; form factor; tribological properties of the lubricating medium; rheological properties of composite materials; wear rate; coefficient of friction

Introduction

To date, in the literature there are many definitions of the process of running tribosystems. Running-in is a non-stationary initial transient process of friction in tribosystems, which results in adaptation of the contacting surfaces and a gradual transition to a stationary process by reducing and stabilizing the values of wear rate, friction coefficient and temperature. It should be noted that even with minor changes in loading conditions, lubricating medium or other friction conditions, the running-in surfaces will go through the stage of repeated (secondary) running-in. The surfaces of tribosystems will adapt to new working conditions.

The most effective tool for studying the running-in processes of tribosystems is mathematical modeling. A large number of mathematical models of such processes have been developed, but their application is limited for the following reasons. Firstly, a large error in modeling the parameters of the running-in process, for example, wear per run-in, run-in completion time. Secondly, the presence of an oscillatory process of wear rate and friction coefficient during running-in. The instability of such parameters reduces the adequacy of the developed models to experimental data, increases the simulation error. There is an opinion among researchers that the running-in of tribosystems has an individual trajectory and depends on design, technological and operational factors. In our opinion, it is this triad of factors that should be taken into account when developing models and modeling the processes of running-in of tribosystems.

Literature review

Authors of the work [1] note that running-in plays an important role in the further operation of machines. This is a transient process involving a complex interaction between friction, lubrication, surface roughness, plastic deformation, and run-in wear. The running-in process involves changing key tribological parameters such as surface roughness, coefficient of friction and wear rate, which tend towards a steady state. This article provides a comprehensive review of the literature on the subject, covering both experimental and analytical developments to date.

In work [2] it is proposed to represent the running-in process of the tribosystem as a time series of friction coefficients and the corresponding attractors. Due to the complexity and nonlinearity of tribosystems, friction attractors exist in multidimensional phase spaces. This makes it possible to visualize the phase trajectory of a complex running-in process. The authors compared and analyzed three methods for visualizing multidimensional datasets. Differences in the results of identification between the temporal and phase-spatial regions are shown. which indicates that recognition of the state of run-in results based on friction-induced attractors is more accurate.

According to the authors of the work [3] the quality of the running-in can be improved by optimizing the process parameters (load, sliding speed and running-in time). The authors analyzed the relationship between the quality of running-in and the parameters that affect the running-in. Based on the analysis, it was concluded that the principles for choosing the running-in parameters for various designs of tribosystems differ. The processing steps are also different. The authors of the work do not provide systemic recommendations on the choice of running-in stages and running-in parameters at these stages. However, it is positive, in our opinion, that the running-in process should be divided into stages and have different optimal parameters for each stage.

Authors of the work [4] note that numerical simulation is a powerful tool for estimating running-in wear. The modeling of the surface topography is taken into account in the form of contact pressure curves on the roughness ridges and, accordingly, wear values dependent on the contact pressure. To confirm the simulation results, the authors present the results of the experiment. It has been experimentally confirmed that taking into account the surface topography is a significant factor influencing the running-in process. A similar approach was used by the authors of the works [5, 6], where the significant factors are the surface roughness parameters [5], contact pressure [6].

In work [7] it is noted that the running-in of tribosystems must be performed at different loads and different sliding speeds. The authors of the work showed that the use of a multi-stage process in the running-in process reduces the running-in time and improves its quality. The authors present simulation results that allow making predictions on the choice of running-in modes.

A similar approach is presented in the work [8]. The authors developed and substantiated the structure of the tribosystems running-in program, which consists of two modes. The first mode is called the adaptation of the tribosystem to external conditions. The second mode is called the trainability and trainability of the tribosystem. The paper presents the transient characteristics of the running-in of tribosystems, which make it possible to establish the relationship between the design of the tribosystem, rational loading modes, running-in time and wear for running-in. The practical significance of the work is to minimize the running-in time and wear during the running-in period.

In work [9] the methodical approach was further developed in obtaining mathematical models that describe the running-in of tribosystems under boundary lubrication conditions. The structural and parametric identification of the tribosystem as an object of simulation of running-in under conditions of extreme lubrication was carried out. It has been established that the processes of running-in of tribosystems are described by a second-order differential equation and, unlike the known ones, take into account the limit of loss of stability (robustness reserve) of tribosystems. It is shown that the processes of running-in of tribosystems depend on the type of the magnitude of the input influence on the tribosystem, the first and second derivatives. This allows us to state that the running-in processes of the tribosystem will effectively take place when the input action (load and sliding speed) will change in time and have fluctuations with positive and negative acceleration of these values from the set (program) value. This requirement corresponds to the running-in program "at the border of seizing".

Summing up the analysis of works devoted to the processes of running-in modeling, we can make a platoon about the inconsistency of opinions about the choice of significant factors affecting the process. A reasonable choice and ranking of factors, according to their degree of importance, will allow to justify the running-in regimes and reduce wear during running-in and running-in time. The following are subject to study as significant factors: the design of the tribosystem; lubricating medium; the structure of conjugated materials in the tribosystem; roughness of friction surfaces; load and sliding speed. This article is a continuation of the work [9], where the mathematical model of the running-in process was obtained. The ranking of factors will allow us to develop a program for the effective running-in of various designs of tribosystems, which will be a continuation of this work.

Purpose

The purpose of this study is to simulate the running-in processes of various designs of tribosystems, experimentally determine the simulation error and build a rating of factors that affect the running-in efficiency.

Methods

In work **[9]** structural and parametric identification of the tribosystem as an object of simulation of run-in under conditions of extreme lubrication. It has been established that the processes of running-in of tribosystems are described by a second-order differential equation and, unlike the known ones, take into account the limit of loss of stability (robustness reserve) of tribosystems.

Modeling the running-in process depends on the following values:

- input impact on the tribosystem W_i, (the power supplied to the tribosystem) is determined by the formula given in the work [10];
- the maximum value of the input impact, when there is accelerated wear of tribosystem materials, or burr of friction surfaces, W_b, is determined by the formula given in the work [10];
- speed of dissipation in the tribosystem W_{TR}, is determined by the formula given in the work [10];
- the maximum value of the Q-factor of the tribosystem Q_{max} during the run-in time, is determined by the formula given in the work [11];
- the design parameters of the tribosystem are taken into account by the form factor K_f, is determined by the formula given in the work [11];
- given value of the coefficient of thermal conductivity of triboelement materials a_{red}, is determined by the formula given in the work [11];
- rheological properties of the structure of composite materials in the tribosystem RS_{TS}, is determined by the formula given in the work [11].

The solution for the given in the work [9] of the differential equation when modeling the volumetric rate of wear, there is the following expression:

$$I(t) = I_{st}\left[1 + (K_0 \cdot K_2)^{\lambda}(t) \cdot e^{\left(-\frac{d_I}{0,3 \cdot T_I} \cdot t\right)} \cdot (\cos \upsilon_I t + A_I \sin \upsilon_I t)\right], \quad (1)$$

where I_{st} – the value of the wear rate of the tribosystem after running-in (stationary mode) is determined by the expression given in the work [12].

The solution for the given in the work [9] of the differential equation when modeling the friction coefficient has the following expression:

$$f(t) = f_{st}\left[1 - (K_0 \cdot K_2)^{\lambda}(t) \cdot e^{\left(-\frac{d_f}{0,3 \cdot T_f} \cdot t\right)} \cdot (\cos \upsilon_f t + A_f \sin \upsilon_f t)\right], \quad (2)$$

where f_{st} – the value of the friction coefficient of the tribosystem after running-in (stationary mode) is determined by the expression given in the work [12];

K_0 and K_2 – gain coefficients are calculated according to the formulas given in the works [9, 13];

λ – exponent, which takes into account the change in the constant T_3, as a function of run-in time, a dimensionless quantity, is calculated according to the formula given in the paper [9];

t – run-in time, which varies from zero to completion of the run-in process, dimension second;

d_I and d_f - decrements of damping of oscillations during run-in for modeling the volumetric rate of wear and friction coefficient, the formulas for calculation are given in the work [9];

T_I and T_f - time constants of the tribosystem for modeling the volumetric rate of wear during run-in and the friction coefficient, the formulas for calculation are given in the work [9];

υ_I and υ_f - frequency of oscillations for modeling the volume rate of wear during run-in and the coefficient of friction, the formulas for calculation are given in the work [9];

A_I and A_f - the amount of deviation of the volume rate of wear from the current value during the oscillating process for modeling the volume rate of wear during run-in and the coefficient of friction, the formulas for calculation are given in the work [9].

Results

Applying formulas (1) and (2), we will simulate the processes of running-in of tribosystems over time when the following input factors are changed:

- geometric dimensions of the tribosystem, which are taken into account by the form factor K_f, 1/m;
- tribological properties of the lubricating medium E_u, J/m^3;
- rheological properties of the structure of combined materials in the tribosystem RS_{TS}, 1/m;
- roughness of friction surfaces Ra, m;
- load, N;
- sliding speed, m/s.

To use the developed mathematical model of the running-in of tribosystems, it is necessary to evaluate the reproducibility and adequacy of the results obtained theoretically and experimentally, as well as the modeling error.

To determine the rate of wear in the process of running in tribosystems (in online mode), we will use the conclusions of the work [14]. The purpose of this study is to develop a methodology for diagnosing various structures of tribosystems with the justification of informative frequencies and amplitudes when recording acoustic emission (AE) signals from the friction zone. In the paper, it is proved that in order to determine the volumetric rate of wear during tribosystem running-in, it is necessary to register and analyze the fourth cluster from the general acoustic emission signal.

The fourth cluster is a packet of AE signals, which is characterized by emissions of large amplitudes, the value of which exceeds the average value of the amplitudes of the first (basic) cluster *K1* in 3.91 ... 4.6 times. Sources of cluster signal generation *K4* are: microcutting and plastic deformation of protrusions of friction surface roughness, which is characteristic of the first stages of running-in.

In work [14] the sequence in the construction of the method of diagnosing tribosystems during running-in is formulated.

1. From the analysis of the design documentation, the materials from which the triboelements are made are determined (modulus of elasticity and Poisson's ratio), as well as the roughness parameters of the friction surfaces (Ra, Sm) and the value of the smaller friction area of one of the triboelements F_{min}.
2. From the analysis of operating conditions, the operating mode of the tribosystem is determined (load and sliding speed).
3. According to the formulas given in [14], the rate of deformation of the triboelement material and the informative frequency that the triboelement will generate during the run-in process are determined. Calculations of the informative frequency must be performed for the triboelement material on which the piezo element will be installed.
4. Taking into account the noise coming from the equipment, the cluster *K1* in the frame is determined, as well as the sufficiency of the length of the frame being registered. The sufficiency of the frame length is established using the value of the autocorrelation coefficient, the calculation method of which is presented in [14].
5. According to the formulas presented in [14], the values of the informative amplitudes of the *K4* cluster are determined.
6. According to the formulas given in [14], the values of the peak factors of the AE signal from the friction zone of tribosystems are determined and a relationship is established with the numerical values of the rate of wear during running-in - the peak factor of the *K4* cluster.

To perform an experimental verification of the modeling results with experimental data, an experimental setup with a ring-ring contact kinematic scheme was used. The block diagram of the experimental equipment for registration and processing of AE signals from the friction zone is presented in Fig. 1.

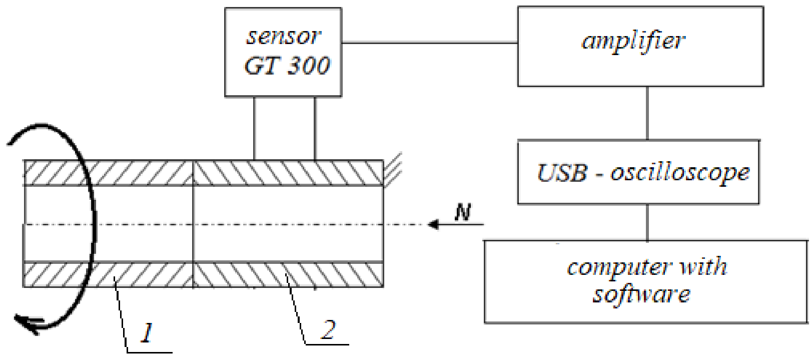

Fig. 1. Block diagram of the experimental equipment for registration and processing of AE signals: 1 - moving triboelement; 2 - fixed triboelement; N - load

The AE signal from the friction zone is registered by a broadband sensor GT300 (100 - 800 kHz), fig. 1, which was installed on a stationary triboelement, was transmitted to the amplifier, then, in analog form, to the PV6501 USB oscilloscope, which performs the functions of an analog-to-digital converter and a spectrum frequency analyzer at the same time. After processing in the USB oscilloscope, the signal in digital code enters the computer, where it is processed by special software.

The lower bandwidth of the signal is 50 kHz, which does not allow recording signals from test equipment (friction machines). The upper bandwidth of the signal is 1,5 MHz.

USB oscilloscope bandwidth, fig. 1, is 20 MHz, which is many times higher than the selected working bandwidth of the signal. Thus, with the help of low- and high-frequency filters, the AE signal from the friction zone in the band 50 - 1500 kHz was recorded and analyzed in the conducted studies.

The USB oscilloscope works in standby mode and is started on command for the registration time, the registration time is 1×10^{-3} s. This time was chosen based on the analysis of the AE signal at a steady state using the autocorrelation function [14].

When checking the homogeneity of variances of selected frames of AE signals in the tribosystem run-in mode, as well as the reproducibility of results from frame to frame, the ISO 5725 standard recommends using the Cochran criterion. The Cochran criterion allows you to compare the homogeneity of dispersions of the results of the analysis of AE signals from different frames. The degree of variability of the results of measurements of AE signals for different designs of tribosystems and their operating conditions was estimated using the coefficient of variation [14].

The root-mean-square absolute deviation for the volumetric wear rate and friction coefficient was calculated according to the formulas given in the ISO 5725 standard. The experimental sample arrays for volumetric wear rate and friction coefficient were checked for compliance with the normal distribution law. The results of experimental studies according to the investigated factors and levels of variation were checked for homogeneity and reproducibility from experiment to experiment according to the Cochrane criterion.

Adequacy of theoretical values obtained by expressions (1) and (2) with experimental data was checked using Fisher's *F*-test. For this purpose, adequacy variances and reproducibility variances were calculated.

In fig. 2 and fig. 3 shows the theoretical and experimental dependences of tribosystem run-in (the value of the change in volumetric wear rate and friction coefficient) over time when the shape coefficient K_f of the tribosystem changes. The shape coefficient of the tribosystem was changed due to the friction area F_{fr} stationary triboelement. Tribosystem "steel 40X+Br.AZH 9-4", lubricating medium - engine oil M-10G2к (E_u= 3,6·10^{14}J/m^3). Roughness of friction surfaces Ra = 0,2 micron; Sm = 0,4 mm. The tests were carried out on three designs of "ring-ring" tribosystems, where the area of the fixed, bronze triboelement was: F_{fr}= 0,00006 m^2, (K_f=5 m^{-1}); F_{fr}= 0,00015 m^2, (K_f=12,5 m^{-1}); F_{fr}= 0,00024 m^2, (K_f=20 m^{-1}). The area of the movable triboelement, steel 40X, in all three designs was F_{max} =0,0003 m^2. Load N = 1500 N; sliding speed v_{sl} = 0,5 m/s.

The results of the obtained array of experimental values allow us to draw a conclusion about the significant influence of the shape factor of the tribosystem on the nature of running-in. A small value of the shape factor of the tribosystem shortens the running-in time, but increases the volumetric rate of wear and the coefficient of friction. Conversely, an increase in the shape factor of the tribosystem makes the running-in process take longer, but the values of the volumetric wear rate and the friction coefficient decrease.

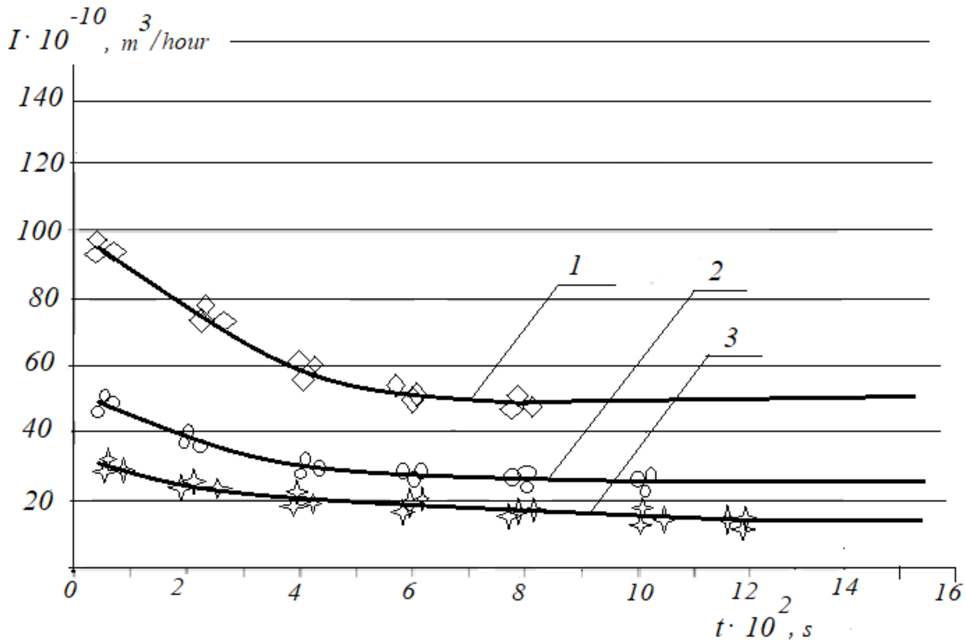

Fig. 2. Dependences of changes in the volume rate of wear during the running-in of tribosystems with different shape factors K_f: 1 – K_f=5 m^{-1}; 2 – K_f=12,5 m^{-1}; 3 – K_f=20 m^{-1}

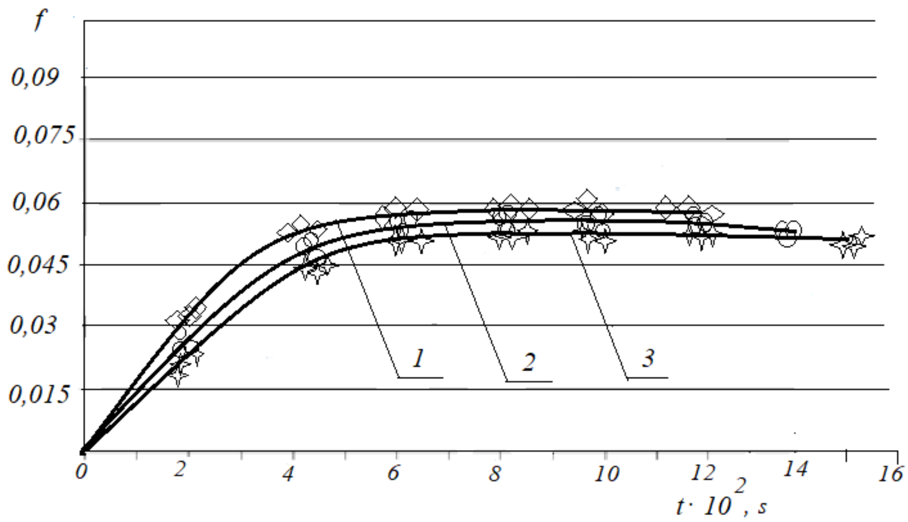

Fig. 3. Dependencies of the change in the friction coefficient during the running-in of tribosystems with different form factors K_f: 1 – K_f=5 m^{-1}; 2 – K_f=12,5 m^{-1}; 3 – K_f=20 m^{-1}

Comparison of estimated values of the Cochrane criterion G_e and table values G_t, for the given conditions of the experiment, allows us to assert that the obtained experimental results are homogeneous and reproducible.

The calculation of the coefficient of variation and the modeling error of the tribosystem running-in process when the shape factor changes from the minimum value to the maximum, for the given conditions of the experiment, shows that the coefficient of variation is v = 15,7%, and the modeling error does not exceed e = 7,7%,

The second constructive factor characterizing the tribosystem is the tribological properties of the lubricating medium, E_u. In fig. 4 and fig. 5 shows the theoretical and experimental dependences of lubrication of tribosystems over time with different lubricating media: hydraulic oil MG–15V (E_u= 2,43·10^{14} J/m^3); motor oil M–10G$_{2к}$ (E_u= 3,6·10^{14} J/m^3); transmission oil TSp-15к (E_u= 4,18·10^{14} J/m^3).

Conditions of the experiment. Combined materials in the tribosystem: steel 40X+Br.AZH 9-4. Roughness of friction surfaces Ra = 0,2 micron; Sm = 0,4 mm. Kinematic scheme of the "ring-ring" tribosystem, shape factor of the tribosystem K_f = 12,5 m^{-1}; load N = 1500 N; sliding speed v_{sl} = 0,5 m/s.

Comparison of estimated values of the Cochrane criterion G_e and table values G_t, for the given conditions of the experiment, allows us to assert that the obtained experimental results are homogeneous and reproducible.

The presented results of experimental studies confirm the results of modeling and allow us to draw a conclusion about the significant influence of the tribological properties of the lubricating medium on the running-in time and the volume rate of wear and the coefficient of friction. The coefficient of variation is constant and is at the level v = 12,3%, the modeling error does not exceed e = 8,9%,

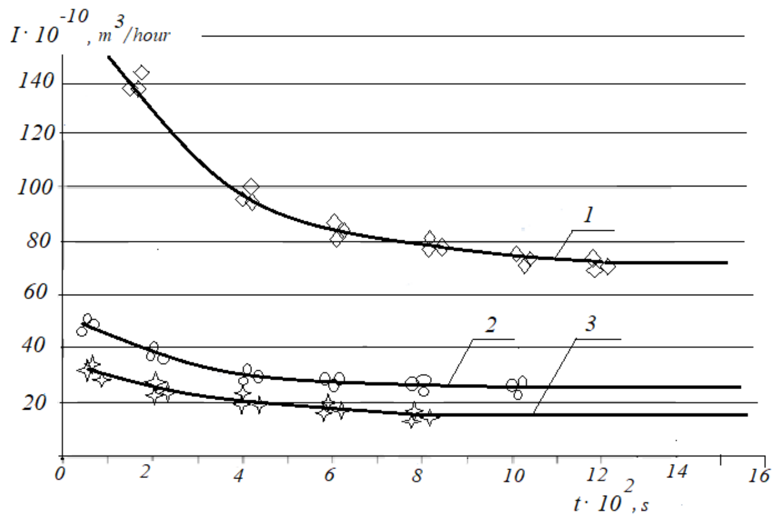

Fig. 4. Dependencies of changes in the volumetric rate of wear during the running-in of tribosystems with different lubricating media E_u: 1 - hydraulic oil MG–15V (E_u= 2,43·10^{14} J/m^3); 2 - motor oil M – 10G$_{2к}$ (E_u= 3,6·10^{14} J/m^3); 3 - transmission oil TSp-15к (E_u= 4,18·10^{14} J/m^3)

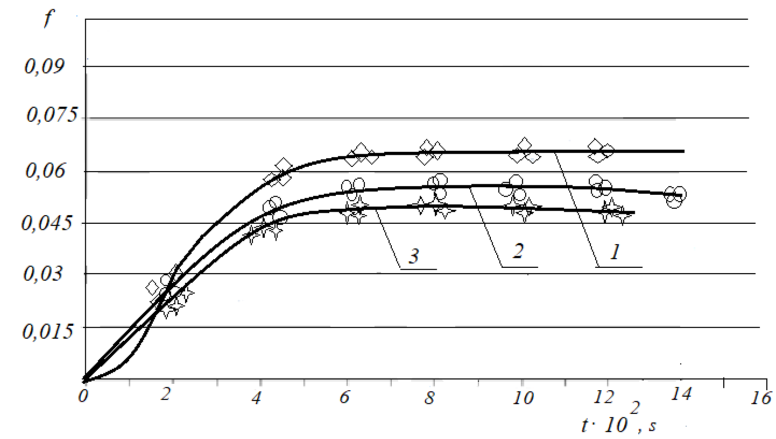

Fig. 5. Dependencies of the change in the friction coefficient during the run-in of tribosystems with different lubricating media E_u: 1 - hydraulic oil MG–15V (E_u= 2,43·10^{14} J/m^3); 2 - motor oil M – 10G2к (E_u= 3,6·10^{14} J/m^3); 3 - transmission oil TSp-15к (E_u= 4,18·10^{14} J/m^3)

The third constructive factor that characterizes the tribosystem is the combination of materials of moving and stationary triboelements. In fig. 6 and fig. 7 presents the theoretical and experimental values of the change in the running-in time (the value of the change in the volumetric rate of wear and the coefficient of friction) for different combinations of materials in the tribosystem. The following designs of tribosystems were tested: steel 40X + steel 40X, (RS_{TS}=249,9 m^{-1}); steel 40X + VCh 70, (RS_{TS}=309 m^{-1}); steel 40X + Br.AZH 9-4, (RS_{TS}=332,5 m^{-1}). For all designs, the moving triboelement was made of steel 40X (HRC 52-54).

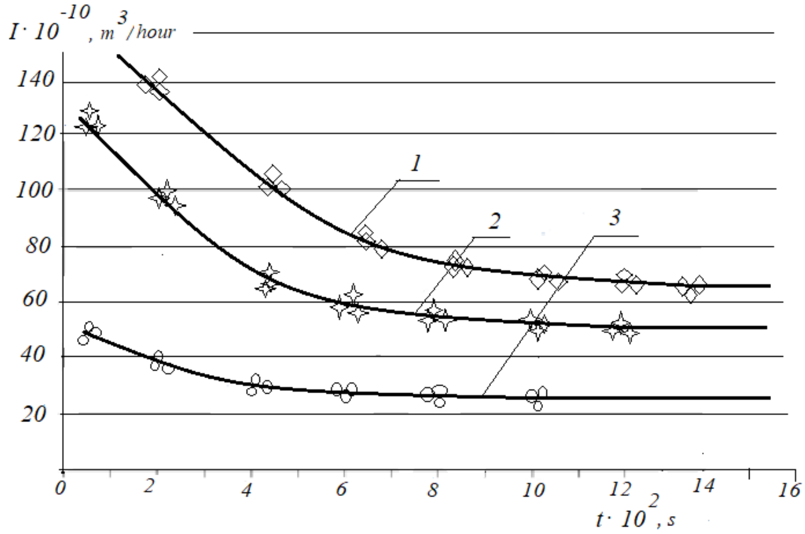

Fig. 6. Dependencies of the change in the volumetric rate of wear during the running-in of tribosystems with different composite materials RS_{TS}: 1 – steel 40X + steel 40X, (RS_{TS}=249,9 m^{-1}); 2 - steel 40X + VCh 70, (RS_{TS}=309 m^{-1}); 3 - steel 40X + Br.AZH 9-4, (RS_{TC}=332,5 m^{-1})

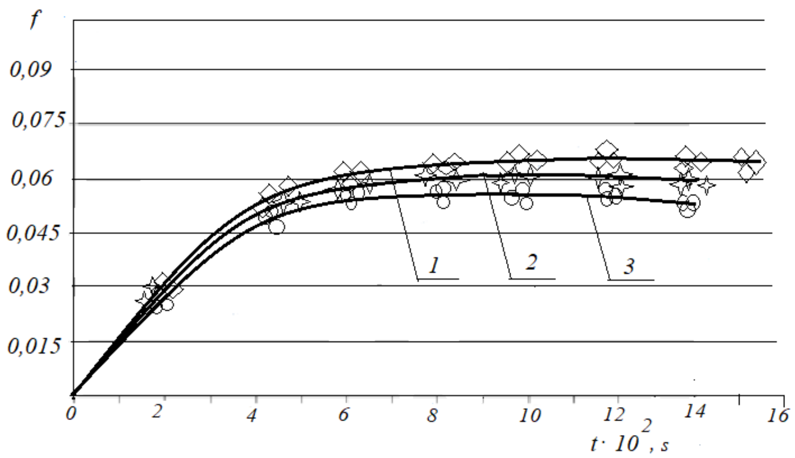

Fig. 7. Dependencies of the change in the friction coefficient during the running-in of tribosystems with different combined materials RS_{TS}: 1 – steel 40X + steel 40X, (RS_{TS}=249,9 m^{-1}); 2 - steel 40X + VCh 70, (RS_{TS}=309 m^{-1}); 3 - steel 40X + Br.AZH 9-4, (RS_{TS}=332,5 m^{-1})

Conditions of the experiment. The lubricating medium is motor oil M-10G2к. (E_u= $3{,}6 \cdot 10^{14}$J/m^3). Roughness of friction surfaces Ra = 0,2 micron; Sm = 0,4 mm. Kinematic diagram of "ring-ring" tribosystems, tribosystem form factor K_f = 12,5 m^{-1}; load N = 1500 N; sliding speed v_{sl} = 0,5 m/s.

Comparison of estimated values of the Cochrane criterion G_e and table values G_t, for the given conditions of the experiment, allows us to assert that the obtained experimental results are homogeneous and reproducible.

The results of the obtained array of experimental values allow us to draw a conclusion about the significant influence of composite materials in the tribosystem on the dependence of tribosystem run-in. Little value of rheological properties of combined materials and tribosystem RS_{TS} increases break-in time and increases volumetric wear rate and friction coefficient. Conversely, an increase in size RS_{TS} reduces the running-in time and reduces the values of the volumetric rate of wear and the coefficient of friction.

Calculation of the coefficient of variation and the modeling error of the tribosystem running-in process when the rheological properties of the combined materials in the tribosystem change RS_{TS}, shows that the coefficient of variation is v = 18,4%, and the modeling error does not exceed e = 10,3%.

Technological factors that affect the change of running-in dependencies are represented by the parameters of the roughness of the friction surfaces (Ra, Sm) moving and fixed triboelements. In fig. 8 and fig. 9 presents the theoretical and experimental values of the change in the volumetric rate of wear and the friction coefficient during the run-in of tribosystems with different values of the roughness of the friction surfaces (Ra, Sm).

Conditions of the experiment. Combined materials in the tribosystem: steel 40X+Br.AZH 9-4. Kinematic diagram of "ring-ring" tribosystems, tribosystem form factor K_f = 12,5 m^{-1}; load N = 1500 N; sliding speed v_{sl} = 0,5 m/s. Roughness of friction surfaces: Ra = 0,16 micron; Ra = 0,2 micron; Ra = 0,24 micron. Average pitch of inequalities: Sm=0,4 mm.

Comparison of estimated values of the Cochrane criterion G_e and table values G_t, for the given conditions of the experiment, allows us to assert that the obtained experimental results are homogeneous and reproducible.

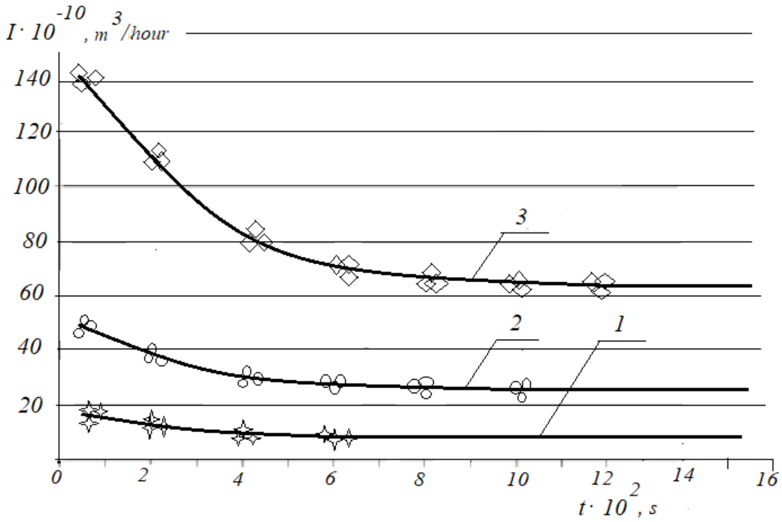

Fig. 8. Dependencies of the change in the volumetric rate of wear during the run-in of tribosystems for different values of the roughness of the friction surfaces *Ra*: 1 – *Ra* = 0,16 micron; 2 – *Ra* = 0,2 micron; 3 – *Ra* = 0,24 micron

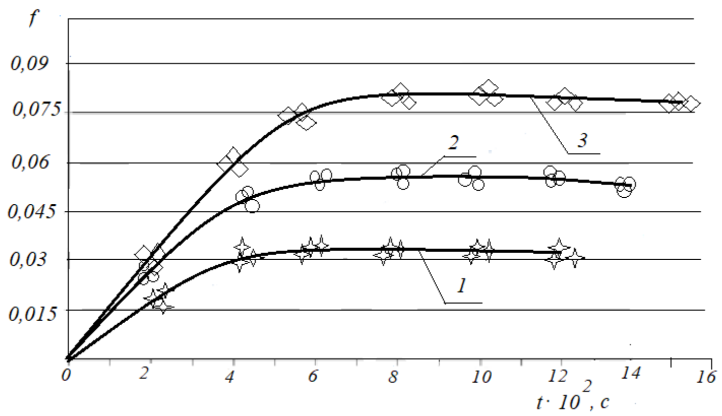

Fig. 9. Dependencies of the change in the friction coefficient during the running-in of tribosystems for different roughness values on the friction surfaces *Ra*: 1 – *Ra* = 0,16 micron; 2 – *Ra* = 0,2 micron; 3 – *Ra* = 0,24 micron

The results of experimental studies confirm the results of modeling and allow us to draw a conclusion about the significant influence of the roughness of the friction surfaces on the character of the tribosystems' running-in. When changing the value Ra = 0,16 micron to the size Ra = 0,24 micron, the coefficient of variation increases from the value v = 4,5% to the size v = 26,5%. The value of the modeling error in the entire range of studies is e = 12,5%. Operating factors that affect the nature of tribosystems running-in are expressed through parameters: load and sliding speed.

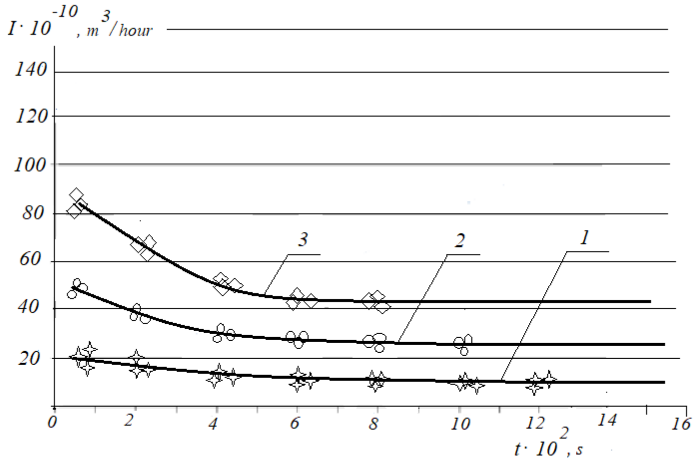

Fig. 10. Dependencies of the change in the volumetric rate of wear during tribosystem running-in for different load values *N*: 1 – *N* = 750 N; 2 - *N* = 1500 N; 3 - *N* = 2250 N

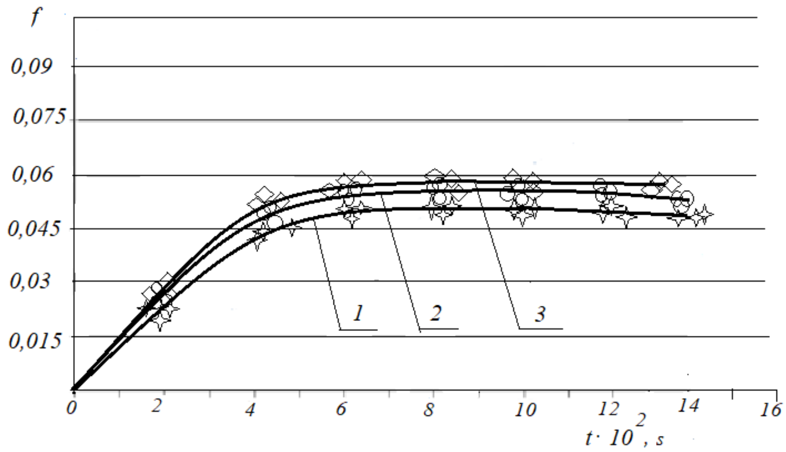

Fig. 11. Dependencies of the change in the friction coefficient during the tribosystem running-in for different load values *N*: 1 – *N* = 750 N; 2 - *N* = 1500 N; 3 - *N* = 2250 N

In fig. 10 and fig. 11 presents the theoretical and experimental values of the change in the character of the tribosystem run-in when the load N changes, and fig. 12 and fig. 13 when changing the sliding speed v_{sl}.

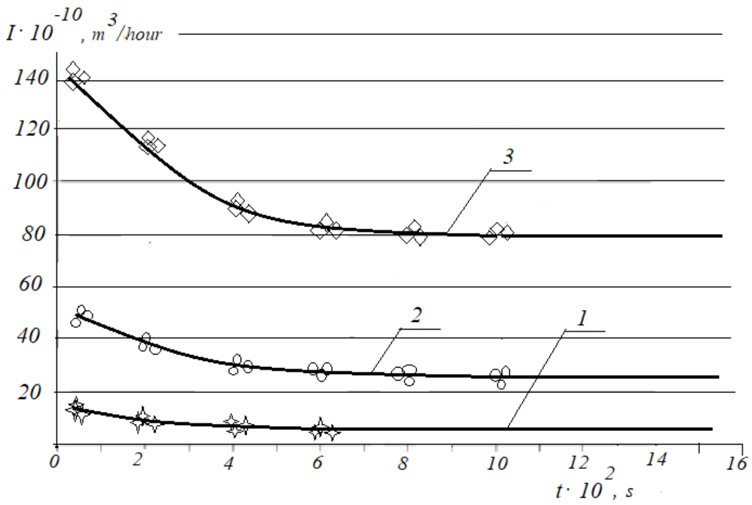

Fig. 12. Dependencies of the change in the volumetric rate of wear during tribosystem running-in for different values of the sliding speed v_{sl}: 1 – v_{sl} = 0,2 m/s; 2 – v_{sl} = 0,5 m/s; 3 – v_{sl} = 0,8 m/s

Conditions of the experiment. Combined materials in the tribosystem: steel 40X+Br.AZH 9-4. Kinematic diagram of "ring-ring" tribosystems, tribosystem form factor K_f = 12,5 m^{-1}. Lubricating medium - motor oil M – 10G$_{2к}$ (E_u= 3,6·10^{14} J/m^3).

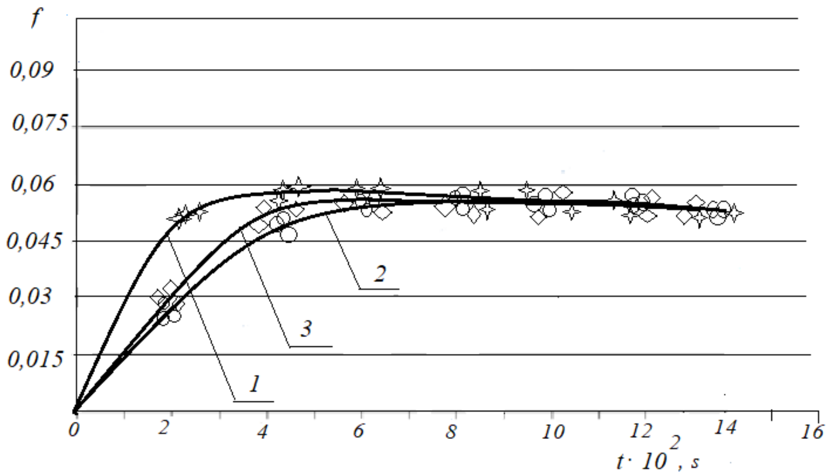

Fig. 13. Dependencies of the change in the friction coefficient during tribosystem running-in for different sliding speed values v_{sl} : 1 – v_{sl} = 0,2 m/s; 2 – v_{sl} = 0,5 m/s; 3 – v_{sl} = 0,8 m/s

Roughness of friction surfaces: *Ra* = 0,2 micron; average step of inequalities: *Sm* = 0,4 mm. Load *N* = 750; 1500; 2250 N; sliding speed v_{sl} = 0,2; 0,5; 0,8 m/s.

Comparison of estimated values of the Cochrane criterion G_e and table values G_t, for the given conditions of the experiment, allows us to assert that the obtained experimental results are homogeneous and reproducible.

The results of experimental studies confirm the significant influence of load and sliding speed on the nature of tribosystems' running-in. An increase in the amount of load contributes to a decrease in the running-in time, which is positive, but it increases the volume rate of wear, fig. 10, and the coefficient of friction, fig. 11. The coefficient of variation of the values of the volumetric wear rate and the coefficient of friction increases from the value *v* = 6,4% to the size *v* = 20,8%. The value of the modeling error in the entire range of studies is *e* = 11,7%.

When changing the value of the sliding speed, it was established that the minimum run-in time is characteristic for the minimum sliding speed. At the same time, the volumetric rate of wear has minimal values, fig. 12, and the friction coefficient, maximum values, fig. 13. The coefficient of variation is within the limits *v* = 13,5 - 18,6%. The value of the modeling error in the entire range of studies is *e* = 12,9%.

Based on the results of theoretical and experimental data, it is possible to build a ranking of factors that have the greatest influence on the running-in process. In the first city - the roughness of the friction surfaces, the coefficient of variation *v* = 26,5%. In the second place – the load on the tribosystem during running-in, the coefficient of variation *v* = 20,8%. On the third city - the value of the sliding speed during running-in, the coefficient of variation *v* = 18,6%. The conclusion made must be taken into account when developing a rational program for running in tribosystems in conditions of extreme lubrication.

Conclusions

An experimental verification of the mathematical model of tribosystem running-in processes was carried out. Comparing the theoretically obtained results, by modeling according to the developed models, with experimental data, it was established that the mathematical model adequately reflects the running-in processes taking into account the changes in constructive, technological and operational factors. Applying the Cochrane criterion, it was established that the obtained experimental results are homogeneous and reproducible. The maximum value of the coefficient of variation of the values of the volumetric wear rate and the coefficient of friction is within the limits *v* = 12,3 - 26,5%. The value of the simulation error is within the limits *v* = 7,7 - 12,9%.

A rating of factors that maximally affect the processes of running-in of tribosystems in the conditions of extreme lubrication has been obtained. In the first place - the roughness of the friction surfaces, the coefficient of variation *v* = 26,5%. In the second place – the load on the tribosystem during running-in, the coefficient of variation *v* = 20,8%. On the third place - the value of the sliding speed during running-in, the coefficient of variation *v* = 18,6%. The conclusion made must be taken into account when developing a rational program for running in tribosystems in conditions of extreme lubrication.

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Войтов А.В. Математична модель припрацювання трибосистем в умовах граничного мащення. Частина 2. Результати моделювання

В роботі наведено результати математичного моделювання процесів припрацювання трибосистем при зміні різних факторів: конструктивних параметрів трибосистем, які враховуються коефіцієнтом форми; трибологичних властивостей змащувального середовища; реологічних властивостей сполучених матеріалів в трибосистемі; шорсткість поверхонь тертя; навантаження та швидкість ковзання. Порівнюючи теоретично отримані результати, шляхом моделювання за розробленими моделями, з експериментальними даними, встановлено, що математична модель адекватно відображає процеси припрацювання з урахуванням зміни конструктивних, технологічних та експлуатаційних факторів. Застосовуючи критерій Кохрена встановлено, що отримані експериментальні результати однорідні і відтворювані. Максимальне значення коефіцієнта варіації значень об'ємної швидкості зношування та коефіцієнта тертя знаходиться в межах v = 12,3 - 26,5%. Значення похибки моделювання знаходиться в межах v = 7,7 - 12,9%.

Отримано рейтинг факторів, які максимально впливають на процеси припрацювання трибосистем в умовах граничного мащення. На першому місті – шорсткість поверхонь тертя, коефіцієнт варіації v = 26,5%. На другому місті – навантаження на трибосистему під час припрацювання, коефіцієнт варіації v = 20,8%. На третьому місті – величина швидкості ковзання під час припрацювання, коефіцієнт варіації v = 18,6%. Зроблений висновок необхідно враховувати при розробці раціональної програми припрацювання трибосистем в умовах граничного мащення.

Представлено методичний підхід застосування метода акустичної емісії при дослідженні процесів припрацювання трибосистем. В роботі доведено, що для визначення об`ємної швидкості зношування під час припрацювання трибосистем, необхідно реєструвати та аналізувати четвертий кластер з загального сигналу акустичної емісії. Джерелами генерації сигналу четвертого кластеру є мікрорізання і пластична деформація виступів шорсткості поверхні тертя, яке характерне для перших етапів припрацювання.

Keywords: трибосистема; припрацювання; математична модель припрацювання; граничне мащення; коефіцієнт форми; трибологічні властивості змащувального середовища; реологічні властивості сполучених матеріалів; швидкість зношування; коефіцієнт тертя