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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.

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

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:

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

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.

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

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-10G$_{2к}$. (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:

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

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.

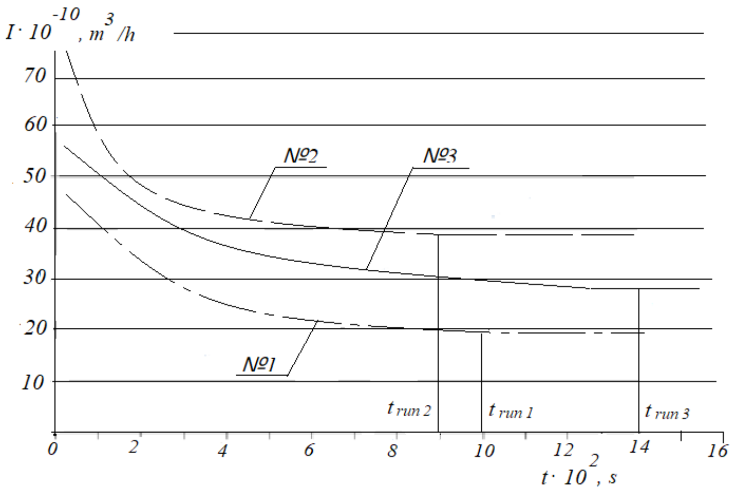

Fig. 1. Dependencies of changes in the volume rate of wear during the running-in of tribosystems under different modes: №1 – mode №1; №2 – mode №2; №3 – mode №3

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.

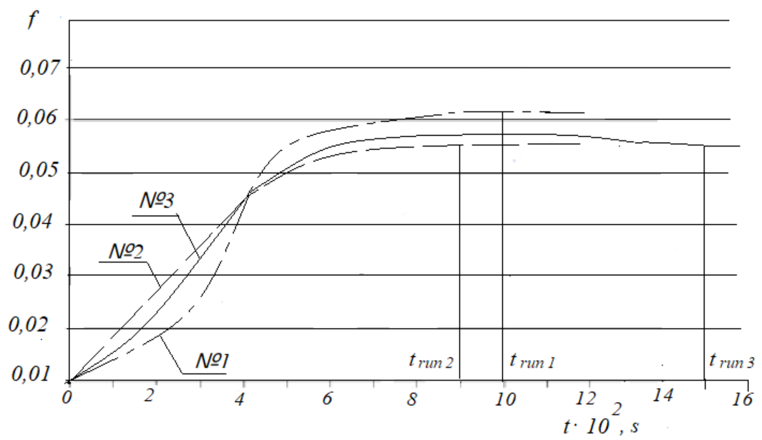

Fig. 2. Dependencies of the change in the friction coefficient during the running-in of tribosystems in different modes: №1 – mode №1; №2 – mode №2; №3 – mode №3

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.

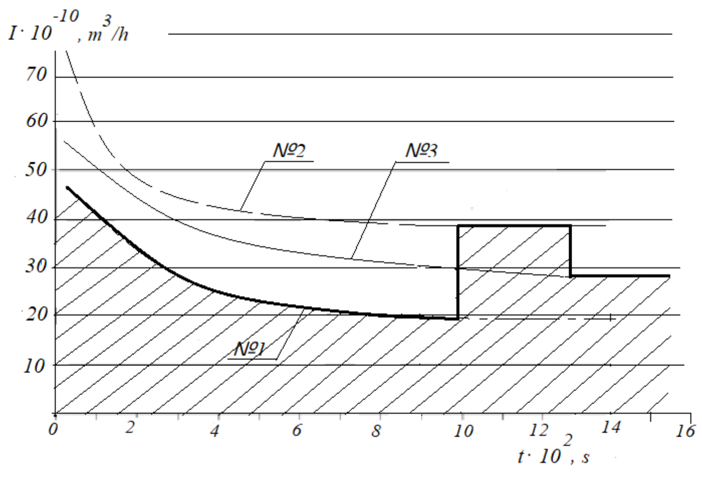

Fig. 3. Dependences of changes in the volumetric rate of wear during the run-in of tribosystems according to a rational program - bold curve. The area under the curve is wear and tear

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.

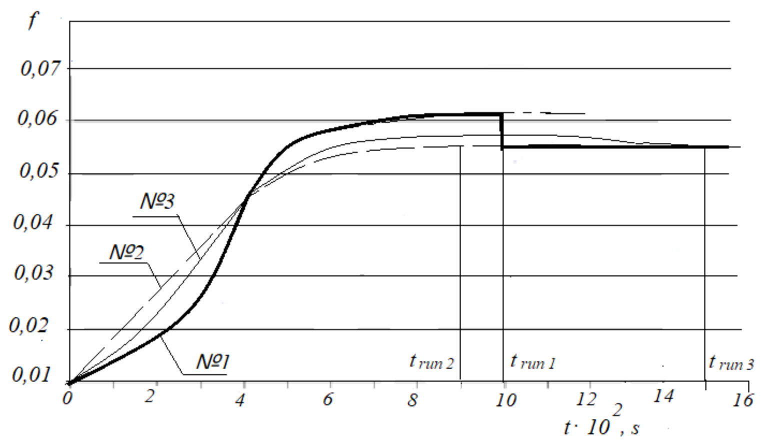

Fig. 4. Dependencies of the change in the friction coefficient during the run-in of tribosystems according to the rational program - bold curve

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.

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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

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The influence of hinges wear on the dynamic load of the articulated boom of a garbage truck's manipulator

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Abstract

The article is dedicated to establishing the relationship between the maximum impact dynamic stresses in the most loaded section of the garbage truck manipulator boom and the wear of the manipulator's hinge and its load level. By utilizing a first-order experimental design with first-order interaction effects using the Box-Wilson method, an adequate dependence of maximum impact dynamic stresses in the most loaded section of the manipulator boom on the wear of the manipulator's hinge and its load level was determined. It has been found that, according to the Student's criterion, among the investigated influencing factors, hinge wear has the most significant impact on the maximum impact dynamic stresses in the most loaded section of the manipulator boom, while its load level has the least impact. The response surface of the objective function is shown – the maximum impact dynamic stresses in the most loaded section of the manipulator boom and their two-dimensional sections in the planes of the impact parameters, which allows to visually illustrate the specified dependence of this objective function on individual impact parameters. It was established that the wear of the hinge by 1000 μm leads to an increase in the maximum impact dynamic stresses in the most loaded cross-section of the boom of the garbage truck manipulator by 2.6...4 times, depending on the level of its load. The expediency of conducting further studies of the effect of antifriction materials on the wear of the friction pairs of the mechanism for loading municipal solid waste into the garbage truck is shown.

Keywords: wear, dynamic load, hinge, boom, manipulator, garbage truck, municipal solid waste, dependence, experimental planning.

Introduction

The problem of increasing wear resistance, reliability, and durability of machine parts holds a leading position among the top priorities in the field of municipal engineering in Ukraine, particularly for manipulator-type machines [1, 2]. The collection and transportation of municipal solid waste (MSW) to further disposal sites in Ukraine are primarily carried out by body garbage trucks, equipped with loading mechanisms in the form of manipulators. Nearly 3700 body garbage trucks are capable of compacting MSW, reducing transportation costs and the required landfill areas. During the technological operation of loading MSW into the body garbage truck, the hinges of its manipulator are subjected to intensive wear. This is due to the substantial weight of the MSW container (up to 500 kg) being lifted, operation in reverse mode (reversing and rotating movement), a high number of work cycles per one route, and operation under conditions of a wide range of temperature fluctuations, relative humidity, and environmental dustiness. Insufficient lubrication or a deterioration in material quality leads to increased friction in the hinges and an increase in vibrations within the system. This, it can affect the dynamic stability of the manipulator and its ability to withstand high loads. Hinge wear can impact the efficiency and safety of the garbage truck manipulator's operation, which can have negative consequences for operators and the environment. According to statistical data, the wear and tear of the municipal waste collection fleet in the Khmelnytskyi region from 2015 to 2020, despite measures taken, decreased only marginally from 63% to 59% [3, 4]. According to the text of the Resolution of the Cabinet of Ministers of Ukraine No. 265 [5], among the important tasks, a prominent place is to ensure the use of modern highly efficient garbage trucks in the country's communal economy, as the main link in the structure of machines for collection, transportation and primary processing of solid waste. This not only helps address various environmental issues but also enhances the overall reliability of municipal services. Planning for the renewal, maintenance, and repair of garbage trucks is facilitated by determining the regression relationship between hinge wear and the dynamic load on the articulated boom of the garbage truck manipulator.

Analysis of recent research and publications

In the work [6], an improved mathematical model of the operation of the solid waste dehydrating drive in a garbage truck, taking into account the wear of the auger, was published, which made it possible to numerically study the dynamics of this drive during start-up and determine the effect of auger wear on the operating characteristics of the drive: with increasing wear of the auger, the pressure of the working fluid at the inlet increases of the drive hydraulic motor, and the angular speed and rotation frequency of the auger are significantly reduced with a constant supply of working fluid. Dependencies in the form of power-law functions of changes in the nominal values of pressures at the hydraulic motor inlet, angular velocity and rotation frequency of the auger depending on the amount of its wear have been determined. At the same time, the dependence of the rotation frequency of the auger on the amount of its wear describes the adjustment from the optimal rotation frequency of the auger in the process of its wear and is used to determine the energy intensity of MSW dehydration taking into account the wear of the auger. In particular, it was found that the wear of the auger by 1000 μm leads to an increase in the energy consumption of solid waste dehydration by 11.6%, and, therefore, to an increase in the cost of the process of their dehydration in the garbage truck and acceleration of the wear process.

The article [7] examines the performance of reversible friction hinges in the control systems of transport vehicles operating in various operating conditions. It is noted that hinged assemblies and connections are among the most responsible and highly loaded power connections of industrial transport machines, and are also the most metal-intensive and most loaded elements of machines that connect the main structural elements and functional units. As a result of the analysis of the wear of the parts of the reversible hinges of transport vehicles operating in a corrosive environment, their increased wear and unreliability in operation was noted. The active loads of the parts of the hinges of coupling devices were studied, as a result of which it was established that there is plastic contact in the friction pair, which causes increased wear of the friction surfaces. As a result of the research, it is proposed to improve the design of the hinges, which allow self-compensation for the wear of the friction surfaces of the coupled parts and improve their operation due to the constant supply of lubricant to the friction zone.

In work [8], an analysis of the types of wear of hinged joints of forest manipulators was carried out, which made it possible to outline possible ways of increasing their wear resistance, which will help design engineers to increase the working life of hinged joints depending on the requirements placed on them in the process of work. It is noted that manipulator-type machines often work under conditions of environmental temperature drops, which negatively affects the properties of lubricants and hinge materials. At a low temperature, the materials of the rubbing pairs become more brittle, the yield strength decreases and the hardness of the working surfaces increases. This complicates the processes of movement and annihilation of dislocations, the occurrence of exoelectron emission, and thus intensifies the wear process. At low ambient temperature, the lubricant hardens or its viscosity increases, which significantly reduces its lubricating properties. In the summer, at high temperatures, the lubricant heats up and it randomly flows out of the friction zone, which negatively affects the process of lubrication and cooling of working surfaces. Therefore, it is proposed to protect the hinge joints of the manipulators from the polluting and corrosive effects of the environment, as well as from the leakage of the lubricant, with special sealing devices. It was established that it is most expedient to introduce contact and labyrinth sealing devices into the design of hinges.

In the article [9], a mathematical model was developed that allows to determine the geometric parameters of the design elements of the manipulator depending on the load capacity, maximum displacement and other kinematic parameters of the machine. It is noted that, taking into account the periodicity of the operation of the hinge joints of the manipulators, there is no hydrodynamic process of friction in them, since the process takes place under conditions of semi-dry and marginal friction. Unlike the established hydrodynamic friction process, the operation of sliding bearings with semi-dry and extreme friction increases the wear of the friction surfaces, which leads to a violation of kinematic accuracy, causes additional dynamic loads, shocks, vibrations, which lead to fretting corrosion and, as a result, to destruction. It is proposed to reduce the force of friction by applying lead, phosphate, and indium coatings to the joint parts of manipulator hinges.

It has been established that contact wear can be reduced by introducing oil and fat-based lubricants or by using consistent lubricants, which at a temperature of 25 °C acquire a thick, ointment-like consistency. For better maintenance of the lubricant on the surface, it is advisable to use phosphate and anodic metal coatings.

The work [10] presents the method of synthesis of the motion trajectory of a manipulative robot by degrees of mobility. It was established that the bending of the rod leads to the occurrence of support reactions in the contact zone, as in a beam on two supports. Having obtained the contact pressure, it is possible to establish the wear of the surfaces of the rod, hydraulic cylinder and ground box. Contact stress reaching a third of the strength limit, with complete safety of the rod from bending, can cause a significant acceleration of the wear of the rubbing surfaces, which makes it possible to specify the causes of the detected wear patterns and the features of their identification.

In the article [11], it was established that when creating new promising designs of hinged joints, it is necessary to apply a complex approach to scientific and technical solutions that take into account a significant number of parameters affecting their performance. At the same time, taking into account the above possibilities and principles of increasing the efficiency of tribotechnical units, it is possible to create new constructive solutions that ensure the increased efficiency of hinged joints of manipulators of logging machines, which allow to significantly ensure the achievement of increased mechanical and tribotechnical characteristics, as well as to optimize the thermal mode of operation node

The authors of the work [12] carried out computer modeling of the process of forming additional dynamic load of metal structures of manipulator cranes with increased clearances in cylindrical joints. A significant drawback of cylindrical hinges is indicated: in the process of operation, over time, the gaps between the hinge fingers and the surfaces of the holes of the eyelets increase monotonously as a result of frictional wear and impact crumpling of their contact surfaces. It is shown that the time-progressive wear of hinges leads to a significant increase in short-term shock stresses in the connections of hinged-jointed booms, an increase in their load level even under stable operating conditions and an increase in the risk of developing permanent destruction, as well as the maximum dynamic shock stresses in the most loaded cross-sections of the manipulator boom for different wear values of the manipulator hinge and its load level.

In the materials of the article [13], using regression analysis, a dependence is determined that describes and allows forecasting the dynamics of wear and tear of garbage trucks in general in the Khmelnytskyi region, as well as planning the infrastructure of communal enterprises (warehouse and renewal of garbage trucks, production base for maintenance and repair), which necessary to solve the problem of solid household waste management.

However, as a result of the analysis of known publications, the authors did not find specific mathematical dependencies describing the effect of wear of hinges on the dynamic load of the articulated boom of the garbage truck manipulator.

Aims of the article

Study of the effect of hinge wear on the dynamic load of the articulated boom of the manipulator of the garbage truck.

Methods

Determining the dependence of the impact of hinge wear on the dynamic load of the hinged boom of the garbage truck manipulator was carried out by planning a second-order experiment with first-order interaction effects using the Box-Wilson method [14]. The coefficients of the regression equations were determined using the developed computer program "PlanExp", which is protected by a certificate of copyright registration for the work and is described in the work [15].

Results

Preliminary processing of the results of experimental studies [12] showed that the maximum impact dynamic stresses in the most loaded section of the manipulator boom are a function of the following 2 main parameters:

$$\sigma_{\max} = f\left(u, \frac{G}{G_n}\right), \tag{1}$$

where σ_{max} – maximum impact dynamic stresses in the most loaded section of the manipulator boom, MPa; u –manipulator hinge wear, μm; G/G_n – load level of the manipulator; G – weight of a solid waste container, N; G_n – nominal load capacity of the manipulator, N.

The study of the influence of the above factors on the maximum impact dynamic stresses in the most loaded section of the boom of the garbage truck manipulator when processing the results of one-factor experiments by the regression analysis method is associated with significant difficulties and amount of work. Therefore, in our opinion, it is advisable to conduct a multivariate experiment to obtain a regression equation for the response functions – maximum impact dynamic stresses in the most loaded section of the manipulator boom using the planning of a multivariate experiment using the Box-Wilson method [14].

The maximum impact dynamic stresses in the most loaded section of the manipulator boom for different wear values of the manipulator hinge and its load level are given in the Table 1 [12].

Table 1

Maximum impact dynamic stresses in the most loaded cross-section of the manipulator boom for different wear values of the manipulator hinge and its load level [12]

#	Maximum impact dynamic stresses in the most loaded section of the manipulator boom σ_{max}, MPa	Wear of the manipulator hinge u, μm	The ratio of the weight of the container with municipal solid waste to the nominal load capacity of the manipulator G/G_n
1	21.9	0	0.25
2	65.6	500	0.25
3	87.5	1000	0.25
4	100	1500	0.25
5	109.4	2000	0.25
6	40.6	0	0.5
7	100	500	0.5
8	134.4	1000	0.5
9	153.1	1500	0.5
10	162.5	2000	0.5
11	62.5	0	0.75
12	121.9	500	0.75
13	162.5	1000	0.75
14	187.5	1500	0.75
15	203.1	2000	0.75
16	78.1	0	1
17	153.1	500	1
18	200	1000	1
19	231.3	1500	1
20	246.9	2000	1

Based on the data in Table 1, using the planning of the second-order experiment with first-order interaction effects, using the developed software protected by a certificate, after discarding insignificant factors and interaction effects according to the Student's criterion, the regularity of the maximum impact dynamic stresses in the most loaded section of the boom is determined of the manipulator from the wear of the manipulator hinge and the level of its load:

$$\sigma_{\max} = 0{,}08552\, u + 89{,}58 \frac{G}{G_n} + 0{,}06243\, u \frac{G}{G_n} - 2{,}99 \cdot 10^{-5} u^2 - 10{,}02 \left(\frac{G}{G_n} \right)^2 . \qquad (2)$$

In Fig. 1 shows the response surface of the objective function – the maximum impact dynamic stresses in the most loaded section of the manipulator boom σ_{ma} and their two-dimensional sections in the planes of the impact parameters, built using the dependence (2), which allows to visually illustrate it.

It was established that, according to the Fisher criterium, the hypothesis about the adequacy of the regression model (2) can be considered correct with 95% confidence. The coefficient of multiple correlation: R = 0.99748, which indicates the high accuracy of the obtained results.

According to the Student's criterion, it was found that among the investigated influencing factors, the maximum impact dynamic stresses in the most loaded section of the manipulator boom are most affected by the wear of the manipulator hinge, and the least by its load level.

It was established that the wear of the hinge by 1000 μm leads to an increase in the maximum impact dynamic stresses in the most loaded cross-section of the boom of the garbage truck manipulator by 2.6...4 times, depending on the level of its load.

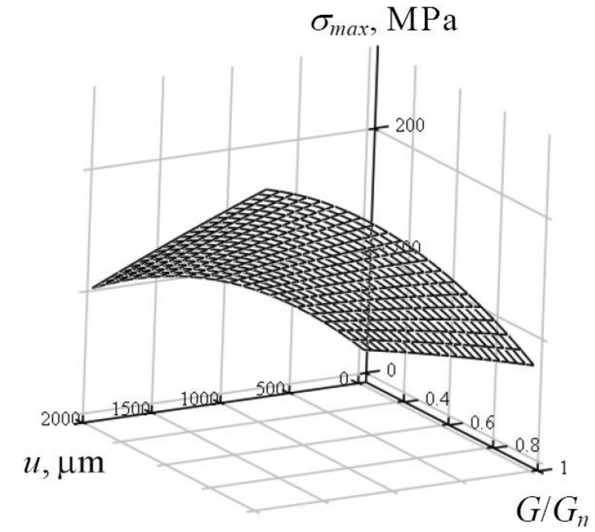

Fig. 1. The response surface of the objective function – the maximum impact dynamic stresses in the most loaded section of the manipulator boom σ_{max}

Determination of the influence on wear and development of recommendations for the selection of anti-friction materials for the friction nodes of the solid waste loading mechanism in the garbage truck require further research.

Conclusions

The dependence of the maximum impact dynamic stresses in the most loaded section of the manipulator boom of the garbage truck due to the wear of the manipulator hinge and the level of its load was determined to be adequate according to Fisher's criterion. It was established that, according to the Student's criterion, among the investigated factors of influence, the maximum impact dynamic stresses in the most loaded section of the manipulator boom are most affected by the wear of the manipulator hinge, and the least by its load level.

The response surface of the objective function is shown – the maximum impact dynamic stresses in the most loaded section of the manipulator boom and their two-dimensional sections in the planes of the impact parameters, which allow you to visually illustrate the specified dependence of this target function on individual impact parameters. It was established that the wear of the hinge by 1000 μm leads to an increase in the maximum impact dynamic stresses in the most loaded cross-section of the boom of the garbage truck manipulator by 2.6...4 times, depending on the level of its load. Determining the effect of antifriction materials on the wear of the friction nodes of the solid waste loading mechanism in the garbage truck requires further research.

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Березюк О.В., Савуляк В.І., Харжевський В.О., Яворський В.Є. Вплив зносу шарнірів на динамічну навантаженість шарнірно-сполученої стріли маніпулятора сміттєвоза

Стаття присвячена встановленню залежності максимальних ударних динамічних напружень в найбільш навантаженому перерізі стріли маніпулятора сміттєвоза від зносу шарніра маніпулятора та рівня його навантаженості. За допомогою використання планування експерименту першого порядку з ефектами взаємодії першого порядку методом Бокса-Уілсона визначено адекватну закономірність максимальних ударних динамічних напружень в найбільш навантаженому перерізі стріли маніпулятора сміттєвоза від зносу шарніра маніпулятора та рівня його навантаженості. Встановлено, що за критерієм Стьюдента серед досліджених факторів впливу найбільше на максимальні ударні динамічні напруження в найбільш навантаженому перерізі стріли маніпулятора впливає знос шарніра маніпулятора, а найменше – рівень його навантаженості. Показано поверхню відгуку цільової функції – максимальних ударних динамічних напружень в найбільш навантаженому перерізі стріли маніпулятора та їхні двомірні перерізи в площинах параметрів впливу, які дозволяють наглядно проілюструвати вказану залежність данної цільової функції від окремих параметрів впливу. Встановлено, що знос шарніра на 1000 мкм призводить до зростання максимальних ударних динамічних напружень в найбільш навантаженому перерізі стріли маніпулятора сміттєвоза в 2,6...4 рази в залежності від рівня його навантаженості. Показано доцільність проведення подальших досліджень впливу антифрикційних матеріалів на знос вузлів тертя механізму завантаження твердих побутових відходів у сміттєвоз.

Ключові слова: знос, динамічна навантаженість, шарнір, стріла, маніпулятор, сміттєвоз, тверді побутові відходи, закономірність, планування експерименту.

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Study of the regularity of wear influence on the service life of cutting elements of bulldozers' working bodies

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Abstract

Our mathematical model describes the regularities of blade wear and takes into account the influence of different operating modes of a bulldozer when dealing with diverse soils that have different degrees of abrasiveness. When calculating the probability of failure-free operation of the bulldozer cutting elements (blades), which depends on the maximum load, it was found that the probability of failure-free operation at an operating time of 600 machine-hours is 0.7...0.75 – for soil category I; 0.5...0.55 – for soil category II; 0.3...0.35 – for soil category III. Comparison of failure-free operation probabilities has made it possible to establish that with an increase in soil density, failure-free operation probability drops by 30-40%, which suggests a significant impact of soil density on reliability of the bulldozer working equipment. In addition, this mathematical model of the total probability allows us to obtain a theoretical description of changes in failure-free operation probability of the bulldozer equipment during working processes, changes in the service life of a bulldozer blade, and taking into account the properties of the blade material. The service life of a bulldozer cutting element can be estimated by its wear, structural features of the material, geometric parameters (thickness in particular), and machine operating modes. It has been established that the regularity of changes in the service life, due to bulldozer blade wear, is exponential. The higher the soil category is, the lower the wear is, and hence the service life of a bulldozer working body. The dependence of the change in the blade service life on the time of its contact with soils of three categories was obtained as well. Thus, the maximum value of a blade service life at the beginning of operation on different soil categories was determined: 450 machine-hours – on soil category I; 350 machine-hours – on soil category II; 280 machine-hours – on soil category III.

Key words: bulldozer, blade, service life, failure-free operation, wear, working equipment, soil category.

Introduction

During the study of bulldozers operation, it was found that a significant number of failures are associated with the failure of working equipment. Besides, according to the data [1, 2, etc.], up to 90% of failures are caused by the rapid wear of the cutting elements of the working bodies (WB).

Bulldozers are known to operate in different conditions. In this case, individual work operations differ from one another by the schemes of applying external loads, so the load of the units is formed independently. Consequently, the statistical characteristics of the workload can generally be constant. It can be assumed, however, that in each case, the amount of accumulated fatigue damage does not depend on the sequence of loading conditions. This makes it possible to represent the operation of a bulldozer consisting of separate typical load modes, which are also determined by certain soil conditions. The bulk of a bulldozer operating time occurs in modes in which its WB performs relatively slow vertical and angular movements. However, the average speed of the latter is low compared to the speed of the machine itself.

Literature review

The results of the experimental studies conducted with the bulldozer's WB in cohesive homogeneous soils show significant high-frequency fluctuations in cutting forces [3]. In real-world conditions, when cutting soil with wide blades, there is not one spall of soil, but a sequence of spalls occurring simultaneously. The vibrations causing this phenomenon cannot be detected due to their damping by the mass of the working equipment.

The numerical characteristics (mathematical expectation, variance, etc.) of the random process of a bulldozer blade's total load are influenced only by the numerical characteristics of the soil strength properties. Due to a rather slow change in the strength properties of homogeneous soils, it is possible to represent their influence by a discrete set of characteristics. In this case, the parameters of soil conditions are immutable in each case.

Bulldozers' WB are known to operate in rather unfavourable conditions. The most noticeable process affecting the durability of the WB is wear and tear. In its turn, bulldozer blades wear mainly depends on the soil abrasiveness, that is, their ability to change the cross-section of the cutting elements. This ultimately leads to their restoration or, in the worst case, to the breakage of the cutting part with the subsequent replacement of the entire blade. Furthermore, the abrasiveness of soils increases with the content, size, and fixed quartz particles (silicon oxide SiO2) [3]. In addition, as shown in [4], with an increase in soil density, the wear of the WB can grow by 5 times (especially with a low content of clay fractions), which negatively affects the service life of the WB blades.

Purpose

Determination of the correlation between service life and wear of a bulldozer blade under various dynamic and alternating loads.

Research Methodology

One of the main indicators of the reliability of the bulldozer WB is the probability of its failure-free operation and service life.

The entire operational load of a bulldozer's working equipment can be divided into categories that are classified by characteristic features [5]. Primarily, it is necessary to consider the following components:

$P(P_{\text{dyn}})$ – the probability of blade failure-free operation, depending on the maximum load applied to the blade edge;

$P(h_{\text{w}})$ – the probability that depends on the value by which the thickness of the blade has changed as a result of wear;

$P(P_{\text{w}})$ – the probability that depends on the load variable.

Being aware of their influence on the probability of failure-free operation of the entire bulldozer's working equipment, it becomes possible to make adjustments at the stage of a cutting element design.

In accordance with [5], we can find the total probability of bulldozer blade failure-free operation:

$$P_{\Sigma} = P(P_{dyn}) \cdot P(h_w) \cdot P(P_w). \tag{1}$$

As a matter of fact, the probabilities $P(P_{\text{dyn}})$, $P(h_{\text{w}})$, and $P(P_{\text{w}})$ are interrelated in the following way: when the blade's working surface wears by h_{w} value, the blade's cross-section changes, as well as its load-bearing capacity. In turn, the latter determines the maximum force on the blade edge it can withstand. The probability $P(P_{\text{w}})$ also depends on the load-bearing capacity.

Results

As a result of analysing the processes of cutting, ploughing, stopping performed by a bulldozer and its hitting a thoug obstacle, the load on the WB was measured. In addition, we studied the influence of the blade angle in the plan on the maximum force on the blade edge when hitting a tough obstacle.

Fig. 1 shows the graph of the maximum $P_{\max}=\max(R_x)$ at the cutting edge of the blade when it hits a tough obstacle, depending on the angle of the blade in the plan α for three categories of soil.

Approximating the dependence $P_{\max}=f(\alpha)$ shown in Fig. 1, we obtain:

$$P_{\max}(\alpha) = A \cdot \sin\left(B \cdot \frac{\alpha - C}{80}\right) + D, \tag{2}$$

where the coefficients A, B, C and D, obtained on the basis of $P_{\max}=f(\alpha)$ dependence approximation, are shown in Table 1.

According to [4], we will consider the first 700 hours of blade operation in the soil. Then the wear dependence of the bulldozer blade as a random function of operating time can be generally described as $h(t)=a_u t^{\beta}+b_u$ (Fig. 2). In this equation, the calculations were based on the statistical data obtained by the authors during the the bulldozer operation. It was assumed that the indicator was $\beta=1/2$, $b_u=0$ [6].

Table 1

Coefficient values *A*, *B*, *C* and *D*

Soil categories	*A*	*B*	*C*	*D*
I	250	1,2	5	-10
II	305	1,25	10	20
III	380	1,4	12	50

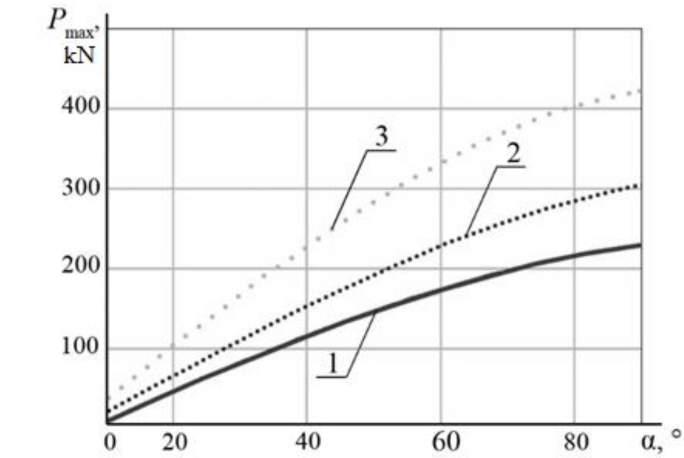

Fig. 1. Dependence of P_{max} on the angle of the blade gripping α: 1 - soil category I, 2 - category II, 3 - category III

The graph in Fig. 2 shows that in the first 50-100 hours of operation, wear is intense and linear. Then the wear gradually quasi-stabilizes, and then after 500-600 hours it starts to increase rapidly. Therefore, the wear rate of the bulldozer blade for each category of soil can be defined as $v=dh_w/dt$ [7].

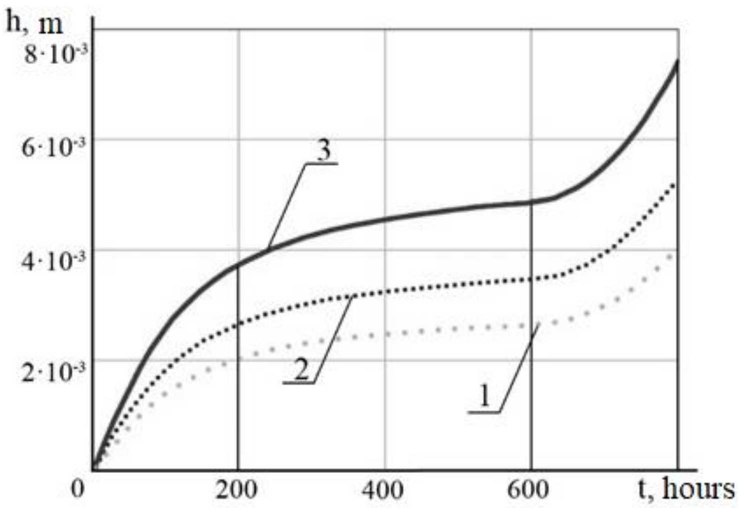

Fig. 2. Graph of wear rate *h* dependence on service life *t* for three different soil categories: 1 - soil category I, 2 - category II, 3 - category III

In equation (1), the first factor, which relates to the probability of blade failure-free operation and depends on the maximum load, was transformed as follows:

$$P(P_{dyn}) = 1 - \frac{1}{2\pi S_x \sigma_v} \int_0^{v_x} \int_0^{R_x} e^{-\left[\frac{(P-\bar{P})^2}{2S_x^2} + \frac{v^2}{2\sigma_v^2}\right]} dPdv, \quad (3)$$

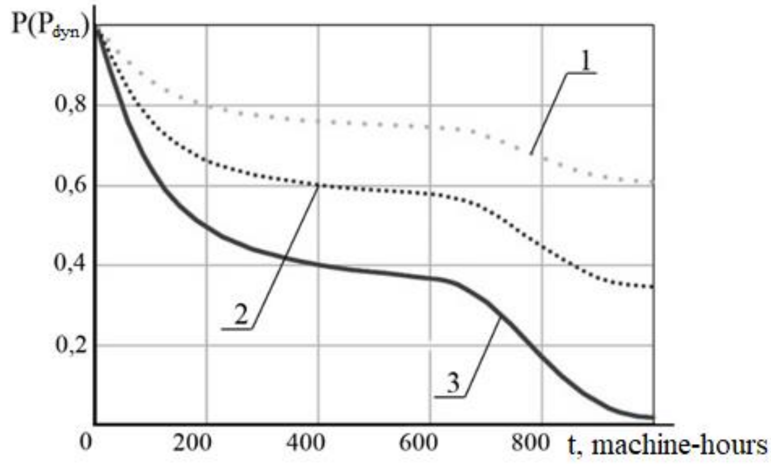

Fig. 3. категорія Graph of changes in the probability of failure-free operation of a bulldozer blade *P*(*P*$_{dyn}$) with the time of its operation in an abrasive environment *t*, h: 1 - I category of soil, 2 - II category, 3 - III category

Fig. 3 shows the dependence of the probability of bulldozer blade failure-free operation $P(P_{dyn})$ on the time of its operation in an abrasive environment, obtained by applying a normal distribution (3).

The declining characteristic of the graphs in Fig. 3 indicates a decrease in the probability of blade failure-free operation $P(P_{dyn})$ during the operation of the bulldozer working equipment.

As a result of approximating the dependence of the probability $P(P_{dyn})$on the blade's operating time in the abrasive environment t (Fig. 3), the following dependence was obtained

$$P(P_{dyn}) = 1 - 0.02 \cdot t^{1/z}, \tag{4}$$

where z = 2,4; 2,13; 2 – or soil categories I, II and III, respectively.

The proposed mathematical model of the total probability (1) allows us to obtain a theoretical description of the change in the probability of failure-free operation of the bulldozer working equipment in the process of performing work operations and describe the change in the service life of the bulldozer blade [8]. Based on the assumptions made, as mentioned above, it is suggested that we consider the probability of failure-free operation as a multiplicative probability function, each argument of which depends on the argument of another probability. In this case, the total probability of failure-free operation of the bulldozer blade will equal to:

$$P_{\Sigma} = P(P_{dyn})\left\{1 - \frac{1}{2}\left[\Phi\left[\frac{P_{-1}^{\max} - m(P_{-1})}{\sqrt{2D(P_{-1})}}\right] - \Phi\left[\frac{P_{-1}^{\min} - m(P_{-1})}{\sqrt{2D(P_{-1})}}\right]\right]\right\}\left\{\Phi\left[\frac{\frac{I_{ex}}{T^{\beta}} - m(a_u)}{\sqrt{D(a_u)}}\right]\right\}, \tag{5}$$

where $\Phi(x) = \frac{1}{\sqrt{2\pi}}\int_0^x e^{-\frac{t^2}{2}}dt$ – the Laplace transform,

$P_{-1} = P_{0\text{-}1} - R_x$;

$P_{0\text{-}1}$ – the load-bearing capacity at fatigue load;

R_x – the applied load on the blade edge;

$m(P_{-1})$ – mathematical expectation (average value) of the limit of the difference between the load-bearing capacity of the bulldozer blade and the maximum load;

$D(P_{-1})$ – standard deviation of the limit of difference between load-bearing capacity and maximum load;

In the dependence $h(t)=a_u t^{\beta} + b_u$, we will consider the case of the extreme wear. In order to do this, we substitute the value of the extreme wear I_{ex} into the wear formula instead of $h(t)$ and solve the resulting equation for $t=T$ with $b_u = 0$. Then the blade service life will be as follows:

$$T = \sqrt[\beta]{\frac{I_{ex}}{a_u}}, \tag{6}$$

where I_{ex} – the extreme blade wear.

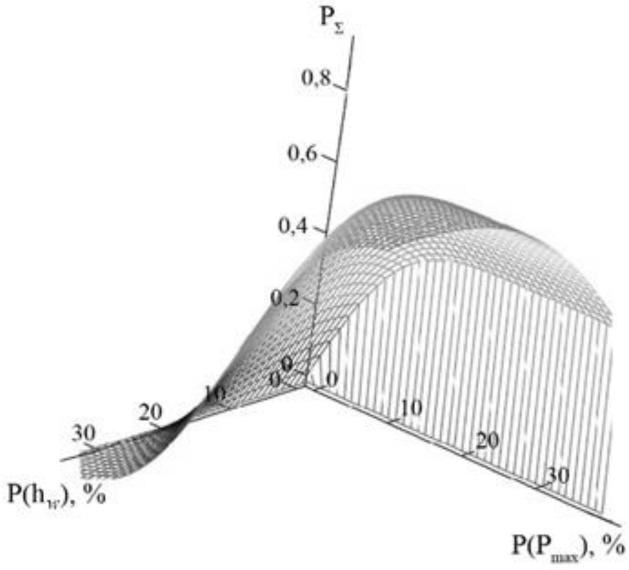

Fig. 4. Dependence of the change in the total probability of failure-free operation P_Σ on $P(P_{max})$ and $P(h_w)$

Fig. 4 shows the graph-surface P_Σ=f$(P(P_{max}), P(h_w))$, built using the dependence (1).

Approximating the dependence of the total probability of failure-free operation of the working equipment P_Σ on the probabilities $P(P_{max})$ and $P(h_w)$, we obtained:

$$P_\Sigma = 0.2 + 1.08P(P_{\max}) + 0.24P(h_w) - 0.13P(P_{\max})^2 - 0.08P(h_w)^2 + 0.846P(P_{\max})P(h_w). \quad (7)$$

Hence, the dependence of the probability of the blade failure-free operation was obtained, which includes wear parameters, dynamic and alternating load (Fig. 4). It should also be noted that the regression equation P_Σ=f$(P(P_{max}), P(h_w))$ is valid only within the limits of the experimental data, in particular the wear value, on the basis of which they were obtained [9]. If the values go beyond the experimental data, then the prediction of the probability of the blade failure-free operation can be obtained with significant errors. To extend the usage scope of the equations, they should be built based on the data regarding several or all modern models of objects of the same functional purpose.

Knowing the total probability of failure-free operation, we can determine the service life of the bulldozer blade. For this purpose, we need to solve equation (5) with respect to the value of *T*.

The Laplace transform is calculated only with the help of a special table. Therefore, equation (5) cannot be solved analytically. Thus, using MATLAB erf(*x*) operators, we will solve this equation numerically to find the total probability.

Taking into account the nonlinearity of the change in the blade wear value with the operating time h_w=f(t) in an abrasive environment during work operations (Fig. 2), we find the service life of the bulldozer blade as the function of *T*=f(*t*) (Fig. 5) for three categories of soil.

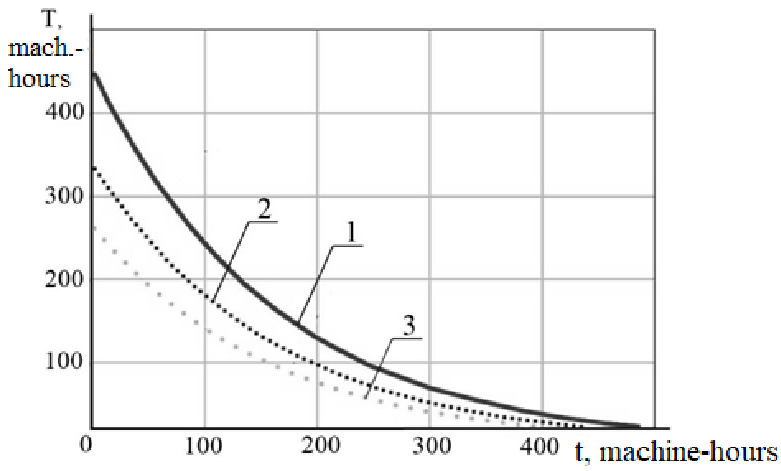

Fig 5. Dependence of the blade service life *T* on the time of its operation in an abrasive environment *t*: 1 - category I soil, 2 - category II, 3 - category III

The graphs in Fig. 5 show that the lower the soil category is, the higher the blade service life in this soil.

Approximating the dependence of the blade service life on the time of its operation in an abrasive environment, we obtain the following exponential dependence:

$$T(t) = x \cdot \mathrm{e}^{-\frac{t}{160}}, \tag{7}$$

Where the coefficient x=447; 340; 260 – for soil categories I, II and III, respectively.

The obtained equation does not contradict the class of solutions of the multiplicative equation (5) for the total probability of the blade failure-free operation of the bulldozer’s WB.

Conclusions

1. On the basis of the multiplicative formula for the total probability of blade failure-free operation, an integral equation was obtained. It allows us measure the blade service life at any time before the start of a bulldozer operation.

2. The proposed mathematical model of the total probability allows obtaining a theoretical description of changes in the probability of failure-free operation of a bulldozer working equipment in the process of performing work operations, as well as changing in the service life of the bulldozer blade, and taking into account the properties of the material from which bulldozer blades are made.

3. The regularity of changes in the service life, due to bulldozer blade wear, is exponential.

4. The higher the soil category is, the more the wear is, therefore the service life of the bulldozer’s working body is shorter.

5. The service life of a bulldozer cutting element can be estimated by its wear, structural features of the material, geometric parameters (thickness in particular), and machine operating modes.

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Щукін О.В., Пруднікова А.О. Дослідження закономірності впливу зносу на ресурс різальних елементів робочих органів бульдозерів

Розроблено математичну модель, що описує закономірності зносу ножа і враховує вплив різних режимів експлуатації бульдозера при роботі його з різними ґрунтами з різним ступенем абразивності. При обчисленні ймовірності безвідмовної роботи різальних елементів (ножів) бульдозера, що залежить від максимального навантаження, встановлено, що ймовірність безвідмовної роботи при напрацюванні 600 маш.-годин становить: 0,7...0,75 – на I категорії ґрунту; 0,5...0,55 – на II категорії ґрунту; 0,3...0,35 - на III категорії ґрунту. Порівняння ймовірностей безвідмовної роботи дало змогу встановити, що при підвищенні щільності ґрунту ймовірність безвідмовної роботи знижується на 30–40%, що дозволяє судити про значний вплив густини ґрунту на надійність робочого обладнання бульдозера. Крім того, розроблена математична модель сумарної ймовірності дозволяє отримати теоретичний опис зміни ймовірності безвідмовної роботи робочого обладнання бульдозера в процесі виконання робочих операцій, зміна ресурсу роботи ножа бульдозера і враховувати властивості матеріалу, з якого виготовляються ножі бульдозера. Ресурс ріжучого елемента бульдозера може бути оцінений, виходячи з його зносу, з урахуванням конструктивних особливостей матеріалу, геометричних параметрів (зокрема, товщини), режимів роботи машини. Встановлено, що закономірність зміни ресурсу від зносу ножа бульдозера носить експоненційний характер. Чим вище категорія ґрунту, тим знос, а отже і ресурс робочого органу бульдозера, менше. Отримано залежність зміни ресурсу ножа від часу його контакту з ґрунтами трьох категорій. Таким чином, максимальне значення ресурсу ножа на початку експлуатації на різних категоріях ґрунту: 450 маш.-годин – на I категорії ґрунту; 350 маш.-годин – на II категорії ґрунту; 280 маш.-годин – на III категорії ґрунту.

Ключові слова бульдозер, ніж, ресурс, безвідмовна робота, знос, робоче обладнання, категорія ґрунту.

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Research of Increase of the Wear Resistance of Machine Parts and Tools by Surface Alloying

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Abstract

The work scientifically substantiates the application of an effective technology for increasing the wear resistance of machine parts and tools due to complex diffusion saturation of the surface layer of parts made of iron-carbon alloys in the process of casting on gasified models based on the optimization of the composition of saturating mixtures and the establishment of patterns of structure formation.

The possibility of strengthening the surface of castings from cast iron SCH20 and steels of various composition (25L, 30L, 35L, 45L, 25HL, 110H13L), obtained by methods of casting in an open mold and on gasified models, has been established. It is shown that the diffusion boride layer on 35L steel, obtained during casting, has an order of magnitude greater thickness (up to 5 mm) compared to the diffusion layers obtained by chemical-thermal treatment methods (up to 0.25 mm). Analytical dependencies have been established that connect the components of the composition of the mixture (chromium boride (CrB_2), boron carbide (B_4C), graphite, bentonite, sodium fluoride (NaF)), which saturates, with wear resistance and the thickness of the diffusion layer after hardening in the process of obtaining a casting by the method of casting on gasified models.

A new composition of the saturating medium has been developed for surface strengthening in the production of cast parts from gray iron, carbon and alloy steels by simultaneous saturation with boron and chromium, containing chromium boride, boron carbide, graphite, bentonite, sodium fluoride (50-60 wt. % B_4C + 20-25 wt. % CrB_2 + 2-3 wt. % + 5-15 wt. % finely dispersed graphite + 5-7 wt. % bentonite). The application of the developed strengthening technology allows to improve operational properties, in particular, the wear resistance of machine parts and tools up to 25 times (compared to previously used methods), as well as to reduce the labor intensity of the strengthening process by up to 3.5 times.

Tests of dies for pressing wood waste into briquettes made of 45L steel, strengthened with the help of the developed technology, showed that their stability increases more than 4.5 times compared to the previously used ones made of HVH steel strengthened by carbonitriding, and the use of the developed strengthening technology allows reduce the cost of manufacturing this part by 1.5 times.

Key words: wear resistance, diffusion saturation, durability, surface hardening, diffusion coating, alloying.

Introduction

In the process of operation of parts of machines and tools, their surface layers are subjected to the most intensive external actions, therefore, often the structure and properties of the surface layers have a decisive influence on the performance of the products as a whole.

There are many ways to strengthen the surface: laser strengthening, surfacing, rolling, application of various coating technologies. However, the use of these technologies requires the use of complex, often unique, expensive and energy-intensive equipment, expensive reinforcing alloys, and highly qualified personnel [1].

Therefore, the development of new highly effective methods of strengthening machine and tool parts due to the diffusion saturation of the surface of metals and alloys with various chemical elements, the method of chemical-thermal treatment (CTT) is of particular interest. In some cases, when it is not necessary to strengthen the entire surface, but only certain parts of the parts, the method of strengthening with saturating coatings is practically the only possible one. At the same time, the widely used traditional chemical-thermal treatment, although it increases the wear resistance of the tool, but in addition to the advantages listed above, requires a large amount of electricity due to the duration of high-temperature diffusion processes. All this leads to an increase in the cost of the tool.

Studies of the effect of saturating media in the form of smears during CRT have shown that the use of boron-chromium compounds as an additive to boron carbide significantly increases the service life of the tool. Boration, chromium plating, titanation and combined processes (borochromization and borotitanization) are more effective than traditionally used cementation, nitriding, etc. in almost all parameters of the properties of the surface layers of the material. Boride layers on steels are characterized by high wear resistance, chrome plating provides heat resistance, and combined coatings combine the original properties of single-component coatings. The performance of borochromized layers is almost twice as high as that of borated ones. However, the known methods of obtaining such strengthening coatings are imperfect and quite time-consuming.

The method of surface strengthening, when the surface strengthening and the process of manufacturing the product are combined into a single process, is devoid of these disadvantages. Such a combination is possible only in the production of machine parts and tools by casting methods. In this case, the formation of a strengthened layer occurs as a result of the interaction of the hot casting material with the alloying facing layer applied to the surface of the mold [2].

The production of the tool by various methods of casting leads to a reduction in the consumption of expensive tool steel, a decrease in the cost of manufacturing the tool and an increase in its stability. When using foundry technologies, it becomes possible to use additional alloying, microalloying and modification of steel to increase the performance of the tool based on the specific conditions of its operation. The most promising in this direction is the method of casting on gasified models (LGM), which allows you to obtain high-precision castings with good surface cleanliness.

Of great practical interest is the production of diffusion layers based on iron boride, which, as is known, has high hardness and wear resistance during the casting process. Increasing the performance of parts of machines and mechanisms, tools and technical equipment, their reliability and durability is ensured to a certain extent by optimizing the technology of applying boron-containing coatings and the chemical composition of the saturating mixture.

Literature review

Surface hardening of steel pursues the following main goals: increasing the hardness of metal products, increasing wear resistance and increasing the endurance limit of parts. After surface hardening, gear teeth, shaft necks, machine bed guides become harder, wear-resistant and durable. The core of the part with such hardening remains viscous and withstands impact and other loads well.

The industry uses various methods of surface hardening of steel:

- surface hardening of steel with induction heating by high-frequency currents (microwave);
- surface hardening of steel with electric contact heating;
- surface gas flame hardening of steel;
- surface hardening of steel in electrolyte.

All of the above methods of surface hardening of steel have one thing in common. A common feature for all methods of surface hardening of steel is that the surface layer of the part is heated to a temperature above the critical point As_3, and then quickly cooled and a martensite (hardened steel) structure is obtained. Surface hardening of steel and mechanical processing with induction heating by high-frequency currents (microwave) have become the most widely used. Somewhat less often, mainly for large parts, the method of surface tempering with gas flame heating is used [3].

The essence of the process of surface hardening of steel when heated by high-frequency currents is that the part is heated on a special installation using a copper inductor made according to the shape of the part being hardened. A high-frequency alternating current is passed through it. The surface of the part is heated to the required depth in a few seconds. After that, the current is turned off and the part is quickly cooled. During the hardening process, cooled water circulates inside the inductor, and therefore it does not heat up.

The method of surface hardening of steel by electric contact heating is as follows. The part is heated when heat is released at the point of contact between the part and the electrode made in the form of a copper roller attached to a special device [4]. The surface of the hardened part is cooled with the help of a shower that moves after the electrode.

The surface hardening of steel by the method of heating with a gas flame burner consists in the fact that the surface of the part is heated in the flame of an acetylene-oxygen burner to the required tempering temperature, and then quickly cooled with a stream of cold water. This happens as follows: the gas burner moves at a certain speed over the surface of the part, and behind the burner, at the same speed, the quenching tube, through which water is supplied, moves. The flame of an acetylene-oxygen burner has a temperature of 2500-3200°C, and therefore it heats the surface of the steel product to the temperature required for hardening in a very short period of time. During that time, the layers of steel lying under the surface do not have time to warm up to a critical point and do not receive hardening. The thickness of the hardened layer is 2-4 mm, and the hardness reaches HRC 50-56. Surface hardening of steel by the gas-flame method deforms the steel part less than volume hardening, and the surface does not pollute. This method of surface hardening of steel is more cost-effective for large parts than hardening with microwave induction heating.

Chemical-thermal treatment is the process of changing the chemical composition, structure and properties of surface layers and metal [5].

This treatment is applicable to parts that require a hard and wear-resistant surface while maintaining a viscous and sufficiently strong core, high corrosion resistance, and high fatigue resistance.

Chemical-thermal treatment of steel is based on the diffusion (penetration) of atoms of various chemical elements into the atomic crystal lattice of iron during heating of steel parts in an environment rich in these elements.

The most common types of chemical and thermal treatment of steel are: cementation - saturation of the surface of steel parts with carbon; nitriding - saturation of the surface of steel parts with nitrogen; cyanation - simultaneous saturation of the surface of steel parts with carbon and nitrogen.

In addition to these main types of chemical and thermal treatment, industry also uses surface saturation of steel with metals: aluminum, chromium, silicon, etc. This process is called diffusion metallization of steel.

Foundry technologies for obtaining composite materials and blanks are the least studied and rarely used in production. This is explained by the complexity and diversity of foundry technologies, a large number of used foundry alloys. At the same time, composite, bimetallic castings are a significant reserve of foundry production, a lever for a sharp increase in the competitiveness of castings in comparison with other billets for machine building. The use of composite materials makes it possible to successfully solve many complex technological and structural problems, the solution of which is difficult, and sometimes impossible, with conventional methods of casting [6].

Castings made of carbon, high-manganese, complex-alloyed steels and cast iron are subjected to strengthening surface alloying. The most common castings are strengthened in a casting mold: tracks tracks, teeth of excavator buckets, cultivator feet, plow blades.

Cast structural steel 45L was chosen as the main metal of composite castings. The choice of this particular steel as a research material is due to its wide application in mechanical engineering for critical parts operating under conditions of high contact and alternating loads, as well as abrasive wear.

Steel 45L has satisfactory casting and mechanical properties. However, its abrasive wear resistance in the hardened state is relatively low.

In accordance with the concepts of the processes of deposition of wear-resistant layers on the surface of the casting, the mechanisms of fusion of alloying powders of different fractions and different chemical compositions were studied. Mixtures of crushed ferroalloys, surfacing powders for welding processes, alloy chips, fluxes, and other materials were used as materials for surface alloying [7].

The process of surfacing castings using a composite material consisting of ferromanganese and sludge, borax should be considered the most rational.

The above composition of the powder makes it possible to obtain on steel castings the largest thickness of the deposited layer, defect-freeness of this layer, maximum hardness up to 55 HRC and high wear resistance. The labor intensity of the production of the powder composition and the cost of materials are minimal.

One of the modern methods of changing the structure and properties of the surface layers of the material is the doping of coatings from a foundry mold. The use of mold coatings in foundry production has been known for a long time, but the main goals of their use are to improve the surface quality of castings, preserve the casting mold and prevent its interaction with the poured molten metal, and eliminate the burning of castings. However, the introduction of special compositions into the composition of the coating makes it possible to produce alloying of the surface layers of the casting in the places of its application. This approach allows in some cases to significantly change the properties of the surface of castings without changing the properties of the inner layer of the casting.

When using this technology, the metal to create a layer on the surface of the formed casting comes from a special coating that is applied to the surface of the mold before pouring. The working mixture is applied, as well as standard coatings and coatings used in metal and sand-clay forms [8].

Grain base. It is a dispersed component of the coating, which gives the surface of the casting the required purity or specified properties. The average particle size of this coating component is usually 30-80 μm. The main substances for the grain base are: graphite, carbon black, ferrochrome slag, zircon, borax, etc.

Purpose

The purpose of the research is to increase the wear resistance of machine parts and tools due to the complex diffusion saturation of the surface layer of parts made of iron-carbon alloys in the process of casting on gasified models based on the optimization of the composition of the saturating mixtures and establishing the patterns of structure formation.

Research methodology

Steels of various purposes (25L, 30L, 35L, 45L, 25HL, 110H13L), as well as cast iron SCH15 and SCH20 were chosen as the materials under study.

The chemical composition of the components of the saturated mixture used for diffusion saturation (boron carbide, chromium and titanium boride, etc.) is given. Chemical and thermal treatment was carried out from saturated smears (pastes) applied to the surface of parts and samples to be strengthened.

Cast samples of steel and cast iron for studying the structure and properties of the hardened layer were obtained in two ways:

1 - casting according to gasified models (size of samples for steel 040 mm, length 830 mm, for cast iron - 90x45x20 mm);

2 - in a mold made of a core mixture (a cold-hardening mixture (HTS), consisting of quartz sand of the 4K20202 brand, orthophosphoric acid and BS-40 resin). Sample size: 0.25 mm, length 40 mm.

Cast iron and steel were melted in an induction electric furnace of the LHGW - 0.5/ISM crucible with a power of W=500 kW, and pouring was carried out with a kettle-type ladle with a capacity of V=250 kg. The melt temperature was measured using a Kelvin 1800P infrared thermometer. The chemical analysis of the studied alloys was determined on the Argon-5 and MSA I spectrometers [9].

Strengthening was carried out with a coating applied to the surface of the gasified model and to the surface of the cavity of the mold with HTS.

After diffusion saturation processes, the structure, phase and chemical composition of the boride layers were studied. Metallographic research was carried out on optical microscopes: MIM-7, MIM-10, Neophot - 21 and by scanning electron microscopy (SEM) methods on a JSM - 6510 LV JEOL scanning electron microscope with a microanalysis system INCA Energy 350, Oxford Instruments, transmission electron microscopy (TEM) on the EM-125K electron microscope and atomic force microscopy (AFM) on the "FEMTOSKAN" microscope in the surface relief scanning mode. For viewing in an optical microscope, sections were prepared by chemical and electrochemical poisoning methods. X-ray structural phase analysis was performed using a DRON-1.5 diffractometer.

Mechanical properties were determined by standard methods. Wear resistance was determined in laboratory conditions on an Amsler machine according to ISO 47421. Durometric tests were performed on a Rockwell TP 5005 hardness tester on a scale according to ISO 9013 and on a PMT-3M device according to ISO 9450.

Research results

At the first stage of selecting the composition of the saturating mixture, four types of saturated coatings based on the boriding mixture (70 wt.% B_4C, 15 wt.% graphite, 5 wt.% NaF, 10 wt.% bentonite) were used: No. 1 - with by adding 20 wt. % chromium diboride; No. 2 - with the addition of 20 wt. % nickel; No. 3 - with the addition of 10 wt. % tungsten carbide; No. 4 - with the addition of 20 wt. % of titanium diboride. The coating was brought to a cream-like state with the help of water and liquid glass, applied to the surface of the gasified model and the surface of the mold cavity with XTS thickness from 0.2 to 2.0 mm, then the coating was dried for 3-4 hours in the air at a temperature not lower than 20°C. Form was prepared. Immediately before pouring, the mold was connected to a vacuum pump and a discharge of 0.05 MPa was created, pouring was performed with melt at a temperature of 1500-1600°C from a teapot-type ladle preheated in the furnace to t=950°C. After crystallization of the casting and its aging, the mold was sent for punching [10].

Strengthening diffusion layers were obtained on steels of different chemical composition (Fig. 1), the distribution of microhardness values in the layers after hardening with boron together with other elements (Cr, Ni, Ti, and W) during casting.

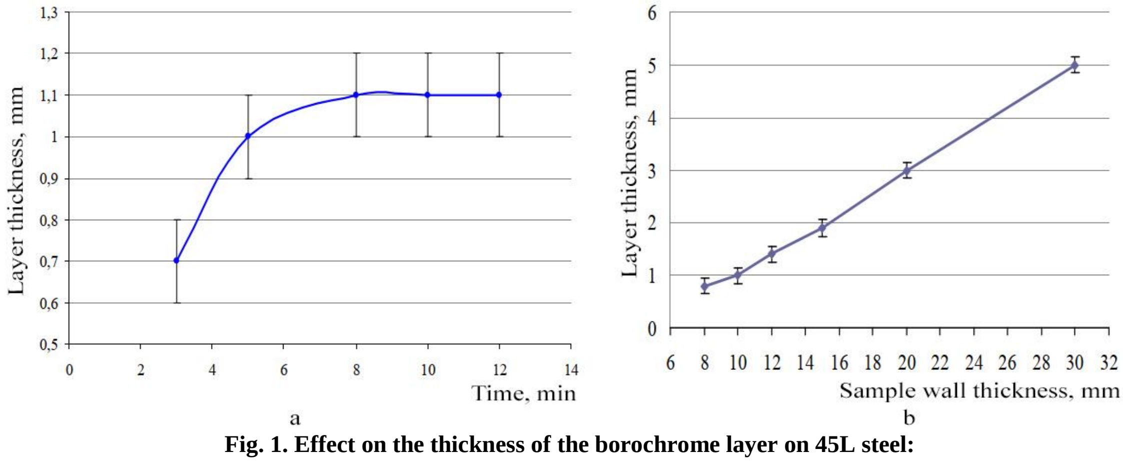


Fig. 1. Effect on the thickness of the borochrome layer on 45L steel:
a - exposure time in the mold (sample thickness 10 mm);
b - wall thickness of the sample (holding time in the form 5 min)

On all steels, layers with a thickness of 0.9 to 1.2 mm were obtained with a casting wall thickness of 10 mm and a holding time in the mold of 5 minutes. The main influence on the formation of the diffusion layer is the duration of the crystallization and cooling process in the austenitic state, which is determined by the thickness of the casting wall (Fig. 1, b) and the time of holding the casting at a temperature above 800°C (Fig. 1, a). The microhardness of the layer varies significantly from 7,500 MPa during borochroming to 14,000 MPa during borotitanization. The data in Fig. 2 are given for samples with a thickness of 10 mm and exposure time in the form of 5 minutes.

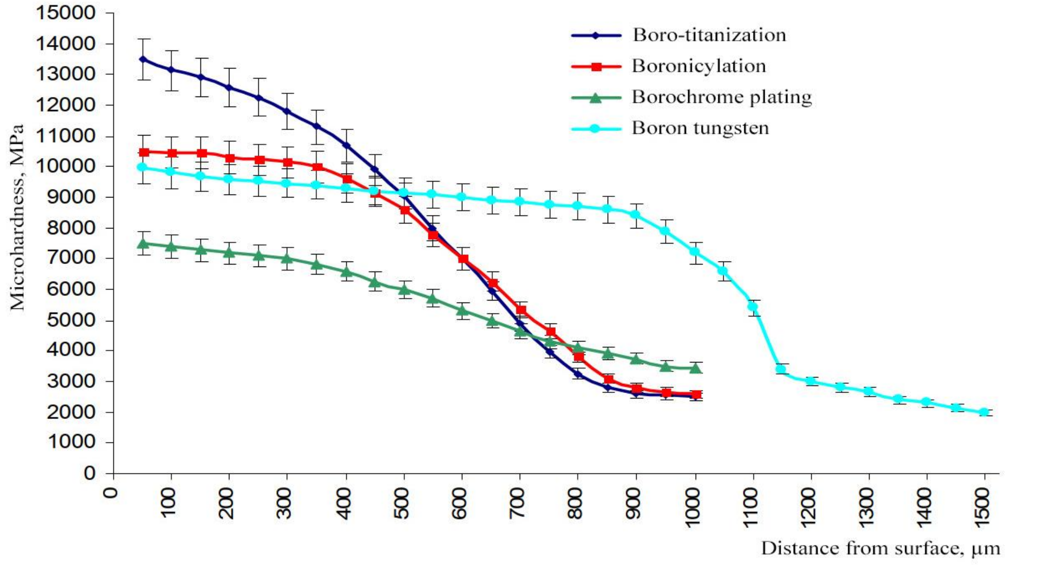
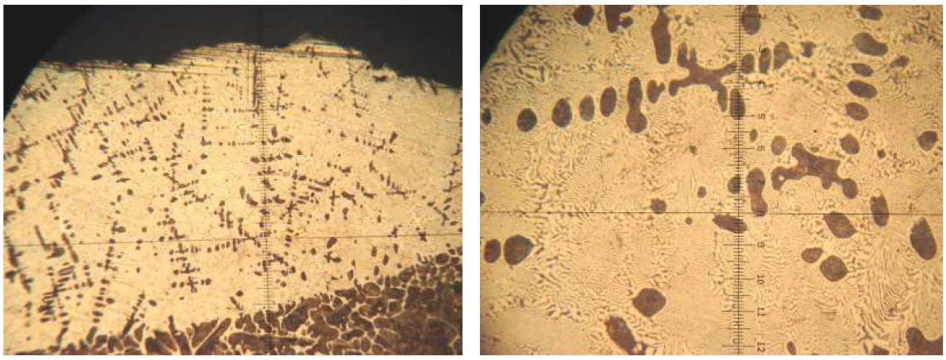


Fig. 2. Distribution of microhardness values in the hardened layer of 45L steel after hardening with boron together with other elements (Cg, Ni, Ti, and W)

The microstructure of the resulting diffusion borochromized layer is shown in Fig. 3. Instead of needle-like layers (Fig. 4), diffusion layers thicker than 1 mm have a boride eutectic structure with large inclusions of pearlite (up to 30 μm), where the eutectic is a finely dispersed mechanical mixture of borides and pearlite.



a b

Fig. 3. Microstructure of the diffusion borochrome layer on steel 45L obtained during casting: a - the price of a scale division of 10 μm, b - the price of a scale division of 2.5 μm

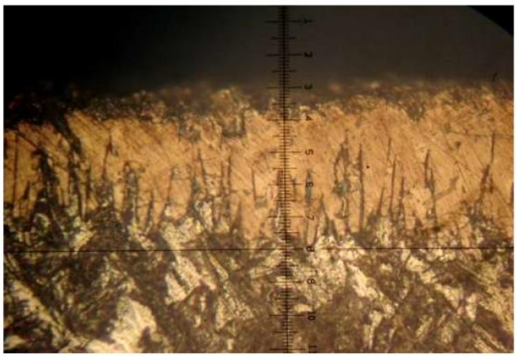
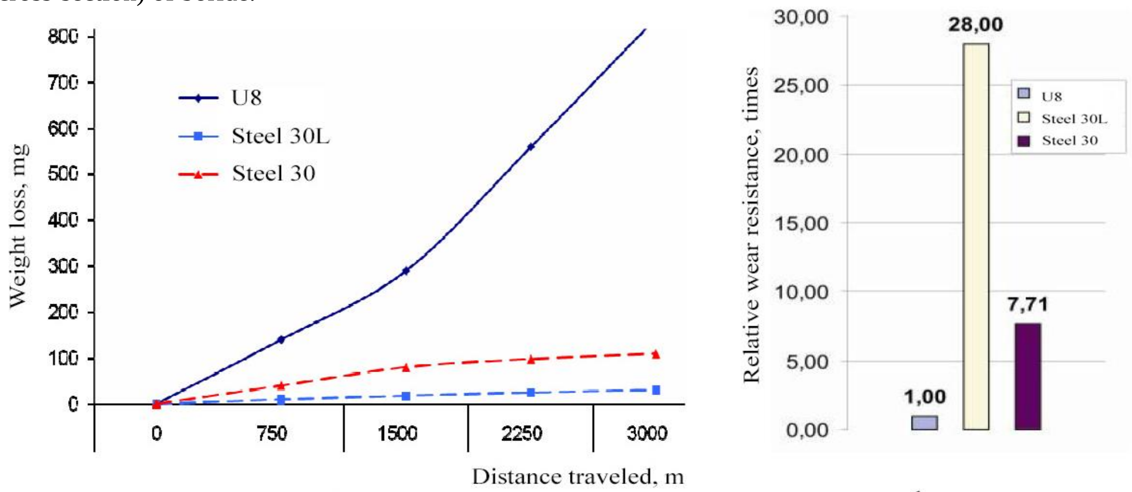


Fig. 4. The microstructure of the diffusion borochromized layer on steel 30: temperature 1000°C, saturation time - 6 h (the price of the scale division is 5 μm)

From Fig. 5, it can be seen that the diffusion boride layer on 30L steel obtained by surface alloying has an order of magnitude greater thickness (2.5 mm) and lower microhardness (up to 16,000 MPa) compared to diffusion layers obtained by chemical-thermal treatment methods (0,25 mm with microhardness up to 30000 MPa, see Fig. 4). Abrasive wear resistance of diffusion layers obtained on cast steel increases by 28.0 times, while the wear resistance of borated ones in the process combined with heating for hardening increases by 7.7 times compared to the standard (U8 steel with a hardness of 51-52 HRC). The diffusion layer on steel 30 has a small thickness and high fragility, therefore, under high loads (above 0.40 MPa), it breaks down faster, and during long-term tests, it wears out much earlier than the layer on steel 30L [11]. In Fig. 6 arrows show the destruction of the brittle phase (cross-section) of boride.



a b

Fig. 5. Wear resistance during abrasive wear of carbon steel (0.3% carbon): steel 30 - solid-phase boronization from coating, steel 30L - saturation of the surface with boron during LGM (a - mass loss, b - relative wear resistance)

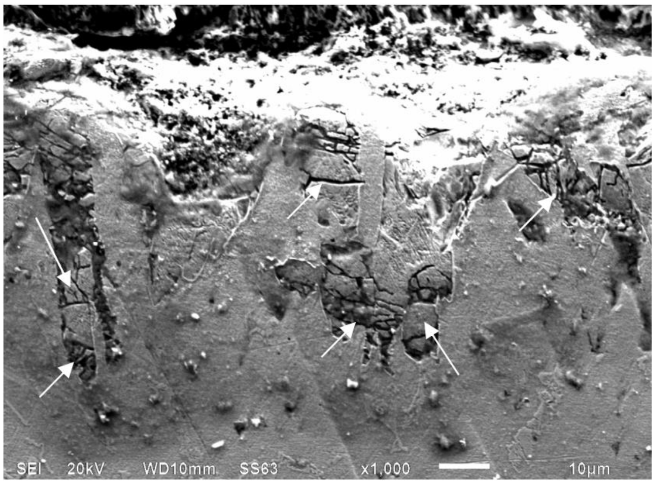


Fig. 6. Destruction of borides in a hardened layer (SEM)

Thus, the possibility and expediency of strengthening the surface layer of parts by complex saturation with boron and chromium during the production of cast products is shown.

Based on previous research, boron carbide was adopted as a boron supplier in the basis of the composition of the saturated mixture for surface hardening of steel parts and tools. The next component included in the coating is chromium diboride, which is a supplier of chromium [12]. Sodium fluoride is used to activate the impregnation process. Finely dispersed graphite provides sufficient thickness of the diffusion layers and easy separation of the coating after the saturation process. Bentonite provides the necessary stiffness of the coating during the saturation process and prevents the coating from falling off during the drying process. In separate experiments, different combinations of these coating components were chosen in percentage ratio of the total mass.

In order to change the number of experiments that were carried out, a more mathematical design of the experiment was carried out when searching for the optimal composition of the chemical coating. To change the area, to determine the optimal value of replacing the skin component of the infused mixture, for surface treatment, the cutaneous component B_4C - 40-80%, CrB_2 - 10-30%, graphite was experimentally established - 5-20%, NaF - 5-15%, bentonite - 2-5%.

For an analytical description of the “warehouse-power” distribution in richly component systems, the simplex method is a useful method, which allows one to derive a mathematical model of the traced distribution and does not require a large volume of experiments [13]. This method is used for stagnation during the injection of a chemical warehouse with a five-component pumped medium for the durability and wear resistance of boron chromium-plated steel coatings.

Among the tested parts, there were high quality rollers made of 35L steel, used to feed the drill to the bench for drilling [14]. The wear resistance of the rollers was determined by the resource by the number of darts supplied (in tons). Robot feed roller mode: feeding a 0.4 mm shot to the workbench for sanding.

The fragments of the historical creation of insatiable sums of this kind are rich in factors, and the song system is the basis for it. Previous studies have shown that in this case, the accumulation of power of boron-chromed balls in a warehouse of compressed coating must be carried out not in the entire area of change in the concentration of components, but rather in a local area.

Conclusions

1. The structures and phase composition of the diffusion layers obtained during the casting process by simultaneous saturation of steels 25L, 30L, 35L, 45L, 25HL and 110G13L with boron together with chromium and boron together with titanium were studied and described. The conditions for the surface alloying process are established, in which there is a possibility of the formation of eutectics of boride, boride, carbides, carboborides, solid solutions based on α-iron.

2. The possibility of obtaining a strengthened surface on structural ferrite-pearlite and pearlite cast iron, medium carbon steels and wear-resistant high-manganese austenitic steel by the method of casting in an open mold from a core mixture and casting on gasified models from expanded polystyrene has been established. It is shown that the boride diffusion layer on 30L steel, obtained during casting, has an order of magnitude greater thickness (up to 5 mm) and a slightly lower microhardness (11,000-16,000 MPa) compared to diffusion layers obtained by chemical-thermal treatment methods (up to 0.25 mm with a microhardness of 16500-25000 MPa).

3. The optimal combination of saturated medium components for surface hardening of steels during the production of machine and tool parts by casting (chromium boride, boron carbide, graphite, bentonite, sodium fluoride) was determined. The study of the ability of the presented saturated media showed that boron-chromium compounds (chromium diboride, ferrochromium), used as components of a saturated coating, are effective both as suppliers of boron and as suppliers of chromium.

4. Analytical dependencies have been established that link the components of the composition of the saturated mixture (CrB_2, B_4C, graphite, bentonite, NaF) with the operational and physico-mechanical properties of steels (microhardness, wear resistance, thickness of the diffusion layer) after hardening in the process of obtaining a casting by the casting method on gasified models.

5. On the basis of the studied ideas about the behavior of steels with a diffuse coating, as well as taking into account the obtained analytical dependences of the properties of hardened steels on the composition of the saturated mixture, a new composition of saturated medium for surface strengthening of cast steels by simultaneous saturation with boron and chromium was developed, containing: 50-60 mass. % B_4C, 20-25 wt. % CrB_2, 2-3 wt. % 5-15 wt. % graphite, 5-7 wt. % bentonite.

A new composition of saturated medium was developed for surface strengthening of cast steels by simultaneous boron and titanium saturation, containing: B_4C - 40-80 wt.%, TiB_2 - 10-30 wt.%, graphite - 10-20 wt.%, NaF - 5- 10 wt.%, bentonite - 2-5 wt.%.

Optimum temperature and time modes of processing are recommended for the developed compositions.

6. The application of the developed technology of the method of processing with the combined technology of laser-plasma-ultrasound hardening allows to improve the operational properties, in particular, the abrasive wear resistance of the diffusion layers obtained on 35L steel increases by 15.4 times during borochroming and by 25.6 times after borotitanization.

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Марченко Д.Д., Матвєєва К.С. Дослідження підвищення зносостійкості деталей машин і інструменту поверхневим легуванням

У роботі науково обґрунтовано застосування ефективної технології підвищення зносостійкості деталей машин і інструменту за рахунок комплексного дифузійного насичення поверхневого шару деталей із залізовуглецевих сплавів в процесі литва по газифікованих моделях на основі оптимізації складу сумішей, що насичують, і встановлення закономірностей структуроутворення.

Встановлена можливість зміцнення поверхні відливок з чавуну СЧ20 і сталей різного складу (25Л, 30Л, 35Л, 45Л, 25ГЛ, 110Г13Л), отриманих методами литва у відкриту форму і по газифікованих моделях. Показано, що дифузійний боридний шар на сталі 35Л, отриманий при литті, має на порядок велику товщину (до 5 мм) в порівнянні з дифузійними шарами, отриманими методами хіміко-термічної обробки (до 0,25 мм). Встановлені аналітичні залежності, що зв'язують компоненти складу суміші (борид хрому (CrB_2), карбід бору (B_4C), графіт, бентоніт, фтористий натрій (NaF)), що насичує, зі зносостійкістю і завтовшки дифузійного шару після зміцнення в процесі отримання відливання методом лиття по газифікованих моделях.

Розроблений новий склад середовища, що насичує, для поверхневого зміцнення при отриманні литих деталей з сірого чавуну, вуглецевих і легованих сталей одночасним насиченням бором і хромом, борид хрому, що містить, карбід бору, графіт, бентоніт, фтористий натрій (50-60 мас. % B_4C + 20-25 мас. % CrB_2 + 2-3 мас. % + 5-15 мас. % дрібнодисперсного графіту + 5-7 мас. % бентоніту). Застосування розробленої технології зміцнення дозволяє поліпшити експлуатаційні властивості, зокрема, зносостійкість деталей машин і інструменту до 25 разів (порівняно з раніше використовуваними способами), а також зменшити трудомісткість процесу зміцнення до 3,5 разів.

Випробування філь'єр для пресування деревних відходів в брикети із сталі 45Л, зміцнених за допомогою розробленої технології, показали, що їх стійкість підвищується більш ніж в 4,5 рази в порівнянні з раніше вживаними із сталі ХВГ зміцнені карбоазотуванням, а використання розробленої технології зміцнення дозволяє зменшити витрати на виготовлення цієї деталі в 1,5 рази.

Ключові слова: зносостійкість, дифузійне насичення, довговічність, поверхневе зміцнення, дифузійне покриття, легування.

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Simulation model of contact interaction during surface strengthening of steel parts

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Abstract

In the processes of surface strengthening of steel parts, the stress-strain state is decisive for explaining the physical processes of strengthening, forming the dimensions of the contact area. Analytical dependences of contact parameters are quite approximate. In this work, based on the Ansys software complex, a simulated model of the contact of a truncated torus with a cylinder is proposed, which demonstrates the kinetics of the process of pressing a hard alloy tool into a steel workpiece - a cylinder. The experiment was conducted for 4 seconds in order to determine the maximum level of stresses, the distribution of stresses and the amount of residual stresses after removing the load. The clamping force was applied mainly in the zone of elastic deformations. The results showed an uneven stress distribution with a maximum in the center of the contact spot of 1082 MPa. After changing the load direction, small residual deformations at the level of 0.00311 μm were observed in the center of the contact patch. This indicates a violation of the elastic region on a small contact area, which does not affect the general nature of the stress distribution and can be removed during the finishing process. The results of simulation of the stressed state are used for the correlation with the observed structural changes of the material during the action of thermal and power stresses. The stress peak was formed at a distance of 200 μm, which contributes to the formation of maximum values of microhardness at this depth.

Key words: stress-strain state, surface, strengthening, contact processing, tool, truncated torus, cylinder, elastic deformations

Introduction

The method of discrete strengthening of steel parts of the "shaft" type requires the need to assess the depth of the strengthened wear-resistant layer. A reinforced layer is a layer characterized by the formation of a so-called white layer. This layer is formed in the volumes of the material, the heating temperature of which exceeds the phase transformation temperature. A high-temperature volume can be defined as a volume in which the temperature is above 600 °C.

Experimental studies show that the width and height of the high-temperature volume in working hardening modes are close to the width and height of the contact of the tool with the part. Therefore, determining the contact surface of the tool and the processed part is one of the first steps necessary for the correct selection of technological parameters.

In addition, knowledge of the geometric parameters of the contact surface is required to determine other characteristics of the technological process, in particular, the current density, which ensures the necessary temperature on the surface of the contact zone.

The purpose of the task is to create a calculation method for assessing the influence of the load of the run-in roller on the resulting stresses and deformations of the shaft when simulating their mutual rotation in the environment of the finite element method (Ansys Static Structural).

Literature rewier

In paper [1] describes the development of a 3D tyre–pavement interaction model to predict the tyre–pavement contact stress distributions for future use in the mechanistic analysis of pavement responses. The steady-state tyre rolling process was simulated using an arbitrary Lagrangian Eulerian formulation. The model results are consistent with previous measurements and validate the existence of non-uniform vertical contact stresses and localised tangential contact stresses. The analysis results show that the non-uniformity of vertical contact stresses decreases as the load increases, but increases as the inflation pressure increases. The model results provide valuable insights into understanding the realistic tyre–pavement interaction for analysing pavement responses at critical loading conditions.

In article [2] have formulated a computational theory based on the 'soft contact' approach that models contact through localized non-permanent deformation in the vicinity of contact. The model of mechanical contact between polyhedral objects that we propose, strikes a balance between realism and computability. The main cost associated with our model is the need for small time steps during contact, which slows down the simulation. The final sections explain the mathematical details of our contact model.

In paper [3], a simple nonlinear contact model is presented for use in computer simulation. The nonlinear model is shown to maintain the computational simplicity of the linear model while addressing many of its deficiencies. One such advantage is that contact forces vary continuously over time. A new phase plane solution for the nonlinear model is obtained which reveals many previously unnoted properties. These include proper variation of the coefficient of restitution with impact velocity over a wide range of impact velocities, independence of model parameters, and lack of tensile (sticking) forces in simple impacts. An example is presented which demonstrates the use of the contact model in simulating the foot-ground interaction during the locomotion cycle of a walking machine.

In [4] the absence of transition curves at the entry and exit of the turnout, and the cant deficiency, leads to large wheel–rail contact forces and passenger discomfort when the train is switching into the turnout track. Two alternative multibody system (MBS) models of dynamic interaction between train and a standard turnout design are developed. The first model is derived using a commercial MBS software. The second model is based on a multibody dynamics formulation, which may account for the structural flexibility of train and track components (based on finite element models and coordinate reduction methods). The variation in rail profile is accounted for by sampling the cross-section of each rail at several positions along the turnout. Contact between the back of the wheel flange and the check rail, when the wheelset is steered through the crossing, is considered.

In [5] based on a numerical strategy previously developed, the present study introduces a numerical-experimental comparison of such occurrence. Attention is first paid to the review and analysis of existing experimental results. Good agreement with numerical predictions is then illustrated in terms of critical stress levels within the blade as well as final wear profiles of the abradable liner. Numerical results suggest an alteration of the abradable mechanical properties in order to explain the outbreak of a divergent interaction.

A general approach to simulate the mechanical behaviour of entangled materials submitted to large deformations is described in paper [6]. The main part of this approach is the automatic creation of contact elements, with appropriate constitutive laws, to take into account the interactions between fibres. The construction of these elements at each increment, is based on the determination of intermediate geometries in each region where two parts of beams are sufficiently close to be likely to enter into contact. Numerical tests simulating a 90% compression of nine randomly generated samples of entangled materials are given. They allow the identification of power laws to represent the evolutions of the compressive load and of the number of contacts.

Main material

The complexity of the experiment lies in the curvilinearity of the forms in contact: the cylinder, represented by the shaft, and the torus, which corresponds to the pressure roller. The geometric parameters of the model elements are as follows: a roller with a diameter of 56 mm and a radius of the working surface of 2.5 mm; shaft with a diameter of 25 mm.

The experiment presented in the current task is aimed at evaluating the influence of material nonlinearity on the results of stresses and strains. The current model simplified in terms of its components was adopted (truncated torus of the roller (segment) and a short segment of the shaft (Fig. 1).

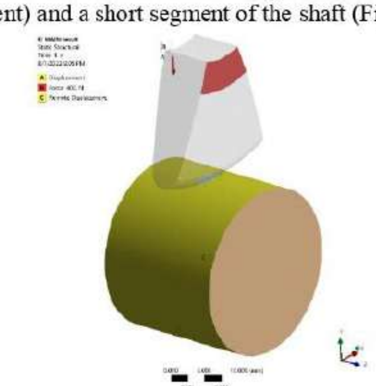
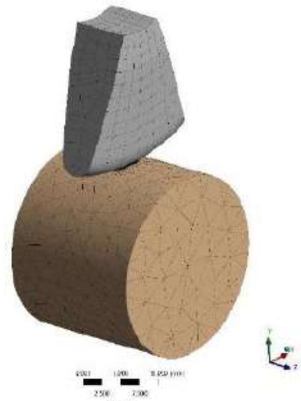


Fig. 1. Model of a truncated segment of a roller-shaft, load 400N

The task required high computational resources, the total calculation time was 1 hour. 42 min. The roller presses in a straight line (along the Y axis) on the surface of the shaft, having only one degree of freedom.

The MKE grid consists of 70,661 elements connected by 115,564 nodes, and the shape of the final elements is mainly Tetrahedrons (Fig. 2).



b)

Fig. 2.Mesh of FEM elements

At the point of contact, the body of the stain itself (area 4.2x1.8 mm and depth 0.3 mm) is modeled separately (Fig. 3.8). The size of the final elements here does not exceed 0.05 mm. Contact Sizing and Contact Match functionality of Ansys with the Tolerance indicator of 0.05 mm and 0.04 mm, respectively, was used to connect the nodes of the shaft model and the spot body.

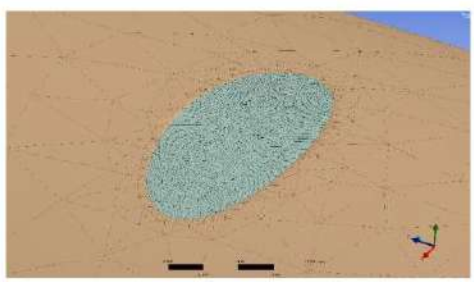
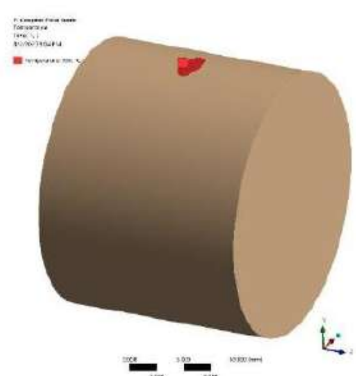


Fig. 3. Spot contact

Nonlinear properties of the Structural Steel material: beyond the yield point, the stress-strain graph abruptly changes its character: instead of being proportionally linear, it acquires a fracture (Bilinear Isotropic Hardering). In fact, this means that beyond the yield point, with the next slight increase in loads (and as a result, stresses), deformations (mm/mm) increase significantly - irreversible inertial plastic processes occur (the body "floats").



b

Fig. 4. Thermal load - 900 0C

In addition, the above-mentioned effect of plasticity is enhanced by the influence of temperatures - a thermal load (900°C). Convection of the medium is 25 W/m2°C at a temperature of 22°C.

Boundary conditions also include forceF_p= 400 N, directed opposite to the Y axis and applied to the sides of the roller. The reason is the heat load, the graph of the temperature distribution along the cross-section of the model is shown in Fig. 5.

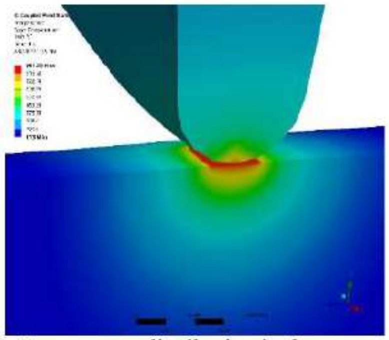


Fig. 5. Temperature distribution in the contact zone

The time of the experiment is 4.0 s, and the load application schedule is stepwise (Fig. 3.10):

- during the period of 0.0-1.0 s, the load increasesF_p from 0 N to 400 N;
- the interval of 1.0-2.0 s has a stabilization character -$F_p$keeps the value of 400 N;
- during the next second (2.0-3.0 s), the load is reduced to 0 N;F_p
- the last interval (3.0-4.0 s) passes at rest for the system - = 0 N.F_p

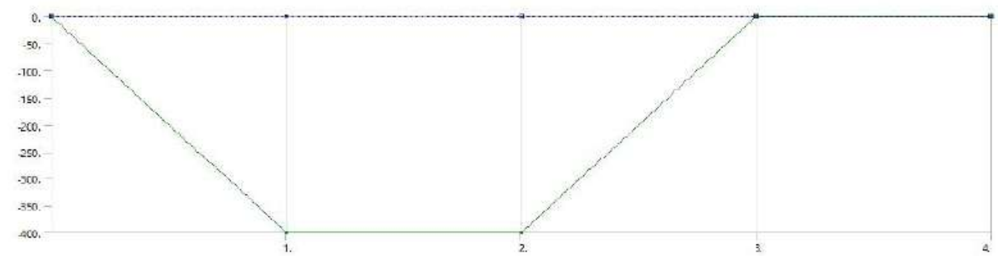


Fig. 6. Load application schedule

The purpose of simulating natural load according to such an algorithm is to identify peak stresses during the steady process of loading and residual stresses after releasing the system from the action of forces on it.

Traditionally, we make sure that the calculation reached a successful conclusion on the basis of the Force convergence graph, no abnormal jumps between iterations or gaps were recorded, and the time and force curves reached the specified limit - 4.0 c. Thus, we can proceed to the evaluation of model stresses: as expected, the largest value of stresseswas 1082.9 MPa andrecorded at a time of 2.0 s when the force$F_p$still kept the value of 400 N. This indicator significantly exceeds the yield point of the material and indicates the appearance of plastic deformations. The stress-strain state of the contact spot is shown in Fig. 3.11 - it visually shows a deflection in the central part, which is expected.

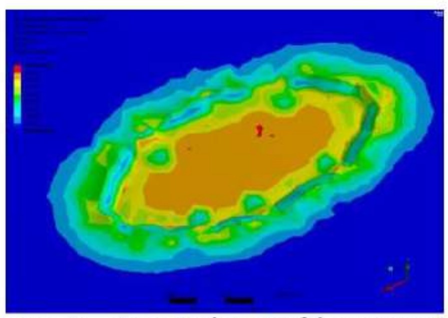


Figure 3.11 – Stress-strain state of the contact patch

The nature of the stress change during loading is the most significant, so let's analyze the key time points of fig. 3.7.

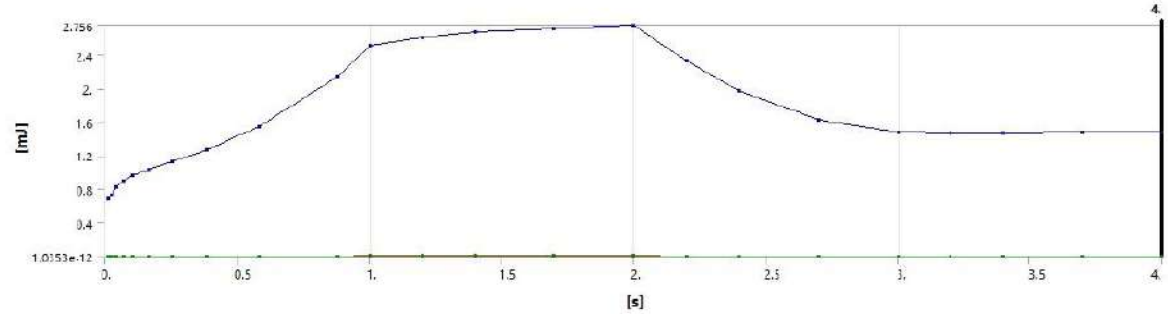


Fig. 7. The graph of changes in stress energy in the contact zone depending on time

t =0.0116 s: at the initial moment of contact between the roller and the shaft (0.0116 s), the stress value was 996.19 MPa and was recorded on the surface of the shaft (max tag). The fact of the location of the max tag is interesting: it is not in the center of the contact patch, as one might expect, but on the periphery. What actually happens: the roller "captured" a certain part of the shaft surface with its contact (the dimensions of the contact surface are 0.8×0.3 mm) and transmits the load to the rest of the shaft body through it. As a matter of fact, maximum stresses are formed at their junctions. Conventionally, this process can be called instant "sticking" of the roller to the shaft in the micro region. Such sticking can also be detected by the contact status graph (Contact Tool > Status) – the spot shows a Sticking-type contact with a sharp contour, which is further smeared, filling with Sliding and Near statuses.

t =0.0406 s: stress drops to the lowest value throughout the experiment (957.83 MPa) with movement closer to the central part of the contact patch. At the same time, the stress extreme is still on the surface of the shaft. This indicates the end of the momentary process of "sticking" the roller to the shaft established in the previous step - the contact has stabilized: the roller begins to act on the shaft as an independent body, bending it (the deformations of the spot body during loading will be analyzed below).

t =1.0 s: starting from the previous characteristic moment of time, there is a gradual increase in stresses up to 1058.7 MPa, when the load reached 400 N. The extremum of stresses migrated to a depth of the order of 0.1-0.2 mm, where, under the conditions of temperature load, the corresponding white layer began to form (Fig. 8) , which corresponds to the defamation process of the metal surface (the typical depth of the defamation layer is 0.2 mm or more).F_p

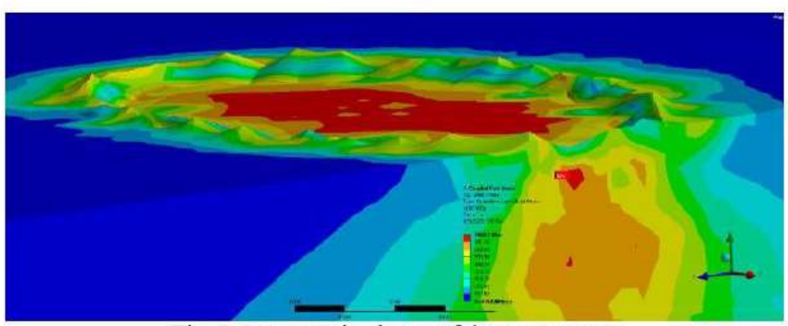


Fig. 8. Stress-strained state of the contact spot when forming a white layer

t =2.0 s: the force is maintained at 400 N - the system has accumulated maximum energy (2.756 mJ), which can be seen on the Strain Energy graph, and the stresses have increased to 1082.9 MPa. The location of the stress extreme has changed only minimally (within 0.05 mm it has sunk into the shaft body) F_p.

t =2.2 s: the force begins to linearly decrease to zero during the period 2.0-3.0 s, therefore turbulent processes appear in the structure of the outer layer - the maximum stress has decreased to 970.05 MPa and moved to the surface of the shaft, but inside the body there is still a zone of high stresses F_p.

t =4.0 s: the force remains zero during the last second of the experiment, so the shaft is free and not subjected to loads. The plastic deformation has stabilized, and the residual stresses are 1036 Mpa F_p.

Confirmation of the presence of plastic deformation can also be found on the graph of the vertical movement of the roller (along the Y axis) - as can be seen, the contact surface of the roller (Fig. 9) did not return to the initial position that corresponded to the beginning of the experiment (0.0 s). The value of the movement of the roller at the end of the experiment was 0.00311 mm, that is, the model did not restore its original location, which means that the shaft received irreversible deformations t =4s.

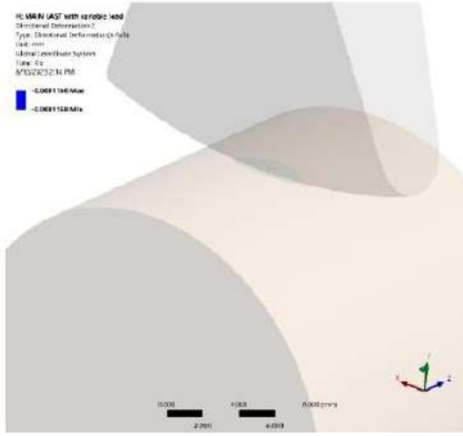


Fig. 9. Stress-strained state of the contact spot when after removing the load

The specified dynamics of the movement of maximum stresses from the surface to the body of the model can also be observed on the displacement maps: at the initial moment of contact (t =0.0116 s) the maximum value was 0.0059 mm, at the time of 1.0 s - 0.0126 mm, and at the end of the experiment - 0.0104 mm. The distribution of heat fluxes over the contact area is expected and adequate in nature - the extremum falls on the central part with a value of 166.06 W/mm2. Deformations at the peak moment of the experiment (2.0 s) were 0.01384 mm/mm.t = t =4s.

Summarizing the conducted research, the following conclusions can be reached:

Non-linearity of the material significantly affects the magnitude of the stresses in the model, and therefore the resulting plastic deformations. The key factor in the case of the graph of bilinear isotropic hardening (Bilinear Isotropic Hardening) of the Structural Steel material used in Ansys the angle of inclination of the straight line, starting from the point of the yield point, protrudes. The closeness of simulated FEM calculations to full-scale tests of material surface slander depends on the veracity of the strengthening schedule entered into the model (Multilinear, Kinematic, Nonlinear, Chaboche and other types). In fact, each experimental laboratory forms original graphsstresses and strainsbased on their own physical research of samples of material that is their intellectual property. Our task is to create a universal technique to which any graph created in Ansys could be applied.

Conclusions

1. The Ansys Static Structural calculation module turned out to be a sufficient tool in terms of its calculation capabilities. The results of the problem are absolutely adequate within the scope of Hooke's law and carry valuable information about the geometric parameters of the body of the contact spot, which is the basis of the boundary conditions of the problem.

2. The heat load of the surface of the contact spot, together with the consideration of the non-linearity of the material, significantly affects the amount of stress in the upper layers of the shaft, including the formation of the so-called white layer at a depth of about 0.2 mm. The extremum of stress migrates during the loading-unloading process of the shaft from the surface to the body of the shaft and vice versa. The regularity is as follows: as the load on the surface of the shaft increases, the extremum of stress moves inward, starting the formation of the indicated white layer.

3. The applied boundary conditions made it possible to obtain an array of information on residual stresses, deformations and displacements of the model, strain energy graphs, a temperature distribution map, as well as data on the type and nature of contact of bodies during the experiment. Undoubtedly, such a multifactorial model in the form of various input parameters (load, temperature, experiment time, convection, etc.) is a promising object of future research on the analysis of surface strengthening of the outer layers of shafts, and the calculations described in the work can serve as a basis for the formation of original FEM simulation methods natural strengthening of the material, which is especially relevant for experimental laboratories in materials science.

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Голенко К.Е., Дитинюк В.О., Диха М.О. Імітаційна модель контактної взаємодії при поверхневому зміцненні сталевих деталей

В процесах поверхневого зміцнення сталевих деталей напружено-деформований стан є визначальним для пояснення фізичних процесів зміцнення, формування розмірів площадки контакту. Аналітичні залежності контактних параметрів є досить наближеними. В даній роботі на основі програмного комплексу Ansys запропонована імітаційна модель контакту усіченого тора з циліндром, що демонструє кінетику процесу втиснення твердосплавного інструменту- тора в сталеву заготовку- циліндр. Експеримент проводився протягом 4с з метою визначення максимального рівня напружень, розподілу напружень і величини залишкових напружень після зняття навантаження. Зусилля притискання приймалось переважно в зоні пружних деформацій. Результати показали нерівномірниq розподіл напружень з максимумом в центрі плями контакту 1082 МПа. Після зміни напрямку навантаження в центрі плями контакту спостерігались невеликі залишкові деформації на рівні 0,00311 мкм. Це що свідчить про порушення пружної області на невеликій площі контакту, яка не впливає на загальний характер розподілу напружень і може бути видалена в процесі фінішної обробки. Результати моделювання напруженого стану використані для співвідношення із спостерігаємими структурними змінами матеріалу в процесі дії термічних і силових напружень. Пік напружень формувався на відстані 200 мкм, що сприяє формуванню максимальних значень мікротвердості на цій глибині.

Ключові слова: напружено-деформівний стан, поверхня, зміцнення, контактна обробка, інструмент, усічений тор, циліндр, пружні деформації

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Mechanisms of formation of wear-resistant dissipative structures in non-stationary lubrication conditions

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Abstract

The work aimed to determine the influence of the processes of supramolecular self-organization in the lubricating layer on the patterns of wear of friction pairs. The mechanisms of structural adaptability of tribocoupler elements were analyzed, and the regularities of the manifestation of a large-scale and energy jump, which characterizes the transition of the tribosystem to a metastable state, were determined. An evaluation of the tribotechnical characteristics of commercial transmission oils was carried out on a software-hardware complex that, using a roller analogy, simulates the operation of gears in conditions of rolling with slipping. It was established that the activation of contact surfaces in the mode of frequent starts and stops leads to active interaction of the lubricant's components and the metal's surface layers with the gradual formation of boundary adsorption layers. For transmission oil 'Bora B' T-Shyp, an increase in anti-friction properties has been established due to the effective lubricating ability of the oil when forming the hydro- and non-hydrodynamic components of the lubricating layer thickness. The effect of the chemical activity of the zinc dialkyl dithiophosphate antiwear additive and the hydrocarbon components of the base of transmission oils on the effectiveness of the formation of boundary films is considered. It was determined that the formation of stable boundary films of the lubricant is the leading process in manifesting their damping properties concerning the localization of elastic-plastic deformation along the depth of the metal. When boundary films are formed on 90-95% of the contact area, the change in the microstructure of the near-surface layers is fixed at a depth of up to 20 microns; when boundary films are formed on 20...50% of the surface area, the spread of elastic-plastic deformation reaches a depth of up to 50 microns. The kinetics of the formation of boundary films by the lubricant and the indicators of the specific work of friction in contact are correlated with the intensity of wear of the contact surfaces.

Key words: wear, microhardness, specific work of friction, lubrication, deformation, microstructure.

Introduction

The improvement of machines and mechanisms, the expansion of their operating conditions in the load-speed and temperature range put forward stricter requirements for lubricant quality and tribotechnical properties of lubricants. A critical aspect affecting the operational properties of lubricants is their ability to change the surface properties of triboelements by forming ordered structures as a result of the internal restructuring of the tribosystem. In each specific case, self-organization manifests itself differently. It depends on the complexity and nature of the tribotechnical system. The process of ordering in the system takes place with the help of internal factors, without external specific influence. Self-organization primarily reduces entropy production of processes occurring within the surface layers [1]. The lubricant is the most critical element in any tribological system, which ensures the modification of the surface layers of the metal due to such processes as passivation, the formation of boundary layers of lubricant of different nature, weakening or strengthening of the metal surface due to the manifestation of external or internal effects of Rebinder et al. The processes of self-organization of the lubricant and the mechanical system, which includes friction nodes, largely depend on the base's hydrocarbon composition and the additive package's functional properties. The essence of the self-organization of the tribotechnical system is that the interaction of the tribocoupling elements' surface layers and the lubricant's activated components is localized in thin near-surface layers. Such interaction causes the formation of secondary friction structures that protect the tribotechnical system from external influences.

Determining the mechanisms of the formation of boundary films of lubricant on contact surfaces activated by friction, the kinetics of changes in the specific work of friction, the patterns of changes in antifriction, and rheological indicators of frictional contact will expand the vision about the ways of ordering secondary protective structures. That will make it possible to control the processes of self-organization of the tribosystem due to the selection of a lubricant with a specific base and multifunctional additives, which will ensure increased wear resistance of friction pairs by localization of adaptation processes in surface metastable structures.

Literature review

One of the most common manifestations of friction in mechanical systems is the release of heat in the area of contacting surfaces. The main activating factor of triboprocesses in the zone of frictional contact is elastoplastic deformation. According to [2, 3], from a thermodynamic point of view, the work of friction forces can be conditionally divided into two components. The first part of the friction work measures material damage and relates to the change in the deformed volumes of materials in the latent (potential) energy of various elementary defects and damages that originate and accumulate in the near-surface layers of materials. The second part of the friction work is related to microscopic mechanisms of the dissipative type. It is related to dynamic recovery processes, during which latent energy and heat of friction are released. There are many contradictions regarding the quantitative indicators of stored energy during friction. According to [4, 5], most of the energy spent on deformation is converted into heat, and only a few percent of this energy is stored to form crystal lattice defects. In [6], it is noted that more than 90% of all stored energy is concentrated inside the surface films, which are stable zone with increased internal energy.

Since the surface layer of tribocoupler elements is an open thermodynamic system, friction, and wear processes can be described by energy balance or entropy balance equations. The total production of entropy in the tribosystem always increases. However, instead of the expected chaos and degradation, self-organization processes dominate the vast majority of tribosystems, which creates prerequisites for the tribosystem to remain in an equilibrium state for a long time. The level of the equilibrium state is determined not by the entire entropy but only by its small part, which is related to the substance of the tribostructure. At a constant temperature, it is proportional to the volume and can increase and decrease [7]. The competition of free energy and entropy gives rise in conditions far from equilibrium to stable periodic processes. As a result of such processes, the formation of dissipative structures is possible, leading to the tribosystem's self-organization. Dissipative structures are characterized by processes producing negative entropy [8]. Due to the occurrence of processes with negative entropy production, the total entropy production in a system with dissipative structures is lower than in a similar system without them. The formation of dissipative structures leads to decreased entropy production and wear rate.

According to [9], the maximum production of entropy is a condition for initiating the self-organization process in tribofilms, capable of significantly reducing the wear rate. The authors consider applying friction body run-in in rigid regimes close to seizure. In such conditions, the activation of triboprocesses is accelerated, and there is a correlative decrease in the run-in period and the time of the start of self-organization, which leads to a decrease in overall wear. In [6], a new technology for selecting wear-resistant materials, based on the selection of materials that accelerate the formation of dissipative structures, is considered. The authors show that the intensity of the wear process for the formation of dissipative structures is lower than for the formation of equilibrium surface structures. Presented in [10, 11], the method of studying self-organization processes based on the parameters of thermo-oxidative stability of lubricants with cyclic temperature changes allows to determine the quantitative indicators of self-organization processes, in which excessive thermal energy is transferred to lower energy levels with the formation of oxidation and evaporation products, according to which the temperature range is established performance of lubricants and their resource. In [12], it was found that when steel is rubbed in a lubricating medium (transmission oils based on pentaerythritol esters and organosiloxane liquids), protective surface films of sulfur and silicon compounds are formed on the surface of the steel. It is noted that the presence of unoxidized iron on the friction track promotes catalytic reactions that form surface films of lubricant molecules that reduce the friction coefficient by 70–80%. The leading indicators characterizing the formation of wear-resistant dissipative structures when lubricating steel with oils for hypoid gears include an increase in antifriction characteristics, the formation of boundary layers of lubricant, strengthening of contact surfaces, and the formation of a heterogeneous deformation microrelief with a fine-grained structure [13]. The formation of chemically modified boundary layers on 90% of the contact area of the tribo-coupling elements ensures an increase in the wear resistance of the leading and trailing surfaces in rolling with slipping by 2 and 1.4 times, respectively.

Thus, establishing the mechanisms of structural adaptability of tribo-coupling elements, determining the patterns of manifestation of a large-scale and energy jump, which characterizes the transition of the tribosystem to a metastable state, will allow determining the ways of controlling dynamic recovery processes in the zone of frictional contact.

Purpose

To determine the influence of the processes of supramolecular self-organization in the lubricating layer on friction pairs' wear patterns.

Objects of research and experimental conditions

Transmission oil for hypoid gears (T-Shyp) of two manufacturers was chosen as lubricants for research. T-Shyp is a universal multifunctional oil containing highly effective anti-seize additives. It can be used as an all-season oil for hypoid gears of trucks and special machines operating in the conditions of a moderate temperate climate zone. Sample 1 - transmission oil ‘Bora B’ T-Shyp (Technical Specification Ukraine 19.2-38474081-017:2018 / SAE 140 / API GL-5). According to the chemical composition, this oil is a mixture of a highly viscous flavored product with high-purity distillate oil and a composition of additives (Infineum C9425 (zinc-dialkylditiophosphate), poly alkylmethacrylate copolymer and alkylaminemine). Sample 2 - transmission oil for hypoid gears T-Shyp (Technical Specification 38.1011332-90). Oil composition: refined mineral oil (a complex mixture of hydrocarbons (C24-C50), obtained by selective purification and hydrogenation of petroleum distillate) and a complex of functional additives (zinc dialkyldithiophosphate and methylene-bis).

Rollers were made as the material of the contact surfaces - steel 45 (HRC 38 - 42, Ra 0.37 µm).

The study of lubricants is developed on the Software-Hardware Complex (SHC) to estimate the tribotechnical parameters of the triboelements [14]. The complex simulates the operation of gears in rolling with slipping condition.

The research was carried out in non-stationary conditions, which involve the recurring operation of the engines of the research installation in the mode: start - stationary work – braking – stop with the support of the software program (Fig. 1). The duration of one complete cycle was 80 seconds.

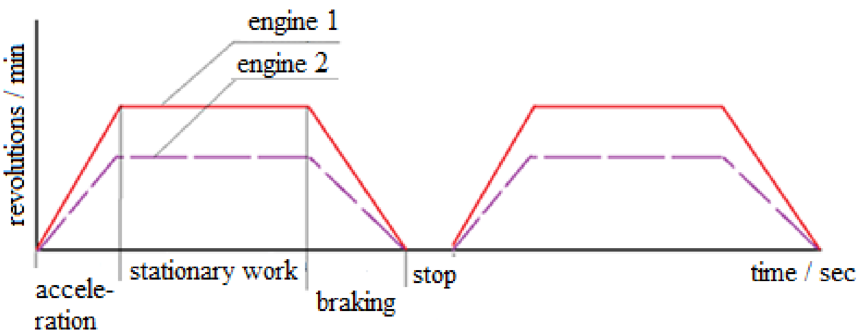

Fig. 1. Scheme of the engines’ operation of the friction installation during the operation of the tribosystem in non-stationary conditions [13].

The maximum rotation frequency for the studied samples was 700 rpm or 1,83 m/s (leading surface) and 500 rpm or 1,31 m/s (lagging surface). Slippage - 30%. The maximum Hertz contact load is 200 MPa. Slippage - 30%. The maximum Hertz contact load is 200 MPa. The maximum number of cycles in the experiment is 100 cycles (from the 1st to the 45th cycle - oil temperature 20 ^{0}C, from 46 to 50 cycle - oil heating, from 51 to 100 cycle - oil temperature 100 ^{0}C).

Analysis of the main results

Table 1 presents the averaged results of the tribotechnical parameters of the frictional contact in conditions of rolling with slipping.

Table 1

Tribotechnical characteristics of the contact

Indicator	**Lubricant**			
	Sample 1		Sampl 2	
	Lubricant temperature, ^{0}C			
	20	100	20	100
Coefficient of friction	0.009	0.015	0.013	0.021
The minimum thickness of boundary layers, µm	0.12	0.09	0.1	0.038
The total thickness of the lubricating layer, µm	5.14	4.7	4.5	3.95
Specific work of friction, J/mm2	12569	15440	39100	19000
Effective viscosity in contact, Pa·s	490.9	58.21	190.4	41.71

The increase in the antifriction properties of tribocontact by 30% when using sample 1 as a lubricant is due to the greater bearing capacity of the lubricating layer. The total thickness of the lubricating layer, which consists of hydro- and non-hydrodynamic components, is on average 12...14% higher for sample 1.

Activation of contact surfaces in the mode of frequent starts and stops leads to active interaction of the lubricant components and metal surface layers, which is manifested in the formation of boundary adsorption layers (Fig. 2).

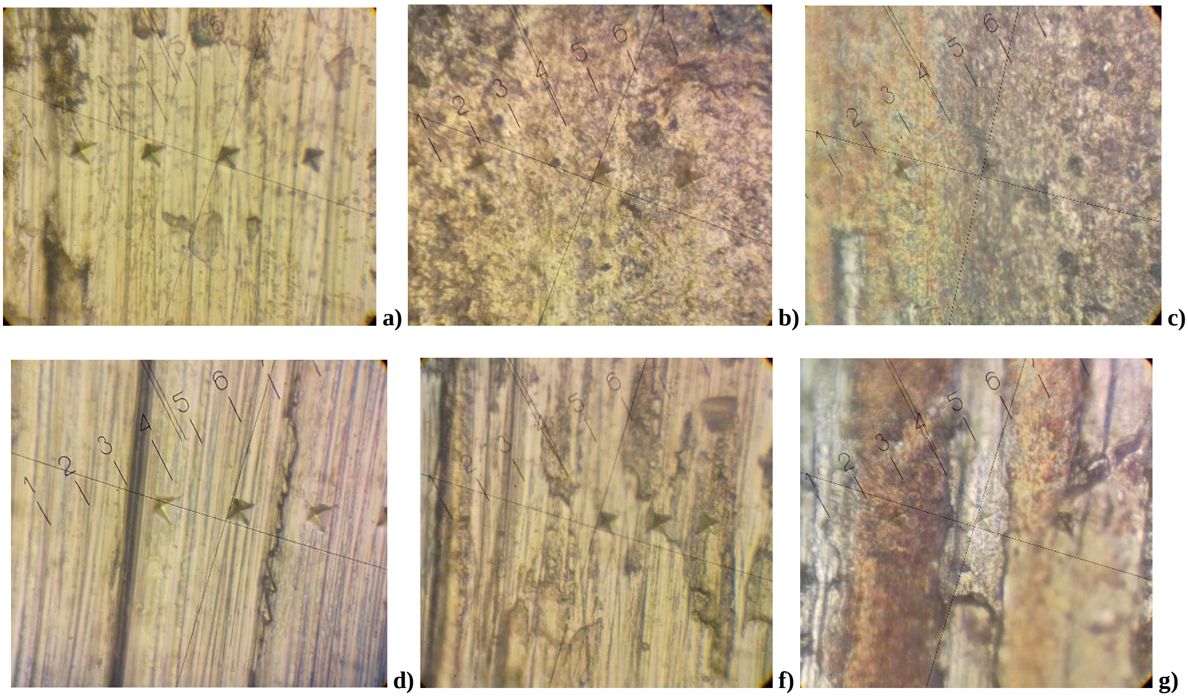

Fig. 2. The initial surface of steel 45 (a, d) and after 100 cycles of lubrication by sample 1 (b, c) and sample 2 (f, g).

However, the mechanism of formation of the non-hydrodynamic component of the lubricating layer thickness is significantly different for the two oils under study. Let us consider this mechanism with the energy parameter of contact-specific friction work. The activation of the surface layers of steel 45 due to elastic-plastic deformation causes the chemical activity of the anti-wear additive zinc dialkyl dithiophosphate and hydrocarbon components of the base of the tested gear oils, which form boundary films on the metal surface. Unlike sample 2, which contains only high-purity distillate oil as a base, sample 1 contains up to 15 % of a highly viscous aromatic product that enhances the activity of zinc dialkyl dithiophosphate [13, 15]. The use of sample 1 ensures the formation of stable boundary films on 90-95% of the contact area (Fig. 2, b, c) with a thickness of 0.09...1.2 μm, which effectively shields the surface from the propagation of elastic-plastic deformations to the upper surface layers. The change in microstructure is recorded at a depth of up to 20 μm and indicates structuring (Fig. 3, b). The values of specific friction work range from 12000...16000 J/mm^2.

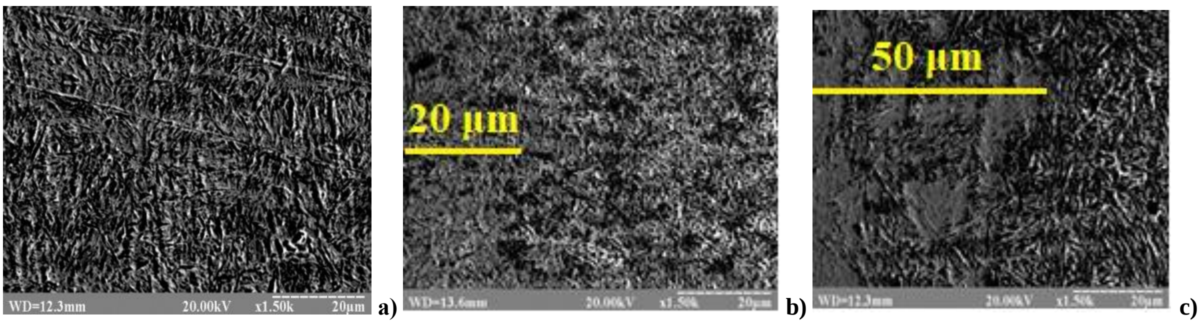

Fig. 3. Microstructure of the surface layers of steel 45 (× 1500) before friction (a) and after 100 cycles of lubrication with sample 1 (b) and sample 2 (c).

When using sample 2, boundary layers of lubricant with a thickness of 0.038....1.2 μm are formed on 20...50% of the surface area (Fig. 2, f, g). Suppose the maximum thickness of the boundary layers is similar to the values established for sample 1. In that case, their minimum value is 1.2 and 2.37 times less, respectively, at an oil temperature of 20 and 100 ^{0}C. Destruction of boundary layers occurs in 10-15% of cycles. Accordingly, the less effective shielding effect of the boundary film of sample 2 causes the propagation of elastic-plastic deformation at the third to a depth of 50 µm. At the same time, the values of the specific friction work are 3.11 and 1.23 times higher than those for sample 1, respectively, at an oil temperature of 20 and 100 ^{0}C.

The kinetics of the formation of boundary films by the lubricant and the indicators of specific friction work in contact correlate with the intensity of wear of the contact surfaces.

The total linear wear of 45 steel rollers is 3.97 µm and 7.6 µm when friction pairs are lubricated with oil samples 1 and 2, respectively (Table 2).

Table 2

Indicators of linear wear and microhardness of friction pairs

Indicators	**Lubricant**			
	Sample 1		Sample 2	
	Leading surface	Lagging surface	Leading surface	Lagging surface
Wear, µm	1.4	2.57	3.1	4.5
Surface microhardness before the experiment (initial), MPa	4382	4380	4376	4385
Surface microhardness after 100 operating cycles, MPa	5100 (strengthening)	4590 (strengthening)	4116 (weakening)	3890 (weakening)

The wear of contact surfaces is significantly affected by both the formation of protective boundary layers of the lubricant and the formation of dissipative structures on the surface of the metal with increased hardness. The change in the microhardness (ΔH) of the surface layers of steel 45 during working depends on the type of the material under study. If when lubricating the friction pairs with sample 1, the leading (ΔH = + 718 MPa) and lagging (ΔH = + 210 MPa) surfaces are strengthened, then when using sample 2, the weakening of the metal surface layers is established for the leading (ΔH = - 260 MPa) and lagging (ΔH = - 495 MPa) surfaces (Table 2).

Thus, the formation of stable boundary films of the lubricant on friction-activated contact surfaces is the leading process in the manifestation of their damping properties concerning the localization of elastic-plastic deformation along the depth of the metal and anti-wear properties in harsh lubrication conditions, which include the investigated non-stationary processes.

Conclusions

1. The study was carried out on a hardware and software complex using a roller analogy to model the operation of gears under rolling and slipping conditions. The tribotechnical characteristics of commercial gear oils from different manufacturers were studied.

2. Compared to the T-Shyp gear oil for hypoid gears (sample 2), a 30% reduction in the coefficient of friction was observed for the T-Shyp gear oil 'Bora B' (sample 1), due to the oil's effective lubricating ability in forming the hydrodynamic and non-hydrodynamic components of the lubricating film thickness.

3. The correlation between the linear wear of steel and the kinetics of the formation of boundary films by the lubricant, the indicators of the specific friction work in contact, and the formation of dissipative structures on the surface of a metal with increased hardness were established.

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Ільїна О. А., Мікосянчик О. О., Мнацаканов Р.Г., Костюннік Р. Є., Ящук О П., Штейник М. А.
Механізми формування зносостійких дисипативних структур в нестаціонарних умовах мащення

Метою роботи було визначення впливу процесів надмолекулярної самоорганізації в мастильному шарі на закономірності зношування пар тертя. Проаналізовано механізми структурної пристосованості елементів трибоспряження, визначено закономірності прояву масштабного і енергетичного стрибка, що характеризує перехід трибосистеми до метастабільного стану. Проведена оцінка триботехнічних характеристик товарних трансмісійних олив на програмно-апаратному комплексі, який за допомогою роликової аналогії моделює роботу зубчастих передач в умовах кочення з проковзуванням. Встановлено, що активація контактних поверхонь в режимі частих пусків – зупинок призводить до активної взаємодії компонентів мастильного матеріалу та поверхневих шарів металу з поступовим формуванням граничних адсорбційних шарів. Для transmission oil ‘Bora B’ T-Shyp встановлено підвищення антифрикційних властивостей за рахунок ефективної змащувальної здатності оливи при формуванні гідро- та негідродинамічної складової товщини мастильного шару. Розглянуто вплив хімічної активності протизношувальної присадки диалкілдитіофосфат цинку та вуглеводневих компонентів базової основи трансмісійних олив на ефективність формування граничних плівок. Визначено, що утворення стійких граничних плівок мастильного матеріалу є ведучим процесом щодо прояву їх демпфуючих властивостей стосовно локалізації пружно-пластичної деформації по глибині металу. При формуванні граничних плівок на 90-95% площі контакту зміна мікроструктури приповерхневих шарів фіксується на глибині до 20 мкм, при формуванні граничних плівок на 20…50% площі поверхні розповсюдження пружно-пластичної деформації при треті сягає глибини до 50 мкм. Кінетика формування граничних плівок мастильним матеріалом та показники питомої роботи тертя в контакті корелюють з інтенсивністю зношування контактних поверхонь.

Ключові слова: знос, мікротвердість, питома робота тертя, змащування, деформація, мікроструктура.

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Detection of changes in the characteristics and properties of friction zones of parts of tribocoupling systems and machine assemblies based on the entropy approach

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Abstract

The role of entropy in the processes of friction and wear of tribocoupling materials of moving parts is clarified. The implementation of the effect of self-organization of materials depending on the production of entropy is theoretically substantiated. The conditions of self-organization with negative entropy production were obtained. The relationship between the rate of volumetric wear of tribocoupled parts and the production of excess entropy and its flow is determined. Expressions for the intensity of wear of tribocoupling parts were obtained, taking into account thermal processes in the friction zone. The trends of changes in the characteristics and properties of tribocouplers of components, systems and machine aggregates with a change in entropy have been clarified.

Key words: entropy approach, tribocoupling of parts, self-organization, friction zone, property.

Introduction

The leading role in synergetics is attributed to the entropy approach [1,2], which consists in the fact that the internal activity of tribocouples of parts, nodes, systems, and machine assemblies is opposed to the disordering element of entropy. Under certain conditions, this leads to the orientation of self-organization of processes and states in them.

At the same time, the processes and states of the materials of the parts must be irreversible, and the tribocouplings of the parts is an open system and far from the state of thermodynamic equilibrium. It is characteristic that entropy, which is produced in tribocouplings of parts, does not accumulate in them, but is brought out. There is a flow of negentropy from the external environment. In non-equilibrium tribocouplings of parts, fluctuations are accumulated and amplified and obey the principle of positive feedback.

As a result of increased fluctuations, the tribocouplings of the materials of the parts becomes more unstable, the previous order and structure are destroyed and qualitatively new ones arise when energy is dissipated in the external environment.

The process of self-organization begins at the micro level in the local areas of the friction zone of the materials of the parts and is accompanied by an increase in fluctuations under the influence of external influences.

The emergence of a new order in tribocoupled materials occurs spontaneously at the moment of extreme instability, when the materials of the parts acquire significant coherence. Irreversibility, instability and imbalance are the most fundamental properties of tribocouples of components, systems and machine assemblies than stability and equilibrium.

The characteristics and properties of materials of tribocouplers of parts have a probabilistic nature and randomness has a significant impact on their further development.

The development of tribo couplings of parts in operation is a non-linear process, and therefore can be described by a non-linear differential equation.

According to the theory of non-equilibrium processes [1-4], the properties of tribocouples of parts far from the equilibrium state become unstable and their return to the initial state is optional. At the same time, their behavior is ambiguous, but there are effects of coordination, correction of the behavior of its elements at macroscopic distances and time intervals [5]. Cooperatively coordinated behavior determines the processes of ordering, the emergence of certain structures from chaos, their transformation and complication [6]. The greater the deviations from equilibrium, the greater the coverage of correlations and interrelationships, the higher the coherence of processes characterized by nonlinearity and the presence of positive and negative feedback [6, 7], and the possibilities of controlling influence on the tribocoupling of node parts, systems and units of machines.

The effectiveness of the implementation of the entropy approach to the evaluation of the properties of the materials of the friction zones of the tribo-coupling parts of assemblies, systems, and machine assemblies increases when using the fundamentals of physical mesomechanics [8]. The study of regularities of the processes of friction and wear of the conjugations of parts and the development of new and improvement of known methods of theoretical evaluation of tribotechnical characteristics and properties is definitely relevant. In this regard, the introduction of the entropy approach to the assessment of tribotechnical characteristics and properties of the friction zone of the couplings of parts and the detection of their changes due to the change in entropy deserves attention.

Literature review

In the process of evolution, the external contribution to the total entropy of tribocoupling of parts can be arbitrary, depending on the parameters of the external environment and the nature of the interaction of parts. At the same time, two types of situations are possible:

– the total entropy decreases due to its return through the boundary surface of tribocoupling of parts:

$$dS/dt < 0\,; \tag{1}$$

– the total entropy is constant and maximal for the given conditions of operation of tribocouples of parts, but less than the entropy of their equilibrium state:

$$S_{\max} = \text{const} < S_{\textit{рівн.}\max}\,. \tag{2}$$

If the flow of entropy is equal to its production, then the material of tribocoupling of parts is in a stable steady state or a state of current equilibrium. With a positive change in entropy, energy processes in tribocouplings of parts are always dissipative, that is, they are accompanied by a decrease and dissipation of energy. Dissipation of energy is the main feature of the current equilibrium, but, in accordance with the principle of self-integrity of equilibrium, the system cannot spontaneously leave it, and under external influence, the processes aimed at its compensation intensify. This is similar to the manifestation of the phenomena of electromagnetic induction [9]. According to the principle of minimum entropy production, the laws of nature [10] assume several options for the development process (organization), and the one that corresponds to the minimum dissipation of energy is realized. At the same time, the driving force behind the processes of self-organization of materials of tribocouplers of parts is phase transformations or their sequence, as a result of which there is a transition to a more ordered state corresponding to lower symmetry [11].

In such conditions, the processes of friction and wear are realized against the background of increased gradient ratios of temperature, stresses, chemical potential, concentration of alloying elements and defects in the crystal structure. A complex set of physico-mechanical, physico-chemical, tribological and rheological phenomena is observed. Since friction and wear are non-equilibrium thermodynamic processes, self-organizing changes in the tribocoupling of parts are inevitable and mandatory [1,2,12-14].

The internal manifestation of self-organization in the materials of tribocouplers of parts is:

– formation of secondary structures on the surfaces of parts with higher strength and wear resistance compared to the initial structures;

– the development of equilibrium roughness, regardless of the initial microgeometry of friction surfaces;

– increasing the actual contact area due to the working wear and, as a result, reduction of contact loads;

– implementation of the effect of selective transfer, etc. [15-17].

The external manifestation of the self-organization of materials in the tribocoupling of parts is: reduction and stabilization of energy, power and tribotechnical characteristics, in particular, the coefficient of friction, temperature, moment of friction, intensity of wear. At the same time, it is advisable to analyze the general patterns of self-organization from the standpoint of a system-oriented approach, dividing the materials of parts and the working (technological) environment into subsystems of local areas of contact interaction, which are united by mode, structural, geometric and other signs of affinity. Local areas, in turn, consist of subsystems – ensembles [18-20], within which microstructural processes are implemented, including internal mass transfer [18-20].

Purpose

The purpose of this work is to use the entropy approach to theoretically substantiate the realization of the state of self-organization of tribocoupling materials of components, systems and assemblies of machines and to identify the direction of the properties and characteristics of the materials of the friction zones from the change in entropy.

Results

On the friction surfaces and in the surface layers of the materials of tribocoupled parts, a whole set of various processes takes place at the same time, due to which the tribocoupled parts lose their thermodynamic stability. Some of them are directly caused by friction, and others are indirectly related to it.

The first group of physical processes includes heat removal, mass transfer from the friction zone, deformation of the surface layers of parts, etc. They are caused, as a rule, by gradients of temperature, chemical potential, stress, concentration of defects, etc., which arose as a result of friction and preliminary strengthening or modifying processing of the materials of the parts.

The second group of processes, according to the equilibrium diagrams of the state of materials of the parts, takes place at the temperature of heating of the surface layers from the work of frictional forces. Basically, these are phase transitions and chemical reactions. At the same time, heating conditions the kinetic possibility of relaxation processes, the driving forces of which are not related to friction and do not depend on it, but exist both in the friction zone and in the adjacent layers and are directed chaotically. It is also necessary to highlight the processes that occur in the friction zone, but are caused not by friction, but by operating conditions. Examples of such processes are processes in the tribocoupling of parts observed during friction with vibration, irradiation, and other influences [22, 23].

The excess production of entropy during the realization of the self-organization effect must be negative and agree with Lyapunov's theorem [1, 24]:

$$\frac{1}{2}\frac{\partial}{\partial t}\left(\delta^2 S\right)=\sum_n \delta X_n \delta J_n\,, \tag{3}$$

where X_n and J_n – thermodynamic forces and thermodynamic flows, respectively.

If $\sum_n \delta X_n \delta J_n \le 0$, then the materials of tribocouples of parts lose stability and self-organization with the formation of dissipative structures can be observed. If friction processes are significant , we have:

$$\frac{dS}{dt}=\frac{(f_{mp}(v,t)Nv)^2}{\lambda_{м}(v,t)S_{mp}T^2}\,, \tag{4}$$

where $f_{mp}(v,t)$, S_{mp} – coefficient and surface area of friction; N – load; v – relative speed of parts; $\lambda_{м}(v,t)$, T – the coefficient of thermal conductivity and the temperature in the friction zone. If the speed of movement is variable, and $\lambda_{м}=\mathrm{const}$, then the excess production of entropy is:

$$\frac{\partial}{2\partial t}\left(\delta^2 S\right)=\frac{N^2}{T^2 S_{mp}\lambda_{м}}\left(\frac{\partial f_{mp}}{\partial v}+f_{mp}\right)^2(\delta v)^2. \tag{5}$$

If $\lambda_{м}\ne\mathrm{const}$ and $v\ne\mathrm{const}$, then we have:

$$\frac{\partial}{2\partial t}\left(\delta^2 S\right)=\frac{N^2}{T^2 S_{mp}\lambda_{м}}\left(\frac{\partial f_{mp}(v,t)}{\partial v}v+f_{mp}(v,t)\right)\left(f_{mp}(v,t)+v\frac{\partial f_{mp}(v,t)}{\partial v}-\frac{f_{mp}(v,t)v}{\lambda_{м}}\frac{\partial\lambda_{м}(v,t)}{\partial v}\right)(\delta v)^2. \tag{6}$$

Analysis of equation (6) shows that when its positive right-hand side tribocoupling of parts does not lose stability, and when it is negative, it does. With negative entropy production, we get the following conditions:

$$\partial f_{mp}(v,t)/\partial v\ge 0\,,\qquad \partial\lambda_{м}(v,t)/\partial v\ge 0\,; \tag{7}$$

$$\partial f_{mp}(v,t)/\partial v\le 0\,,\qquad \partial\lambda_{м}(v,t)/\partial v\le 0\,. \tag{8}$$

Note that conditions (7) and (8) are sufficient for the realization of self-organization in the tribocoupling of parts, in the presence of synergistic interaction of two or more processes in the friction zone. At the same time, the material of the tribocoupling parts is complicated, new structures appear in the surface layer of the material and in the adjacent layers of the working (technological) environment.

From the point of view of entropy production, the self-organization of the tribocoupling materials of parts can create such conditions when the absolute value of the negative entropy associated with friction increases, but the overall entropy production does not change [1, 2, 24]. This indicates that the tribocoupling of parts from the outside can receive high-power energy without a significant change in the intensity of wear, and a significant part of the work of friction forces will be spent on unbalanced processes. The analysis of the self-organization of the materials of the tribocoupled parts and the working (technological) environment within the limits of nonlinear thermodynamics [24-26] confirms that with strong excitation of the equilibrium tribocoupled parts, their behavior becomes diverse and non-linear. In this regard, a more active and effective way of improving the tribocoupling of parts is the combination of the Schrödinger approach and nonlinear thermodynamics [25, 26], and the powerful and targeted excitation of the tribocoupling materials can be implemented by highly ordered energy flows (laser radiation [1]) or substances that ensure their transition to a more organized and stable state.

The above makes it possible to formulate the main provisions of the entropy approach to changes in the properties of the friction zones of tribocoupling parts of assemblies, systems and machine assemblies:

1. Tribocoupling of machine parts is an open thermodynamic system that exchanges energy and mass between their elements and the environment. The entropy balance equation is used to describe their behavior:

$$\frac{d}{dt}\int_V s dV = \int_V (\sigma_s - divJ_s) dV , \tag{9}$$

where σ_s, J_s – production and flow of entropy density, respectively; s is the volume density of entropy.

2. Friction is a process accompanied by fluctuations of fields, speed, pressure, and temperature, which are not destroyed during the evolution of the state of tribocouples of parts and the development of their parameters over time. When they fade, there is a transition to thermodynamic states with minimal entropy production, which are bifurcation points with an optimal mode of operation, from the point of view of wear and manifestation of the synergistic principle of self-organization.

3. In thermodynamics of open systems, including and in the tribocoupling of parts, the driving forces of the processes are gradients of temperature, concentration, chemical and electrical potentials, which determine various processes of transfer of heat flows, matter (diffusion and chemical reaction) and electrical charges.

The use of the entropy criterion of destruction and the equation of the entropy balance shows that the process of wear of the materials of the tribocoupling parts with a volume of V is not responsible for the entire density of entropy accumulated by it, but a part of it, that is, the coefficient k_S – the entropy utilization coefficient.

In this case, the entropy balance equation has the form:

$$\frac{d}{dt}\int s dV = k_s\left(\int_V (\sigma_s - divJ_s) dV\right). \tag{10}$$

It should be noted that the entropy criterion of destruction acts as a measure of the workability of the material of tribocoupler parts. At the same time, the effects of thermal, mechanical, chemical, electrical and convective processes on the production and formation of the entropy flow are taken into account. The entropy density accumulated by the material of the parts, in its physical essence, characterizes its wear resistance.

To evaluate the tribotechnical characteristics, the dynamic development of the processes in the materials of the tribocouplers of the parts, due to various mechano-physical and chemical-physical reasons, should be considered. This is taken into account primarily in the production of excess thermal entropy on the spots of actual contact of the tribocoupler parts.

After integrating equation (10) over the investigated time interval (0,t), we have:

$$\int_V \frac{sdV}{dt} = k_s \int_0^{V_u} (\sigma_s - divJ_s) dV . \tag{11}$$

At the same time, the rate of volume wear of the material is equal to:

$$\frac{dV_u}{dt} = \frac{k_s \int_V (\sigma_s - divJ_s) dV}{s} . \tag{12}$$

Considering the contact area S_k, we have:

$$\frac{dV_u}{dt}=\frac{k_s\int_0^{V_u}(\sigma_s-divJ_s)S_k dV}{s}. \qquad (13)$$

At the nominal contact area S_{nk}, the volumetric wear rate is equal to:

$$\frac{dV_u}{dt}=\frac{k_s S_{nk}\int_0^{u}(\sigma_s-divJ_s)dx}{S_r}, \qquad (14)$$

where S_r is the limiting entropy density of the part material.
By definition, the intensity of wear of tribocoupling parts is equal to:

$$I_{1u}=\frac{dV_{1u}}{dt}\frac{1}{S_{1k}v_{mp}};\;\; I_{21u}=\frac{dV_{2u}}{dt}\frac{1}{S_{2k}v_{mp}}, \qquad (15)$$

where v_{mp} – the relative speed of movement of the part.
Considering (14) in expressions (15), we have:

$$I_{1u}=\frac{k_s\int_0^{u1}(\sigma_s-divJ_s)dx}{v_1\cdot S_{u1}};\;\; I_{1u}=\frac{k_s\int_0^{u2}(\sigma_s-divJ_s)dx}{v_2\cdot S_{u2}}. \qquad (16)$$

Considering the significant contribution to friction and wear of thermal processes, it can be assumed that $k_s=\frac{T_{cn}}{T}$, where T_{cn} – the flash point, T – the temperature of the working surface of the part. At the same time, the entropy density in the worn material of the parts has two components: the standard (zero) value and the addition from the influence of thermal effects:

$$s_u=s_0+\int_{T_0}^{T}\frac{C_p}{T}dT, \qquad (17)$$

where C_p – the heat capacity of the surface layer of the part material.

If the components of thermal processes, including oxidizing ones, are taken into account, then the cumulative production of entropy of the materials of tribocoupler parts is added to the expression in brackets of expressions (16):

$$\sigma_T=\sum_{i=1}^{k}G_{Ti}\frac{du_i}{dt}\eta_{Ti}\frac{1}{T}=\sum_{i=1}^{k}(H_{Ti}-TS_{Ti})\frac{du_{Ti}}{dt}\eta_{Ti}\frac{1}{T}, \qquad (18)$$

where G_{Ti}, H_{Ti} and S_{Ti} – the Gibbs potential, enthalpy and entropy, i – a component of thermal processes; the formation of the i -th grade oxide; $\frac{du_{Ti}}{dt}$ – wear rate.

Taking into account the predominant role of thermal processes in material wear and dependence (18), we finally have:

$$I_u=\frac{\int_0^{u}\lambda_T\left[\left(\frac{dT}{dx}\cdot\frac{1}{T}\right)^2-\frac{d^2T}{dx^2}\cdot\frac{1}{T}\right]dx+\sum_{i=1}^{k}\left[(H_{Ti}-TS_{Ti})\frac{du_{Ti}}{dt}\eta_{Ti}\cdot\frac{1}{T}\right]\cdot\frac{T_{cn}}{T}}{Vs_u}. \qquad (19)$$

From the last dependence, it follows that to reduce the intensity of wear, it is necessary to reduce the contact temperature T in various ways, including the use of triborecovery technologies to form coatings of the optimal composition, reducing the parameter k_s, increasing the entropy of the material of the part s_u and the entropy of the component thermal processes S_{Ti}.

In thermodynamics and statistical physics, entropy is a function of the state of the system. It is included in the mathematical expression of the second principle of thermodynamics:

$$TdS = dU + dA, \tag{20}$$

where T – the thermodynamic temperature, dU – the change in internal energy; dA – a change in the work of internal forces. If a certain amount of heat is introduced into the thermodynamic system (tribocoupling of parts) dQ, then the entropy change dS in the reverse process is equal to $dS = dQ/T$. Note that thermal entropy, in contrast to configurational entropy, is related to processes in the crystal lattice of the material of the tribocoupler parts.

Due to the fact that the tribocoupling of parts functions under conditions of intense heat generation, depending on the assessment of the intensity of wear and tear, I_u value s_u has the content of specific thermal entropy. Entropy – the most important thermodynamic characteristic of the material of the elements of tribocoupling of parts, which determines the speed and direction of the chemical reaction, the magnitude of the Gibbs and Helmholtz potentials, etc.

The theoretical justification of the experimental results revealed a number of generalized patterns of change in the entropy of materials of tribocoupling of parts:

– the complication of the composition of the materials of parts leads to an increase in its entropy;

– the harder the material of the part, the lower the entropy;

- the value of the standard specific entropy of an element s_0 depends on its serial number z in the. table. D.I Mendeleev and changes in a certain direction, having a minimum point;

– in the amorphous state, the materials of the surface state of parts have an entropy greater than in the crystalline state;

– entropy is sensitive to the degree of dispersion of the material: as the grain size decreases, entropy increases;

– the greater the density of the substance, the material of the part, the lower its entropy, there is an inverse linear relationship between these values: $\rho_м \sim 1/s$.

Existing materials for tribocoupling parts are mainly multi-component materials with a heterogeneous structure, which mainly consist of two phases: hard alloys – carbides and metal bond, alloyed cementite, martensite and residual austenite. The components of materials differ in mechanical and physicochemical characteristics and properties. It is known from the thermodynamics of non-equilibrium processes that for multicomponent systems, if they are considered as ideal solid solutions, all thermodynamic potentials – Gibbs, Helmholtz, enthalpy and entropy - have the property of additivity. It follows that the entropy density of a hard alloy can be calculated as the sum of products of the molar fraction of each component by the value of its standard entropy density:

$$s_{ij} = \eta_1 s_i + \eta_2 s_j, \tag{21}$$

where $\eta_1 + \eta_2 = 1$, η_1 and η_2 – the corresponding molar fraction of the component, and s_i, s_j – the entropy density of each component.

One of the methods of managing performance indicators of tribocoupler parts made of hard alloy is to improve the structure of the material in the broadest sense of the word. The effect is also taken into account that with the reduction of the size of the initial components of the alloy to the nanolevel, as well as the optimization of the phase components of the carbide and binder phases, the entropy of the material of the parts decreases, and the wear resistance increases.

This determines the implementation of the improvement of the structure and composition of materials of tribocoupler parts and the reduction of their entropy in the following ways:

– change in the composition of the carbide phase;

– development of new hard alloys;

– change in the composition of the binding phase;

– reducing the size of the carbide phase from 2.0...2.5 μm to nanosize, ensuring an increase in the density, strength of the alloy and the corresponding wear resistance of the parts and their tribocoupling as a whole.

Conclusions

1. The implementation of the self-organization effect associated with excess entropy production is theoretically substantiated.

2. The relationship between the tribotechnical characteristics of the friction zone and the rate of change of entropy in the tribocouplings of parts was obtained.

3. With the negative production of the entropy of tribocoupling of parts, the conditions for realizing self-organization are obtained.

4. The main provisions of the entropy approach to changes in the properties of the friction zones of parts of tribocouplings of assemblies, systems and machine assemblies are formulated.

5. Derived expressions for estimating the intensity of wear of tribocoupling parts. They were refined taking into account the predominant role of thermal processes in the wear of parts materials.

6. Based on the experimental results, the directions of changes in the characteristics and properties of materials of tribocoupling parts from the change in entropy based on the entropy approach are substantiated.

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Аулін В.В., Тихий А.А., Кузик О.В., Лисенко С.В., Гриньків А.В., Жилова І.В. Виявлення змін характеристик і властивостей зон тертя деталей трибоспряжень систем і агрегатів машин на основі ентропійного підходу

З'ясовано роль ентропії в процесах тертя і зношування матеріалів трибоспряження рухомих деталей. Теоретично обґрунтовано реалізацію ефекту самоорганізації матеріалів в залежності від виробництва ентропії. Отримано умови самоорганізації при від'ємному виробництві ентропії. Визначено зв'язок швидкості об'ємного зношування трибоспряження деталей від виробництва надлишкової ентропії і її потоку. Отримано вирази для інтенсивності зношування деталей трибоспряження з урахуванням теплових процесів в зоні тертя. З'ясовано тенденції зміни характеристик і властивостей трибоспряжень деталей вузлів, систем і агрегатів машин зі зміною ентропії

Keywords: ентропійний підхід, трибоспряження деталей, самоорганізація, зона тертя, властивість.

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INFORMATION ABOUT JOURNAL"PROBLEMS OF TRIBOLOGY"

POLICY (GOAL AND TASKS)

"Problems of Tribology (Problems of Tribology)" - an international scientific journal.

Along with the main task of collecting information from tribology, the journal also performs organizational and coordinating functions:

- coordination of scientific and technical work in the field of tribology;
- organization of conferences, sympsiums;
- organization of work on the creation of databases and expert systems in the field of tribology;
- the organization of communications and information exchange between specialists in the field of tribology internationally.

2. The journal contains articles directly or indirectly related to tribology, including:

- theoretical problems (physics, chemistry, mechanics, mathematics)
- experimental methods and research results;
- contact mechanics, friction, wear, lubrication, durability and reliability of friction units of machines and units;
- scientific, technical and production problems of manufacturing, repair, improving the quality, reliability and durability of friction;
- technological and structural methods of improving wear resistance, frictional and anti-friction properties of friction units;
- problems of tribo materials science;
- methodological and methodological issues of training specialists in tribology.

3. The main requirements of the article is the novelty and completeness of information.

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Experimental articles should contain complete information about the methodology, conditions and results of the experiment.

Technological profile articles should contain a description of the technology as much as possible. If it is impossible to disclose "know-how", the method of obtaining the necessary detailed information must be indicated.

4. All articles are reviewed by a closed double review for compliance with the topics and level requirements. At the same time, the authors are fully responsible for the content of the articles.

5. Due to the international nature of the journal it is preferably submit articles in English.

REQUIREMENTS TO THE ARTICLES

In order to publish an article in the journal authors should submit it by e-mail.

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Article structure:

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The recommended length of articles (including text, tables, and figures) is 6–9 pages. Figures should not exceed 25 % of length of an article. The text should be laconic, and should not contain duplicated information. No running titles and section brakes should be applied in the file.

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References(no more than 15 items, published not earlier than 5 years before, no more than 20%of self-citations) should be listed in the order of appearance in the text of the article. The in-text references should be given in square brackets.

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