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Substantiation of a rational program for the running-in of tribosystems

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Abstract

The paper presents the results of studies on the justification of a rational program for running-in of tribosystems. It is shown that the first component of the program is the fulfillment of the condition on the verge of loss of stability due to the appearance of accelerated wear, with the maximum load on the tribosystem and the minimum sliding speed. This mode performs the function of "training" the surface layers for future operating conditions due to deformation processes and changes in the roughness of the friction surfaces. The mode is characterized by minimum wear rate values and maximum friction coefficient values.

The second component of the running-in program is the fulfillment of the condition on the verge of loss of stability due to the appearance of burrs on the friction surfaces, with minimal load on the tribosystem and maximum sliding speed. This mode performs the function of "adaptation" of the surface layers to the future operating conditions by increasing the rate of deformation of the materials of the surface layers on the spots of actual contact. The mode is characterized by maximum wear rate values and minimum friction coefficient values.

The third mode of the program aims to form surface structures and roughness on the friction surfaces of tribosystems that correspond to operational modes. This mode performs the function of "sufficient adaptation" of the surface layers to the future operating conditions, and corresponds to the condition with the maximum value of the stability margin. The final result of the running-in process is the transition of the tribosystem from an unbalanced, thermodynamically unstable state to a stationary, equilibrium state, as a result of which such parameters as wear rate, friction coefficient, temperature and roughness of the friction surfaces are stabilized. Such a step-by-step transition is associated with the formation of a special, dissipative structure of the surface layers of triboelements as a result of self-organization.

The use of the three-mode program will reduce the time for tribosystems to run in by 23.0 - 38.4% compared to other programs. The effectiveness of the developed three-mode program is proven by experimental studies with the calculation of the modeling error.

Keywords: tribosystem; practice; training program; marginal lubrication; wear rate; coefficient of friction; running-in time; wear and tear during the running-in period; loss of stability of the tribosystem

Introduction

An analysis of scientific publications devoted to the study of running-in processes and running-in programs allows us to formulate a general definition of the process. The running-in of tribosystems is a non-stationary transient friction process, 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. In the process of running-in, bearing surface layers are formed in tribosystems, providing in the future a maximum resource and minimum friction losses.

The running-in process is the final technological stage in the production of machines and the initial stage of their operation. The fact of the completion of the running-in process is reduced not only to the formation of the optimal roughness of the mating friction surfaces. The running-in process includes physical and chemical phenomena in the surface layers of triboelements, such as thermal, diffusion, deformation, which take place on actual contact spots in the presence of lubricating media and the environment. Therefore, reducing the running-in process, with a simultaneous decrease in wear for running-in and friction losses, will significantly increase the resource of machines, which will provide an economic effect during operation.

When developing rational running-in programs, a necessary and sufficient condition for their effectiveness is the substantiation of the modes and parameters that affect the process under study. Namely, taking into account the design of the tribosystem, the lubricating medium, the structure of the materials from which the triboelements are made, the initial roughness of the friction surfaces, the load-speed range during the running-in process, as well as during operation.

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 effective programs for the running-in of tribosystems.

Literature review

Author of the work [1] notes that running-in processes are not always subject to the systematic analysis that is used in other forms of friction and wear testing. Run-in modes are often developed by trial and error. In the author's opinion, burn-in studies are relatively rare in the tribological literature. Based on the analysis of various technologies for running in machines, the author concludes that running in is a property not only of contacting materials, but also of loading modes. In later works of this author [2] it is noted that the terms break-in and wear are related, but not identical. All of them belong to special cases within the framework of the general topic of tribological transitions. Tribological transitions may be caused by changes in operating conditions or may occur naturally as the tribosystem wears out. The author concludes that the changes in friction and wear that occur during running-in are not only the result of changes in surface roughness. Depending on the tribosystem, these may include changes in surface composition, microstructure, and distribution of third bodies. Examples are given of how factors such as roughness reduction and surface pretreatment affect the shape of transient curves. The relationship of friction and wear during running-in is discussed, as well as scale effects, the relative influence of which also varies with time. The author notes that the initial burn-in behavior can be influenced by nanometer-sized surface films and progress to micrometer-sized asperities and larger surface structures.

Authors of the work [3] note that the initial roughness of the friction surfaces undergoes various changes and deformations of the surface layers, which leads to a nonlinear wear rate during running-in. This article presents an experimentally tested model for predicting the development of the running-in process and changes in the friction coefficient, roughness parameters, as a function of running-in time. To do this, the authors use a three-dimensional numerical model.

Works [4-6] devoted to the study of the effect of initial roughness on the process of running-in of tribosystems. For example, at work [4] it is concluded that the value of the initial roughness of the friction surfaces is the main factor influencing the running-in time. In work [5] it is concluded that in order to reduce the running-in phase, an effective option is to select point topographic parameters of the friction surface to optimize the initial contact conditions. The authors explore various technological methods (milling, grinding, polishing) in order to reduce the running-in time. In work [6] based on the results of transmission electron microscopy and X-ray diffraction studies, it was found that each material is characterized by its own specific state of the surface layer structure, which corresponds to friction conditions. The author found that the running-in process consists of an increase in the density of dislocations, the formation of dislocation clusters and a fragmented structure. The kinetics of microstructure formation in surface layers during friction during running-in predetermines the processes of hardening, negative hardening, and wear of the material.

Authors of the work [7] state that the running-in process involves changing key tribological parameters such as surface roughness, coefficient of friction and wear rate until a steady state prevails. It is important to note that the stationary behavior of the tribosystem depends on the running-in program. This article provides a comprehensive review of the literature on the subject, covering both experimental and analytical developments to date. In work [8] it is concluded that running-in can be interpreted as a process in which the fractal dimension of the friction parameters increases, and the opposite surfaces spontaneously adapt and modify each other, forming a spatial ordered structure. Based on experimental data by the authors of the work [9] dependences are obtained in the form of a transition curve, which allows you to establish a functional relationship between the duration of running-in, friction coefficient, wear for running-in with load, sliding speed and initial roughness of the friction surface. A model has been developed to predict the coefficient of friction after the completion of running-in.

In works [10, 11] tribosystem, in the process of running-in, is considered as a running-in attractor built on the basis of signals of fluctuations of friction parameters obtained as a result of experiments. The authors established the stages of "formation-stabilization-disappearance" of the processed attractor. The authors argue that the run-in attractor has a high stability. This approach can help identify burn-in conditions, predict the process, and control.

The authors of the work [12] proposed criteria for high-performance running-in. Based on the analysis of the change in the friction force, under various conditions of external influence, the conditions for accelerated running-in of tribosystems are established. The authors conclude that the first criterion is the wear rate. The second criterion for running in can be the instantaneous wear rate. According to the authors, the criteria obtained make it possible to optimize the technological regimes of running-in.

In work [13] describes a statistical approach aimed at identifying the burn-in phase and the most significant time intervals during the steady state for each test replica of the transient process. The authors proposed a two-stage running-in program procedure based on the application of the initial load method. The program allows you to automatically determine the run-in time interval and filter steady state outliers. In work [14] a multi-purpose optimization of the two-stage process of running complex tribosystems is proposed. According to the authors, the quality of running-in can be improved by optimizing the running-in parameters (load, speed and running-in time).

In work [15] 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 [16]. 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 learning 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 run-in time and wear during the run-in period.

In work [17] 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 run-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 "on the border of jamming".

Continuation of work [17] there is work [18], which gives 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%.

Summing up the analysis of works devoted to the processes of running-in of tribosystems, we can make a platoon about the inconsistency of opinions about the choice of modes that affect the process. A reasonable choice of running-in modes and their sequence constitutes a running-in program. The break-in program aims to reduce run-in wear and run-in time. As follows from the analysis of publications, which is given above, these are programs that provide running-in “on the border of jamming”. In this case, the input action on the tribosystem must change in time, have a positive and negative gradient.

Purpose

The purpose of this study is to substantiate a rational program for running in various designs of tribosystems, to experimentally confirm the effectiveness of a multi-mode program.

Methods

From the review of the works given in the review of literary sources, it can be concluded that the most promising program or mode of running-in of tribosystems is running-in "on the edge of burr", in our case "on the edge of loss of stability of the tribosystem". From the conclusions of the work [19] it follows that the loss of stability of the tribosystem, depending on the magnitude of the load and speed of sliding and the speed of external influence, may occur in the form of the appearance of accelerated wear or burr. Therefore, the term "on the verge of loss of stability of the tribosystem" is more correct. The final result of the running-in process is the transition of the tribosystem from an unbalanced, thermodynamically unstable state to a stationary, balanced state, as a result of which such parameters as wear rate, friction coefficient, temperature and roughness of the friction surfaces are stabilized. Such a transition is associated with the formation of a special, dissipative structure of the surface layers of triboelements as a result of self-organization.

Creation of such warm-up conditions is possible using several stages. At the same time, the running-in process must meet the following requirements.

1. Practice time t_{pr} must have a minimum value, $t_{pr} \rightarrow$ min;
2. The amount of wear during the run-in time U should be minimal, $U \rightarrow$ min.
3. Friction losses (friction coefficient) go to minimum values during running-in, $f_{st} \rightarrow$ min.

4. The running-in program should provide a minimum value of the wear rate at a steady state after the running-in is completed, $I_{st} \rightarrow \min$.

The purpose of running-in modes is determined by the limit of loss of stability of the tribosystem, the method of determining which is given in [19]. During running-in, the process of converting the mechanical energy of friction into internal energy, primarily thermal energy, which is dissipated into the environment due to thermal conductivity, as well as the energy of structural changes in the surface layers of triboelement materials, takes place.

If the amount of mechanical energy (power - W) will exceed the permissible limit, $RR = 1$, the formula for calculation is given in [19], loss of stability of the tribosystem may occur, i.e. burr or accelerated wear of the triboelements of the tribosystem occurs.

We justify the first running-in mode on the basis of the dependencies given in the work [18]. Selection of the maximum load – N_{max}, (on the verge of loss of stability) at a minimum sliding speed will ensure a minimum rate of wear during run-in. In this case, the coefficient of friction will have a maximum value, but a minimum running-in time. The loss of stability of the tribosystem is possible due to accelerated wear, this has been proven in the work [18]. Therefore, the first component of the training program is the fulfillment of the condition $RR = 1$, at maximum load and minimum sliding speed.

$$№1 = (N = N_{\max}; v_{sl} = v_{sl(\min)}; W = W_b), \quad (1)$$
$$RR = 1, t_l = 20s.$$

where N – load on the tribosystem, dimensions N;

N_{max} – maximum load on the tribosystem, on the verge of loss of stability, dimension N;

v_{sl} – sliding speed, dimension m/s;

$v_{sl(min)}$ – minimum sliding speed, dimension m/s;

W – the power supplied to the tribosystem, dimension W;

W_b – the power supplied to the tribosystem on the verge of loss of stability, dimension W;

RR – the value of the range of robustness of the tribosystem, a dimensionless value, is calculated according to the formula given in the work [19];

t_l – tribosystem load time, dimensions – s.

The load on the tribosystem increases for 20 seconds.

The second mode of the program can be justified on the basis of the working-in dependencies, which are given in the work **[**18**]**. After the coefficient of friction reaches its maximum value during run-in and temporary stabilization, it is necessary to switch to the second run-in mode. The purpose of the second mode is to increase the rate of deformation in the surface layers of triboelement materials to complete the formation of the structure of the surface layers (increase in hardness, formation of secondary structures and oxide films). Increasing the sliding speed reduces the coefficient of friction, which is positive, but increases the volumetric wear rate. The use of such a mode can be justified by the transition of the tribosystem to the limit of loss of stability due to burr [18].

Based on the above, let's write the second mode of the running-in program:

$$№2 = (N = N_{\min}; v_{sl} = v_{sl(op)}; W = W_b), \quad (2)$$
$$RR = 1, t_l = 5s.$$

where $v_{sl(op)}$ – sliding speed, which is equal to the operating mode, dimension m/s;

Therefore, the second component of the training program is also the fulfillment of the condition $RR = 1$, at the minimum load and the maximum sliding speed, which is equal to the operating speed. Such a mode also corresponds to the mode "on the verge of loss of stability of the tribosystem", i.e $RR = 1$. The load on the tribosystem increases for 5 seconds.

The third mode of the program can be justified by the need to form roughness on the friction surfaces of tribosystems that corresponds to the operating modes. The use of such a mode can be justified by the transition of the surface layers of the tribosystem to the operating mode.

$$№3 = (N = N_{op}; v_{sl} = v_{sl(op)}; W \langle W_b), \quad (3)$$
$$RR \rangle 1, t_l = 5s.$$

where $N_{(op)}$ – the load on the tribosystem, which is equal to the operating mode, dimension N.

At the same time, the value of the load and sliding speed is equal to the value that will be in operation, that is, the condition is fulfilled $W<W_b$. This mode has a margin of robustness, i.e $RR > 1$. The load on the tribosystem increases for 5 seconds.

The proposed program differs from the known ones in that it takes into account the load speed of the tribosystem, which is presented in the paper [19] in the form of load dynamic coefficient k_d. This requirement is justified by the right-hand side of the differential equation [19] and represented by the parameter t_l – load time, s.

The completion time of the first mode of the program, as well as the second mode, is determined by the simulation results. At the same time, experimentally, by the AE method, work [18], the following values are determined: the maximum value of the wear rate I_{max} and friction coefficient f_{max} during practice; constant wear rate value I_{st} and friction coefficient f_{st} after completion of practice; break-in time according to the wear rate and friction coefficient parameters t_{run} and values of linear wear during the run-in period U.

Results

For simulation of the running-in process and experimental verification of the running-in results, we will choose the following conditions.

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}. Roughness of friction surfaces: Ra = 0,2 micron; average step of inequalities: Sm=0,4 mm. The lubricating medium is motor oil M-10G2к. (E_u= 3,6·10^{14}J/m^3). For registration of AE signals on a stationary triboelement (Br.AZH 9-4), with a smaller friction area, an acoustic emission sensor was installed, as shown in the paper [18]. The purpose of the experiment is to confirm the effectiveness of the proposed three-mode training program.

The results of mathematical modeling according to the developed method are shown in fig.1 and fig.2.

First mode, curve №1: N = 5500 N; v_{sl} = 0,2 m/s; W_b = 2100 W; RR =1; t_l = 20 s.

The second mode, the curve №2: N = 2100 N; v_{sl} = 0,5 m/s; W_b = 2100 W; RR =1; t_l = 5 s.

The third mode, curve № 3, operating mode: N = 1700 N; v_{sl} = 0,5 m/s; W_b = 2100 W; RR >1; t_l = 5 s.

The number of the curve indicates the number of the mode, and the time: t_{run1}; t_{run2}; t_{run3} – run-in time for each of the modes.

Values of wear for running-in U_1; U_2; U_3 we define as the area under the corresponding curve according to the formula:

$$U = \sum_{i=1}^{n} \frac{I_i \cdot t_i}{F_{fr}}, m, \quad (4)$$

where n – number of division of the area under the curve into rectangular uniform sections;

I_i – the wear rate per unit area, m^3/h, is determined using the AE method;

t_i – the time of work on a unit area is equal to 100 seconds, that is, 0.0277 hours;

F_{fr} – the friction area of the stationary triboelement on which the AE sensor is installed is equal to 0,00015 m^2.

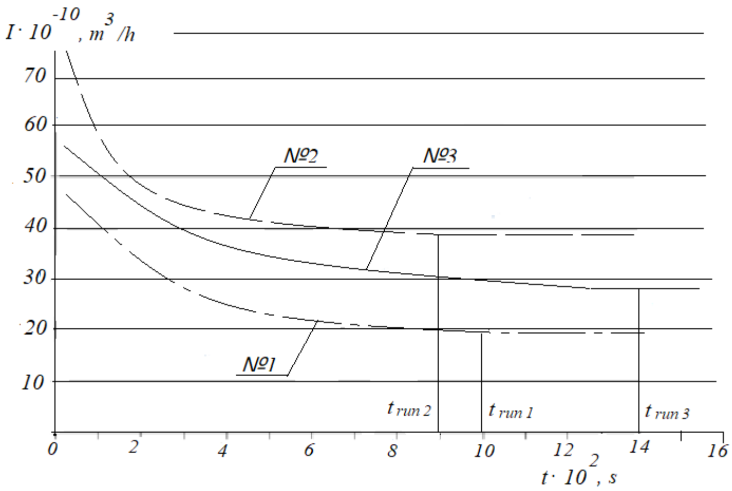

Fig. 1. Dependencies of changes in the volume rate of wear during the running-in of tribosystems under different modes: №1 – mode №1; №2 – mode №2; №3 – mode №3

Analysis of the curves in fig. 1 allows us to conclude that the maximum wear during running-in U_2 = 7,88 micron will be when using the mode №2, the area under the curve has the maximum value. At the same time, it is time to get used to it $t_{run\,2}$, has a minimum value of 900 seconds. Friction coefficient for mode №2 has a minimum value of 0,056, fig. 2.

Analysis of transition curves for the mode №1, fig. 1, allows us to conclude that this regime is characterized by minimal wear during running-in U_1 = 4,84 micron, the area under the curve has a minimum value.

At the same time, it is time to get used to it $t_{run\ 1}$, compared to mode №2, increased, and is equal to 1000 seconds. Friction coefficient for mode №1 has a maximum value equal to 0,061, fig. 2.

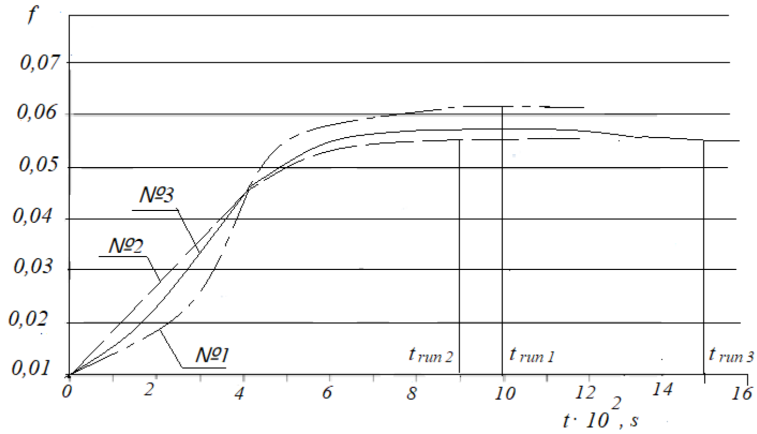

Fig. 2. Dependencies of the change in the friction coefficient during the running-in of tribosystems in different modes: №1 – mode №1; №2 – mode №2; №3 – mode №3

When applying the mode №3, fig. 1, wear for running-in U_3 = 9,24 micron. At the same time, it is time to get used to it $t_{run\ 3}$, has a maximum value of 1500 seconds. Friction coefficient for mode №3 is equal to 0,055, fig. 2.

A joint analysis of the running-in curves shown in fig. 1 and fig. 2, allows you to substantiate the tribosystem run-in program when the conditions are met: $U \rightarrow$ min, $t_{run} \rightarrow$ min. Such a program is shown in fig. 3 and fig. 4, bold curve. According to fig. 3 run-in must be started on the first mode, curve №1: N = 5500 N; v_{sl} = 0,2 m/s; W_b = 2100 W; RR =1; t_l = 20 s.

When the time is reached t_{run} = 1000s, when the rate of wear stabilizes, it is necessary to switch to the second mode, the curve №2: N = 2100 N; v_{sl} = 0,5 m/s; W_b = 2100 W; RR =1; t_l = 5 s.

When the time is reached t_{run} = 1300s, when the wear rate and friction coefficient stabilize, it is necessary to switch to the third mode, the curve №3, mode of operation: N = 1700 N; v_{sl} = 0,5 m/s; W_b = 2100 W; RR >1; t_l = 5 s.

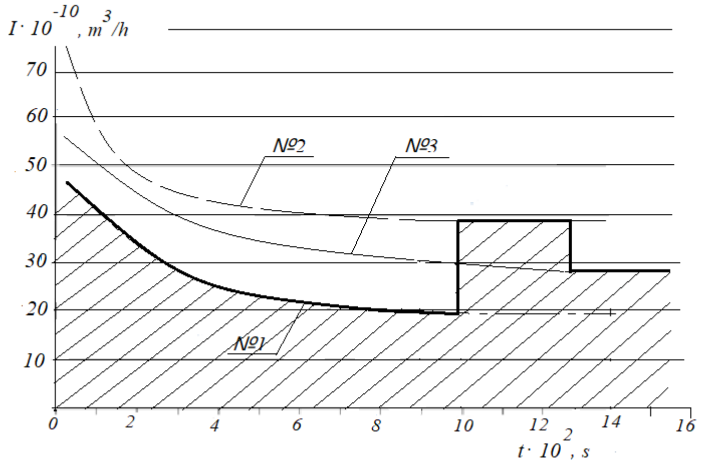

Fig. 3. Dependences of changes in the volumetric rate of wear during the run-in of tribosystems according to a rational program - bold curve. The area under the curve is wear and tear

The transient characteristic of such a program is shown in fig. 3 and fig. 4 with a bold line. The total wear during running-in (the area under the bold curve) will U = 6,84 micron, and the period of running-in t_{run} = 1300s.

Experimental verification of the tribosystem run-in program. The purpose of this subsection is to experimentally confirm the simulation results, and therefore to confirm the effectiveness of the three-mode warm-up program.

During the experiment, after every 100 seconds, the value of the moment of friction was recorded, which was converted into a coefficient of friction, as well as the value of the amplitude of the acoustic emission, the value of which was used to determine the rate of wear. The running-in time was determined by the stabilization of the wear rate and the friction coefficient relative to a constant value.

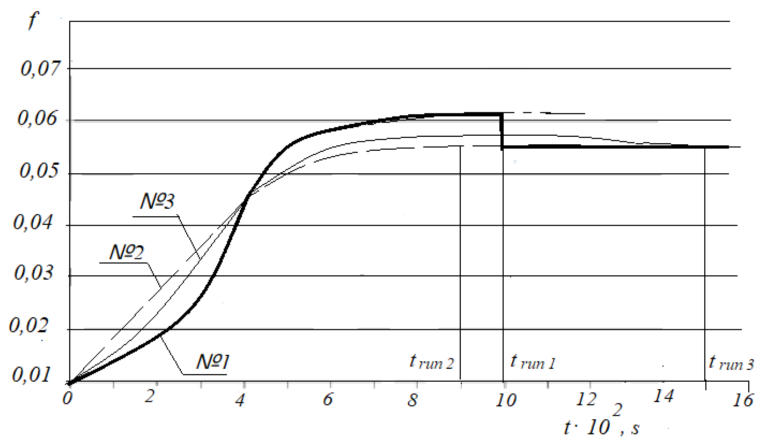

Fig. 4. Dependencies of the change in the friction coefficient during the run-in of tribosystems according to the rational program - bold curve

The results of the experiments were repeated 3 times, with the calculation of the values Cochrane criterion to confirm the reproducibility of the results from experiment to experiment. The relative error of the simulation and experiment results was determined for the rate of wear e_I, coefficient of friction e_f according to the expressions given in the work [18].

The relative error of the simulation for the running-in time e_t we determine by the expression:

$$e_t = \left| \frac{t_{run,\exp} - t_{run,s}}{t_{run,\exp}} \right| \cdot 100\,\%\,, \tag{5}$$

where $t_{run,exp}$ and $t_{run,s}$ – the value of the run-in time, which is obtained due to the experiment and due to simulation, the dimension is seconds.

Table 1. Comparison of simulation and experiment results by run-in mode №1

The time of the running-in process t,s	$I_s \cdot 10^{-10}$, m^3/h	$I_{exp} \cdot 10^{-10}$, m^3/h (average value)	e_I, %	f_s	f_{exp} (average value)	e_f, %
100	46	56,81	19,0	0,008	0,0096	16,6
200	36	44,8	19,6	0,018	0,021	14,2
300	31	37,9	18,2	0,025	0,029	13,7
400	26	32	18,7	0,046	0,052	11.5
500	23	28	17,8	0,052	0,058	10,3
600	22	26,5	16,9	0,056	0,063	11,1
700	21	25,0	16,0	0,058	0,064	9,3
800	20	23,8	15,9	0,06	0,066	9,0
900	19,5	22,5	13,3	0,061	0,065	6,1
1000	19	21	9,5	0,061	0,064	4,6
1100	18,5	20	7,5	0,061	0,064	4,6
1200	18,5	20	7,5	0,061	0,064	4,6

Comparison of simulation and experiment results for steel tribosystem 40X + Br.AZH 9-4 when using the mode №1 (curve №1 in fig. 1 and fig.2) presented in the table 1.

The running-in time according to the simulation results is equal to $t_{run,s}$ = 1000 s. The average value of the running-in time according to the results of the experiment (three times) is equal to $t_{run,s}$ = 1200 s. The error of simulation of the run-in time, formula (5), is equal to 20%.

The analysis of the results of table 1 allows us to conclude that the error of modeling the running-in process according to the wear rate parameter is within e_I = 7,5 – 19,0%, by the friction coefficient parameter e_f = 4,6 - 16,6%.

Comparison of simulation and experiment results for tribosystem steel 40X + Br.AZH 9-4 when using the mode №2 (curve №2 in fig. 1 and fig.2) presented in the table 2.

Table 2. Comparison of simulation and experiment results by run-in mode №2

The time of the running-in process t,s	$I_s \cdot 10^{-10}$, m^3/h	$I_{exp} \cdot 10^{-10}$, m^3/h (average value)	e_I, %	f_s	f_{exp} (average value)	e_f, %
100	76	91	16,4	0,008	0,0094	14,8
200	59	70,2	15,9	0,026	0,030	13,3
300	48	56	14,2	0,038	0,043	11,6
400	45	51	11,7	0,047	0,053	11.3
500	42	47	10,6	0,050	0,056	10,7
600	41	46	10,8	0,054	0,060	10,0
700	40	44,0	9,0	0,055	0,061	9,8
800	39	43	9,3	0,056	0,062	9,6
900	38	41	7,3	0,056	0,062	9,6
1000	37	40	7,5	0,056	0,062	9,6
1100	37	40	7,5	0,056	0,062	9,6
1200	37	40	7,5	0,056	0,062	9,6
1300	37	40	7,5	0,056	0,062	9,6

The running-in time according to the simulation results is equal to $t_{run,s}$ = 900 s. The average value of the running-in time according to the results of the experiment (three times) is equal to $t_{run,s}$ = 1100 s. The error of modeling the run-in time is equal to 18,18%.

The analysis of the results of table 2 allows us to conclude that the error of modeling the running-in process according to the wear rate parameter is within e_I = 7,5 – 16,4%, by the friction coefficient parameter e_f = 9,6 - 14,8%.

Comparison of simulation and experiment results for tribosystem steel 40X + Br.AZH 9-4 when using the mode №3 (curve №3 in fig. 1 and fig.2) presented in the table 3.

The running-in time according to the simulation results is equal to $t_{run,s}$ = 1500 s. The average value of the running-in time according to the results of the experiment (three times) is equal to $t_{run,s}$ = 1850 s. The error of modeling the run-in time is equal to 18,9%.

Table 3. Comparison of simulation and experiment results by run-in mode №3

The time of the running-in process t,s	$I_s \cdot 10^{-10}$, m^3/h	$I_{exp} \cdot 10^{-10}$, m^3/h (average value)	e_I, %	f_s	f_{exp} (average value)	e_f, %
100	56	70	20,0	0,014	0,018	22,2
200	44	55	20	0,031	0,038	18,4
300	40	49	18,3	0,035	0,043	18,6
400	35	43	18,6	0,048	0,056	14.2
500	33	40	17,5	0,050	0,057	12,2
600	32	38	15,7	0,055	0,062	11,2
700	31,5	37,0	14,8	0,056	0,062	9,6
800	31	35	11,4	0,057	0,063	9,5
900	30,5	34	10,2	0,057	0,063	9,5
1000	30	33	9,0	0,057	0,063	9,5
1100	29,5	32	7,8	0,057	0,063	9,5
1200	29	31	6,4	0,056	0,062	9,6
1300	28,5	30,5	6,5	0,056	0,062	9,6
1400	28	30	6,6	0,056	0,062	9,6
1500	27,5	29	5,1	0,055	0,062	11,2
1600	27	28,5	5,2	0,055	0,062	11,2
1700	27	28,5	5,2	0,055	0,062	11,2
1800	27	28,5	5,2	0,055	0,062	11,2
1900	27	28,5	5,2	0,055	0,061	9,8
2000	27	28,5	5,2	0,055	0,061	9,8

The analysis of the results of table 3 allows us to conclude that the error of modeling the running-in process according to the wear rate parameter is within e_I = 5,2 – 20,0%, by the friction coefficient parameter e_f = 9,5 - 22,2%.

Comparison of simulation and experiment results for tribosystem steel 40X + Br.AZH 9-4 when applying the developed program, presented in the table 4.

Table 4. Comparison of simulation and experiment results when applying the developed running-in program

The time of the running-in process *t,s*	$I_s \cdot 10^{-10}$, m^3/h	$I_{exp} \cdot 10^{-10}$, m^3/h (average value)	e_I, %	f_s	f_{exp} (average value)	e_f, %
The first mode, curve №1: N = 5500 N; v_{sl} = 0,2 m/s; W_b = 2100 W; RR =1; t_l = 20 s.						
100	46	56,81	19,0	0,008	0,0096	16,6
200	36	44,8	19,6	0,018	0,021	14,2
300	31	37,9	18,2	0,025	0,029	13,7
400	26	32	18,7	0,046	0,052	11.5
500	23	28	17,8	0,052	0,058	10,3
600	22	26,5	16,9	0,056	0,063	11,1
700	21	25,0	16,0	0,058	0,064	9,3
800	20	23,8	15,9	0,06	0,066	9,0
900	19,5	22,5	13,3	0,061	0,065	6,1
1000	19	21	9,5	0,061	0,064	4,6
The second mode, the curve №2: N = 2100 N; v_{sl} = 0,5 m/s; W_b = 2100 W; RR =1; t_l = 5 s.						
1100	37	40	7,5	0,056	0,062	9,6
1200	37	40	7,5	0,056	0,062	9,6
1300	37	40	7,5	0,056	0,062	9,6
The third mode, the curve №3, mode of operation: N = 1700 N; v_{sl} = 0,5 m/s; W_b= 2100 W; RR >1; t_l = 5 s.						
1400	28	30	6,6	0,056	0,062	9,6
1500	28	30	6,6	0,056	0,062	9,6
1600	28	30	6,6	0,056	0,062	9,6

The running-in time according to the simulation results is equal to $t_{run,s}$ = 1300 s. The average value of the running-in time according to the results of the experiment (three times) is equal to $t_{run,s}$ = 1300 s.

The analysis of the results of table 4 allows us to conclude that the error of modeling the running-in process according to the wear rate parameter is within e_I = 6,6 – 19,0%, by the friction coefficient parameter e_f = 4,6 - 16,6%. Comparison of simulation and experiment results for tribosystem steel 40X + Br.AZH 9-4 when using a step program, presented in table 5. The first stage N = 500 N. The second stage N = 1100 N. The third stage 1700 N.

Table 5. Comparison of simulation and experiment results when using a step-by-step running-in program

The time of the running-in process *t,s*	$I_s \cdot 10^{-10}$, m^3/h	$I_{exp} \cdot 10^{-10}$, m^3/h (average value)	e_I, %	f_s	f_{exp} (average value)	e_f, %
The first stage N = 500 N						
100	17	20	15,0	0,02	0,024	16,6
200	12	14	14,2	0,032	0,038	15,7
300	9,8	11	10,9	0,039	0,045	13,3
400	8,8	9,7	9,2	0,043	0,049	12,2
500	8,2	9	8,8	0,046	0,052	11,5
600	7,9	8,5	7,0	0,048	0,054	11,1
700	7,8	8,3	6,0	0,049	0,054	9,2
The second stage N = 1100 N						
800	17	20	15,0	0,055	0,061	9,8
900	16,8	19	11,5	0,055	0,061	9,8
1000	16,5	18	8,3	0,055	0,061	9,8
1100	16,2	17,6	7,9	0,055	0,061	9,8
The third stage N = 1700 N						
1200	29	36	19,4	0,057	0,063	9,5
1300	29	35,5	18,3	0,057	0,063	9,5
1400	28,9	35	17,4	0,057	0,063	9,5
1500	28,5	34	16,1	0,057	0,063	9,5
1600	28,3	33	14,2	0,056	0,062	9,6
1700	27,5	31	11,2	0,055	0,061	9,8

1800	27,0	30	10,0	0,055	0,061	9,8

The running-in time according to the simulation results is equal to $t_{run,s}$ = 1800 s. The average value of the running-in time according to the results of the experiment (three repetitions) is equal to $t_{run,s}$ = 1700 s. The error of modeling the run-in time is equal to 5,8%.

The analysis of the results of table 5 allows us to conclude that the error of modeling the running-in process according to the wear rate parameter is within e_I = 6,0 – 19,4%, by the friction coefficient parameter e_f = 9,2 - 16,6%.

The general conclusion of the conducted research is a comparison of three running-in programs. The first, developed, three-mode program, which is presented in fig. 3 and fig. 4. The values of the running-in process parameters are given in table 4. The second run-in program at a constant load and sliding speed that corresponds to the operating mode. The values of the running-in process parameters are given in the table 3. The graphic representation of the program is curve № 3 in fig. 1 and fig. 2. The third running-in program - with a gradual change in the load from the minimum value to the value that corresponds to the operating mode. The values of the running-in process parameters are given in the table 5.

The results of practice on the three listed programs are presented in the table 6.

Table 6 – Comparative characteristics of various running-in programs

Running-in program	Wear during running-in U, micron	Time during running-in t_{run}, s	The rate of wear after completion of running-in $I \cdot 10^{-10}$, m^3/h	Friction coefficient after running-in, f
A three-mode program has been developed	6.84	1300	27,0	0,055
At constant load and sliding speed	9,75	1600	27,0	0,055
When the load gradually changes from the minimum value to the value that corresponds to the operating mode	6,9	1800	27,9	0,055

Conclusions

A three-mode rational program for running-in of tribosystems is substantiated. It is shown that the first component of the program is the fulfillment of the condition on the verge of loss of stability due to the appearance of accelerated wear, with the maximum load on the tribosystem and the minimum sliding speed. This mode performs the function of "training" the surface layers for future operating conditions due to deformation processes and changes in the roughness of the friction surfaces. The mode is characterized by minimum wear rate values and maximum friction coefficient values.

The second component of the running-in program is the fulfillment of the condition on the verge of loss of stability due to the appearance of burrs on the friction surfaces, with minimal load on the tribosystem and maximum sliding speed. This mode performs the function of "adaptation" of the surface layers to the future operating conditions by increasing the rate of deformation of the materials of the surface layers on the spots of actual contact. The mode is characterized by maximum wear rate values and minimum friction coefficient values.

The third mode of the program aims to form surface structures and roughness on the friction surfaces of tribosystems that correspond to operational modes. This mode performs the function of "sufficient adaptation" of the surface layers to the future operating conditions, and corresponds to the condition with the maximum value of the stability margin. The final result of the running-in process is the transition of the tribosystem from a non-equilibrium, thermodynamically unstable state to a stationary, equilibrium state, as a result of which the following parameters are stabilized, such as wear rate, coefficient of friction, temperature and roughness of friction surfaces. Such a step-by-step transition is associated with the formation of a special, dissipative structure of the surface layers of triboelements as a result of self-organization.

Experimental studies have proven that the use of a three-mode program will reduce the running-in time of tribosystems by 23,0 – 38,4% compared to other programs.

References

1. Blau, P. J. Running-in: art or engineering?. *Journal of materials engineering*, 1991, *13*(1), 47-53. https://doi.org/10.1007/BF02834123 [English]

2. Blau, P. J. On the nature of running-in. *Tribology international*, 2005, *38*(11-12), 1007-1012. https://doi.org/10.1016/j.triboint.2005.07.020 [English]

3. Ghatrehsamani, S., Akbarzadeh, S., & Khonsari, M. M. (2022). Experimentally verified prediction of friction coefficient and wear rate during running-in dry contact. *Tribology International*, 2022, *170*, 107508. https://doi.org/10.1016/j.triboint.2022.107508 [English]

4. Mezghani, S., Demirci, I., Yousfi, M., & El Mansori, M. Running-in wear modeling of honed surface for combustion engine cylinderliners. *Wear*, 2013, *302*(1-2), 1360-1369. https://doi.org/10.1016/j.wear.2013.01.026 [English]

5. Stickel, D., Fischer, A., & Bosman, R. Specific dissipated friction power distributions of machined carburized martensitic steel surfaces during running-in. *Wear*, 2015, *330*, 32-41. https://doi.org/10.1016/j.wear.2015.01.010 [English]

6. Garbar, I. Microstructural changes in surface layers of metal during running-in friction processes. *Meccanica*, 2001, *36*, 631-639. https://doi.org/10.1023/A:1016392618802 [English]

7. Khonsari, M. M., Ghatrehsamani, S., & Akbarzadeh, S. On the running-in nature of metallic tribo-components: A review. *Wear*, 2021, *474*, 203871. https://doi.org/10.1016/j.wear.2021.203871 [English]

8**.** Zhou, Y., Zuo, X., & Zhu, H. A fractal view on running-in process: taking steel-on-steel tribo-system as an example. *Industrial Lubrication and Tribology*. 2019. https://doi.org/10.1108/ILT-08-2018-0319 [English]

9. Mehdizadeh, M., Akbarzadeh, S., Shams, K., & Khonsari, M. M. Experimental investigation on the effect of operating conditions on the running-in behavior of lubricated elliptical contacts. *Tribology Letters*, 2015, *59*, 1-13. https://doi.org/10.1007/s11249-015-0538-x [English]

10. Ding, C., Zhu, H., Jiang, Y., Sun, G., & Wei, C. (2019). Recursive characteristics of a running-in attractor in a ring-on-disk tribosystem. *Journal of Tribology*, 2019, *141*(1), 011604. https://doi.org/10.1115/1.4041018 [English]

11. Zhou, Y., Zuo, X., Zhu, H., & Wei, T. (2018). Development of prediction models of running-in attractor.*Tribology International*, 2018, *117*, 98-106.https://doi.org/10.1016/j.triboint.2017.08.018 [English]

12. Volchenkov, A. V., & Nikitina, L. G. The Problem of Choosing the Modes of Running-In Curved Parts. In *Proceedings of the 8th International Conference on Industrial Engineering: ICIE*, 2022 (pp. 567-575). Cham: Springer International Publishing.https://doi.org/10.1007/978-3-031-14125-6_56 [English]

13. Ruggiero, A., Di Leo, G., Liguori, C., Russo, D., & Sommella, P. Accurate measurement of reciprocating kinetic friction coefficient through automatic detection of the running-in. *IEEE Transactions on Instrumentation and Measurement*, 2022, *69*(5), 2398-2407.DOI: 10.1109/TIM.2020.2974055 [English]

14. Zhou, Y., Wang, Z., & Zuo, X. Multi-objective optimization of three-stage running-in process for main bearing of marine diesel engine. *Journal of Tribology*, 2023, *145*(8), 081701. https://doi.org/10.1115/1.4062298 [English]

15. Ghatrehsamani, S., Akbarzadeh, S., & Khonsari, M. M. Experimental and numerical study of the running-in wear coefficient during dry sliding contact. *Surface Topography: Metrology and Properties*, 2021, *9*(1), 015009. DOI 10.1088/2051-672X/abbd7a [English]

16**.** Vojtov V. A., Biekirov A. Sh., Voitov A. V., Tsymbal B. M. Running-in procedures and performance tests for tribosystems // *Journal of Friction and Wear*, 2019, Vol. 40, No. 5, pp. 376–383. DOI: 10.3103/S1068366619050192 [English]

17. Voitov, A. Mathematical model of running-in of tribosystems under conditions of boundary lubrication. Part 1. Development of a mathematical model**.** *Problems of Tribology***,** 2023, V. *28*, No 1/107, P. 25-33. https://doi.org/10.31891/2079-1372-2022-107-1-25-33 [English]

18. Voitov, A. Mathematical model of running-in of tribosystems under conditions of boundary lubrication. Part 2. Simulation results. *Problems of Tribology***,** 2023, V. *28*, No 2/108, P. 44-55. https://doi.org/10.31891/2079-1372-2023-108-2-44-43 [English]

19. Tareq M. A. Al-Quraan, Fadi Alfaqs, Ibrahim F. S. Alrefo, Viktor Vojtov, Anton Voitov, Andrey Kravtsov, Oleksandr Miroshnyk, Andrii Kondratiev, Pavel Kučera, Václav Píštěk. Methodological Approach in the Simulation of the Robustness Boundaries of Tribosystems under the Conditions of Boundary Lubrication. *Lubricants*, 2023**,** 11, 17. https://doi.org/10.3390/lubricants11010017 [English]

Войтов В.А., Войтов А.В. Обгрунтування раціональної програми припрацювання трибосистем

В роботі наведено результати досліджень по обгрунтуванню раціональної програми припрацювання трибосистем. Показано, що першою складовою програми є виконання умови на межі втрати стійкості за появою прискореного зношування, при максимальному навантаженні на трибосистему та мінімальної швидкості ковзання. Такий режим виконує функцію «тренування» поверхневих шарів до майбутніх умов експлуатації за рахунок процесів деформування та зміну шорсткості поверхонь тертя. Режиму притаманні мінімальні значення швидкості зношування та максимальні значення коефіцієнта тертя.

Другою складовою програми припрацювання є виконання умови на межі втрати стійкості за появою задиру поверхонь тертя, при минимальному навантаженні на трибосистему та максимальної швидкості ковзання. Такий режим виконує функцію «адаптації» поверхневих шарів до майбутніх умов експлуатації за рахунок збільшення швидкості деформування матеріалів поверхневих шарів на плямах фактичного контакту. Режиму притаманні максимальні значення швидкості зношування та мінімальні значення коефіцієнта тертя.

Третій режим програми має на меті формування на поверхнях тертя трибосистем поверхневих структур та шорсткості, які відповідають експлуатаційним режимам. Такий режим виконує функцію «достатньої адаптації» поверхневих шарів до майбутніх умов експлуатації, та відповідає умові з максимальним значенням запасу стійкості. Кінцевим результатом процесу припрацювання є перехід трибосистеми з нерівноважного, термодинамічно нестійкого стану, в стаціонарний, рівноважний стан, в результаті якого стабілізуються такі параметри, як швидкість зношування, коефіцієнт тертя, температура і шорсткість поверхонь тертя. Такий покроковий перехід пов'язаний з утворенням особливої, дисипативної структури поверхневих шарів трибоелементів в результаті самоорганізації.

Застосування трьохрежимної програми дозволить зменшити час на припрацювання трибосистем на 23,0 – 38,4% в порівнянні з іншими програмами. Ефективність розробленої трьохрежимної програми доведена експериментальними дослідженнями з розрахунком похибки моделювання.

Keywords: трибосистема; припрацювання; програма припрацювання; граничне мащення; швидкість зношування; коефіцієнт тертя; час припрацювання; знос за період припрацювання; втрата стійкості трибосистемоюсередовища; реологічні властивості сполучених матеріалів; швидкість зношування; коефіцієнт тертя